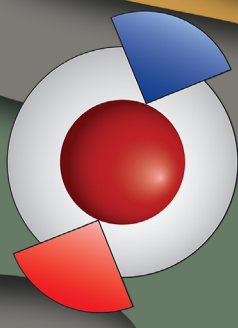
2020

Annual Report



CCFS

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

- CCFS information is accessible on WWW at:

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

- Contact CCFS via email at:

  ccfs.admin@mq.edu.au

The CCFS Annual Report is available from our website http://www.ccfs.mq.edu.au/ as a downloadable pdf file or in html format.

Continuing achievements of CCFS are given under "Flagship Programs", p.21, and the cumulative Research Highlights compilation at http://ccfs.mq.edu.au/Research%20Highlights/

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 2020 (formally commenced mid 2011). Activities include research, technology development, stakeholder engagement, international links and research training. It also provides the research plans for 2021.

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

The 7-year allocated Centre funding from the ARC ceased at the end of 2018, but ARC formally granted continuation of the status of CCFS as an ARC Centre of Excellence for three years, contingent on demonstration of a relevant, funded continuing research program and retention of key researchers. As highlighted in the 2018 CCFS Report, eight of the Future Fellows awarded in CCFS transitioned to continuing academic positions and the two Laureate Fellowships (awarded 2015 and 2018) across two nodes of CCFS, increasing the critical research mass within areas fundamental to understanding "*Core to Crust Fluid System*". These prestigious Fellowships with associated generous grants thus help to underpin funding, expertise and research personnel to continue the frontline research characteristic of CCFS aimed at better defining Earth's 4D evolution and its composition and architecture today - the Earth framework that enables our civilisation to inhabit this amazing planet.

How has CCFS made a difference?

Selected examples are listed below.

Pioneering Integrative approach to understanding Earth across deep time and space (4D)

The conceptual framework of integrating geochemical, geophysical, geological, tectonic and geodynamic datasets in a GPS environment has revolutionised our holistic understanding of the inaccessible deep Earth. It has lead to the predictive modelling of the location of large economic deposits and enhanced understanding of how the Earth works and has evolved. CCFS advances in these geoscience disciplines seamlessly incorporate Bayesian mathematical approaches and innovative imaging techniques to probe planetary, global terrain and nanoscales advancing geoscience capabilities.

Training a new generation and thus spreading new knowledge across critical areas in society

CCFS has so far graduated 126 PhD students and 50 early-career researchers have participated in CCFS. 42 PhD students undertook research aligned with CCFS in 2020. In addition, over 30 international PhD students and more early-career researchers have had extended periods of research in CCFS on externally-funded scholarships, resulting in significant research outputs with CCFS bylines (see *CCFS publications*). CCFS postgraduates are producing world-class research with authorship of 26 publications (21 first-authored) in high-impact journals in 2020 and 15 presentations at peak international workshops and conferences (most by virtual mechanisms due to travel restrictions under COVID-19).

This cohort forms the future generation of frontline researchers and professionals with comprehensive experience in solving difficult problems with tantalisingly incomplete datasets, into a world future with increasingly complex problems requiring clever integrative approaches.

We are particularly proud that CCFS-aligned early-career researchers have populated a broad cross-section of professions including industry, government and commercial environmental agencies, stock exchange advising, state and national geological surveys, commercial geochemical laboratories (e.g., Rio Tinto has employed 8 former CCFS/GEMOC geochemists) as well as fulfilling valuable high positions in academia (research and teaching). This CCFS diaspora is thus bringing critical knowledge and new understanding of Earth's behaviour to many areas of society at a serious tipping point in managing climate change and in providing critical minerals for a sustainable national (and global) future.

Outstanding Fundamental Research

CCFS produced 153 publications in 2020 in both high-impact journals and books, and in journals targeted for specific audiences

Clarivate/Thomson Reuters have recognised CCFS' frontline research through citation-, innovation- and highly-cited awards to CCFS researchers, in addition to the Google Australian Researcher of the Year award, and recognition of a CCFS Chief Investigator as one of the "*World's Most Influential Minds*" across several years. Numerous awards of *'annual best paper'* in prestigious journals, a constant flow of keynote presentations and awards of best posters and talks at peak and influential conferences and international workshops, by senior, early-career and postgraduate CCFS researchers, all provide evidence of peer recognition internationally.

Frontline advances in geophysics were enabled because of the funding and timeframe provided by the Centre funding including: further development of ambient-noise adjoint-tomography; LitMod's 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle; new inversion techniques to understand earthquake generation in Western Australia; revolutionary multiphase multicomponent reactive transport modelling of disequilibrium melt-rock processes and geochemical geodynamics (e.g., CCFS publication #1510). All of these seminal contributions embed geochemical, tectonic, geological and/or advanced imaging and modelling components, emphasising integration across diverse datasets and methodologies.

Another example (among the many in CCFS) of research that could not have been achieved without the funding, scale and focus of a Centre of Excellence is the ongoing "*Tibet Project*" that involves all nodes, more than 30 CCFS researchers from Chief Investigators to PhD students and international collaborators, and three Flagship Programs. This program has generated four IGCP (International Geological Correlation Project) Programs. Outcomes so far include breakthroughs in understanding in detail: the tectonic history of the Himalayas from palaeomagnetic evidence; the sources and mechanisms for mineralisation (e.g. copper, gold, chromite and critical minerals) in different collision zone scenarios, not only in Tibet but along the entire Tethyan Belt and analogue tectonic environments; identifying domains of highly-reduced mantle environments; demonstrating that some collision zone domains are excavated from Earth's transition zone 450 km beneath the surface, and recognising the analogue relevance for mineral exploration in the Australian Tasmanides.

International Collaborations

Global alliances with leading international geoscience groups have been forged through formal collaborative partnerships, programs and exchanges across multiple institutions (including China, Spain, France, Canada, Norway, Germany, South Africa, Taiwan, India, USA). These collaborations leverage the Centre funding, expertise and researcher resources and commonly include cotutelle PhD programs, which provide the basis for a new generation of productive global research alliances. The collaborations are active and productive with ongoing mutual interaction - mostly through digital platforms in 2020, including international workshops and more individual research discussions and planning.

Technology Development and New Directions

The *Technology Development* section of this report documents the ongoing frontline developments related to *in situ* geochemical analysis and imaging technologies using the outstanding array of advanced instrumentation accessible across CCFS nodes. Of increasing value is the co-registration of data across all types of digital information so that overlays of multiple datasets provide new insights into the distribution of physical properties, specific elements and chemical domains in the Earth (in many regions to depths of ~400 km) and relationships to the physical properties detected in seismic, magnetotelluric, gravity and magnetic surveys.

Significant novel geochemical instrumental methodologies have resulted in step-changes for characterising element distributions and concentrations at increasing resolution and smaller spatial scales. Outstanding advances (at MQGA) include: delivery of first *"routine"* methodology for the *in situ* analysis of Rb-Sr isotopic data (and pushing age determinations to younger than 20 Ma), a new benchmark in time- and cost-effective geochronology; *in situ* sulfur isotope analysis in sulfides using tandem LA-ICP-MS and *in situ* zirconium isotopes (See *Technology Development* for a comprehensive list.)

CCFS has been a very active participant in the nascent AuScope Australian Geochemistry Network (AGN: https://www.auscope.org.au/agn). AGN is implementing a national geoscience database, capturing legacy and real-time geochemical datasets aligned with FAIR (Findable, Accessible, Interoperable and Reusable) principles. This will enable the co-registration of multiple digital datasets (e.g., geophysical, geochemical, physical state and property, time) in multidimensional space for unprecedented imaging of Earth characteristics.

One of the most exciting achievements encapsulates the intrinsic goals of CCFS. A paper just submitted is a world-first demonstration that robust first-principle modelling using multiple high-resolution geophysical datasets from both land and satellite surveys can image nuanced physical and chemical differences vertically and horizontally in the lithosphere. This modelling has not only replicated detailed high-resolution lithospheric sections constructed using the traditional approach based on geochemical data from the virtual drill-holes provided by mantle-derived xenoliths; it bridges the regions in between and is thus validated for regions lacking groundtruthing from xenolith data. This methodology can be employed wherever appropriate high-resolution geophysical datasets are available or can be acquired – the location is not restricted by the spatial occurrence of xenolith-bearing volcanics: therefore

this joint inversion approach delivers a validated shortcut and greater spatial coverage than the more time-intensive xenolith methodology (months versus years).

CCFS Equity and Diversity

Since CCFS commenced, the gender balance in PhD students has been approximately equal, with a moderately higher cohort of women; the ECR cohort has had slightly fewer women than men. The Macquarie CCFS academic staff have had approximately even women/men ratios throughout, underpinned by CCFS family-friendly policies including consideration of meeting times to accommodate those with school and pre-school children, and provision of child care during CCFS meetings. Diversity has always been exceptionally high in CCFS, with participants (junior and senior) from over 25 countries. I have had a significant role in shaping national STEM policies for women, as Chair of the Australian Academy of Science Equity and Diversity Reference Group, and participated in the preparation and launch of the STEM Decadal Plan in 2019 for Minister Karen Andrews (www.science.org.au/support/analysis/decadal-plans-science/women-in-stem-decadal-plan). Implementation of the plan so far includes a dedicated webpage on STEM Women, capturing and sharing national sector progress and gender equity activity.

Industry and end-user engagement

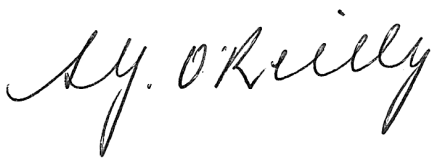
Industry interaction has been an integral component of CCFS. Collaborative projects with industry input (including guidance from CCFS Board members) have shaped the relevance of the fundamental research directions, and enabled continuation of relevant CCFS activities. These include the ongoing work in CET (UWA) in training courses and in research responses relevant to industry needs. Geophysical research has attracted significant industry and end-user collaborations. One example is the large-scale fully funded collaboration with IGG CAS to undertake a 900-km-long dense (station spacing of 10-15 km) seismic profile across Western Australia from Port Hedland to the southwestern border of Kimberly Craton, using 60 broadband seismic stations from IGG CAS, and 20 from ANSIR (ongoing in 2020 and projected for funding in 2021). Other funded examples (detailed in the Industry interaction section) include: a de Beers-resourced *"Multiobservable Thermochemical Tomography of Central and South Africa"*; *"Developing thermochemical models of Australia's lithosphere"* with Geoscience Australia; and a Linkage Project *"Illuminating AusLAMP"*, targeted at joint interpretation of magnetotelluric and seismic datasets. Ongoing collaboration with MTI (Mineral Targeting International) is not only focussing on high-resolution interpretation of seismic tomography to reveal paleotectonics; the principal, Dr Graham Begg, is also providing invaluable mentoring especially for early-career researchers with ambitions to work in the exploration industry.

Shaping International and National Science policy

CCFS researchers are now sought as thought-leaders globally for research related to Earth's lithosphere and the integrated use of large datasets across geochemistry, geology and geophysics. CCFS researchers nationally provide advice to local, state and federal departments and members of parliaments, and through Australian Academy formal reports and reviews to the Chief Scientist and the Australian government on a wide range of geoscience-related issues. CCFS has indeed fulfilled its Vision of *"Delivering the fundamental science needed to sustain Australia's resource base"* and its new generation of researchers are a vital part of the CCFS legacy and continuation.

In the future?

2020 was one of the most difficult years for Australian universities in many decades (ever?), and all are making hard choices that may topple Australia's position as one of the most outstanding global performers in research in many fields (including geoscience) on a per capita basis. CCFS may not be immune from these effects, and as Macquarie faces 2021, a foreshadowed *"change process"* may see the demise of its geoscience undergraduate teaching and dramatic curtailment of its research capability, determined on the basis of low undergraduate student numbers and hence income rather than performance. As rumours are circulating, dozens of CCFS alumni across the world have sent unforgettable emails about their experiences in CFFS and its antecedents (including GEMOC) all expressing in some way that *"your legacy will never be lost as you did not only construct a building or a lab, but a worldwide family of top-performing scientists who respect each other, which is even more difficult ….".* It has been deeply rewarding and the highest privilege to have a part in shaping and enriching the scientific futures of so many talented, dedicated and outstanding people, now members of the world geoscience community.
I have been very touched by all of these messages and to see such evidence of the strength of the global CCFS network. So, as always, for the future, we must remember to carpe diem at every opportunity!



Professor S.Y. O'Reilly

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

Vision

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

GOALS - THE MISSION

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

CONTEXT

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

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

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

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

CENTRE RESEARCH

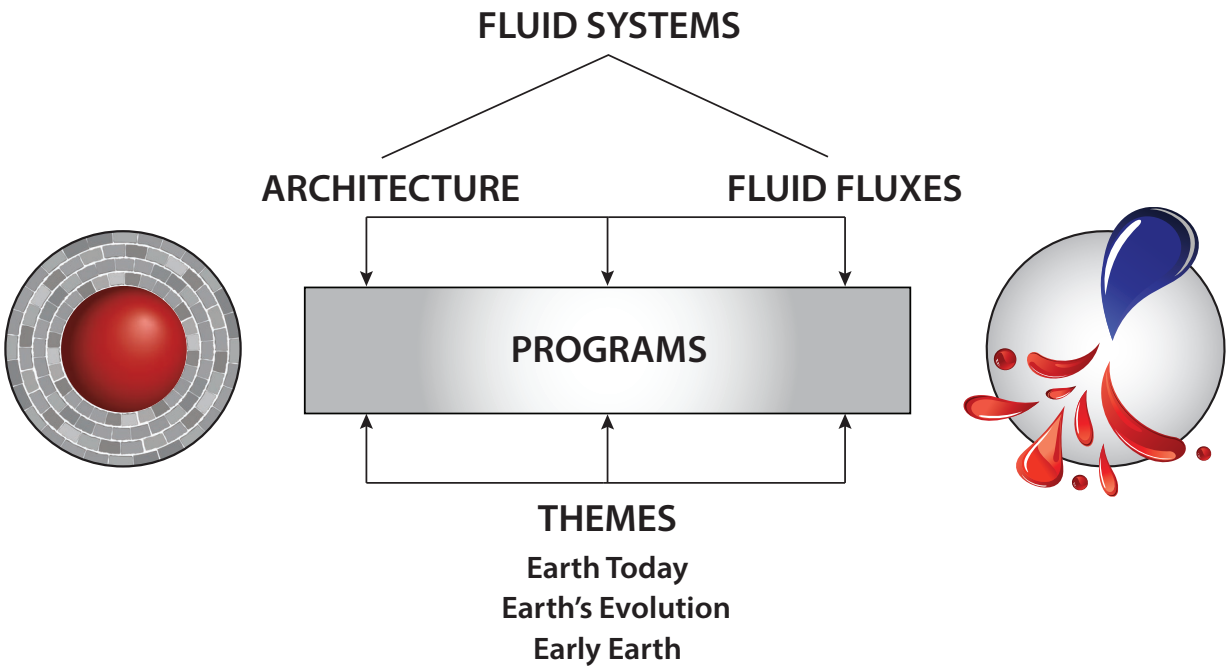
Research programs within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research is carried out in parallel, supported by other funding sources. The Research Program structure was revised in 2014 to ensure the overarching goals were being fulfilled. The resulting Flagship Programs (see *p. 12*) 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"*.

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 and Programs are 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 allows us to test the involvement of biological processes in ancient deposits.

The earliest record of Earth's magnetic field provides new information on when the core's geodynamo formed and the geometry and intensity of its field and is used to track the movement of Archean tectonic plates. The geochemical nature and dynamic behaviour of the mantle in the early Earth continues to 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 define the rates of continental growth *vs* recycling through time and test linkages between crust and mantle events. Geophysical imaging and dynamic modelling have been used to build 3D models of subduction dynamics, thermal evolution and geodynamic cycles. Stable-isotope studies track water and other fluids in their cycles through the Earth and the hydrosphere.

THEME 3: EARTH TODAY

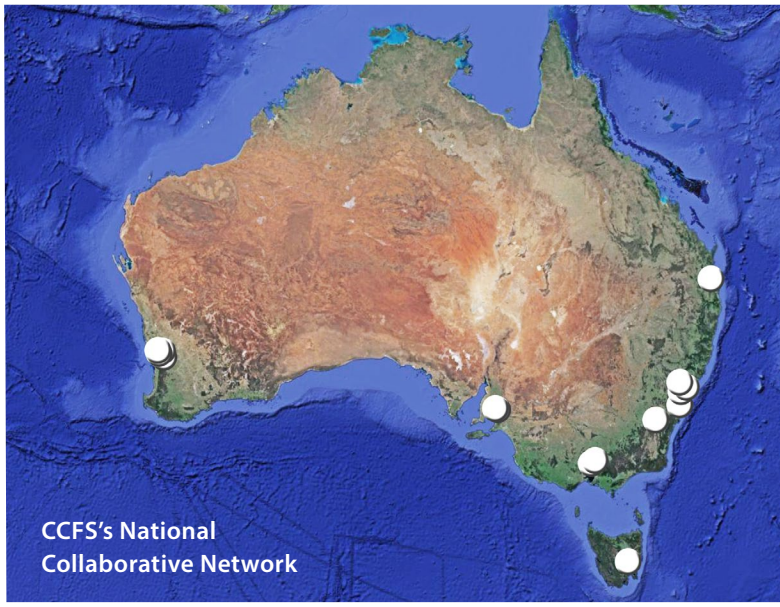
Earth Today - Dynamics, decoding geophysical imaging, and Earth resources. Geophysical imagery gives us a snapshot of the current status of the deep Earth but also carries the imprints of past processes. Realistic interpretation of these data provide us with new insights into Earth's internal dynamics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

Measurements of the physical properties of potential deep Earth materials at extreme conditions 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 provides new ways to interpret observations on fluid/melt inclusions in minerals. CCFS is investigating 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.

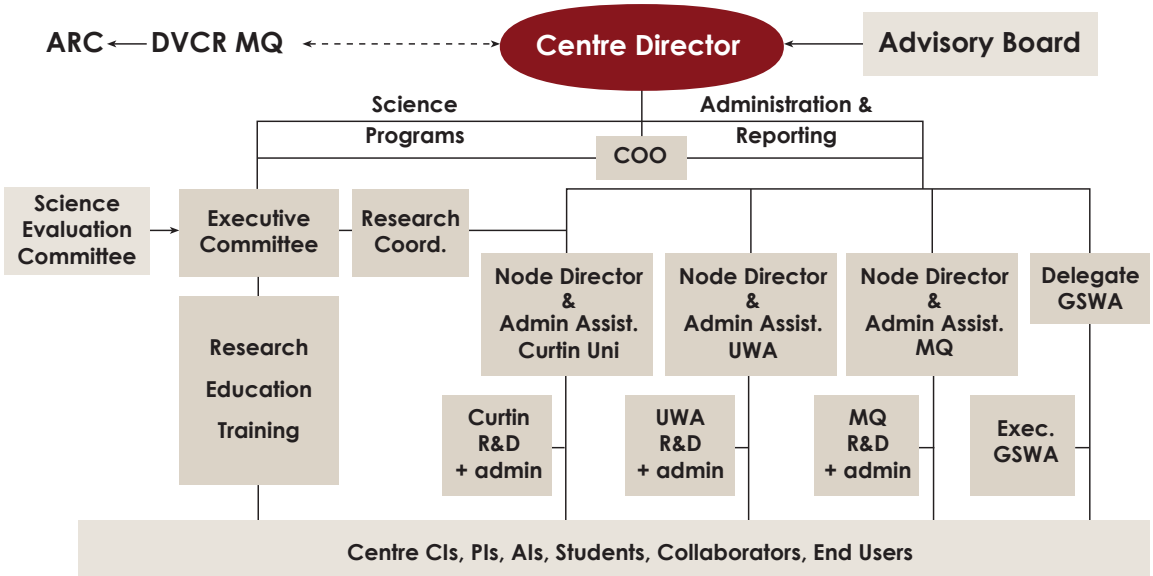
Yasur volcano, Tanna island Vanuatu

Structure

CCFS builds on a world-class infrastructure base and multiplies the capabilities of three internationally recognised centres of research excellence: Macquarie University (Administering Institution), Curtin University and the University of Western Australia. The Geological Survey of Western Australia is a Partner Institution and researchers from Melbourne University and the University of New South Wales are formally affiliated. The overseas nodes led by Partner Investigators in France, China, Germany and the USA are contributing resources and provide access to a wide variety of expertise and instrumental capabilities. Memoranda of Understanding (MOU) for research collaboration and postgraduate exchange and joint programs, provide formal affiliations with six additional global institutions with leading reputations in the field. CCFS also has formal Cotutelle MOU with a further fourteen global institutions (*see p. 53*). 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.

During the ARC funding period, the Advisory Board's external membership comprised senior representatives from industry and other end-users such as Geoscience Australia. This model had proven highly productive during the lifetimes of the GEMOC Key Centre and CET. The Board met at least annually to provide advice on the research program and governance, and any other matters relevant to CCFS.

The Science Advisory Committee had a rotating membership and provided valuable evaluations of 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

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

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

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

Professor Zheng-Xiang Li
Department of Applied Geology,
Curtin University

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

Associate Professor Matthew Kilburn
Deputy Director, CMCA
University of Western Australia

(Ex Officio)
Professor Stephen Foley - Research Coordinator
Department of Earth and Planetary Sciences
Macquarie University

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

Advisory Board

Dr Ian Gould
Former Chancellor, University of South Australia

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

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

Dr Jon Hronsky
Principal, Western Mining Services

Dr Phil McFadden
Treasurer and Executive Committee,
Fellow, Australian Academy of Science;
driver of the UNCOVER initiative

Dr Roric Smith
Consulting Geologist
Evolution Mining

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

plus the Executive Committee

Participants

Organisations

Administering Organisation

Macquarie University (MQ)

Collaborating Organisations

Curtin University (CU)

University of Western Australia (UWA)

Partners

Australian Partner

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

International Partners

CNRS and Université de Montpellier, France

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

University of Maryland, USA

University of Saskatchewan, Canada

Bayreuth University, Germany

Chief Investigators

Associate Professor Elena Belousova - MQ

Professor Simon Clark - MQ

Associate Professor Marco Fiorentini, Node Leader - UWA

Professor Stephen Foley, Research Coordinator - MQ

Honorary Professor William Griffin - MQ

Associate Professor Matthew Kilburn - CMCA/UWA

Professor Zheng-Xiang Li - CU

Associate Professor Alexander Nemchin - CU

Associate Professor Craig O'Neill - MQ

Professor Suzanne Y. O'Reilly, Director - MQ

Professor Martin Van Kranendonk - UNSW

Professor Simon Wilde, Node Leader - CU

Associate Professor Yingjie Yang - MQ

A full list of CCFS participants is given in *Appendix 2* and at http://www.ccfs.mq.edu.au/

Partner Investigators

Australian Partner Investigator

Dr Klaus Gessner - GSWA

Dr T. Campbell McCuaig - BHP Billiton

International Lead Partner Investigators

Professor Michael Brown - University of Maryland

Dr David Mainprice - Université de Montpellier

Professor Catherine McCammon - Bayreuth University

Professor Fuyuan Wu - CAS Beijing

Associate Investigators

Professor Juan Carlos Afonso - MQ

Dr Olivier Alard - MQ

Associate Professor Nathan Daczko - MQ

Dr Richard Glen - MQ

Dr Masahiko Honda - ANU

Professor Dorrit Jacob - MQ / ANU

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

Associate Professor Christopher Kirkland - CU

Professor Jochen Kolb - GEUS

Dr Yongjun Lu - GSWA

Professor Louis-Noel Moresi - University of Melbourne

Professor Steven Reddy - CU

Dr Svyatoslav Shcheka - MQ

Associate Professor Bruce Schaefer - MQ

Dr Michael Wingate - GSWA

Professor Shijie Zhong - University of Colorado, USA

CCFS FUTURE FELLOWS

The application for the CoE CCFS foreshadowed that such a Centre of Excellence would become an attractor for rising stars and research leaders in relevant disciplines and fields of interest. The success of CCFS participants in the ARC Future Fellow rounds emphasises this role of our Centre in recruiting high-flyers at early to mid-career levels. Eleven Future Fellows; Associate Professor Elena Belousova, Associate Professor Marco Fiorentini, Associate Professor Heather Handley, Professor Dorrit Jacob, Associate Professor Craig O'Neill, Professor Sandra Piazolo, Associate Professor Yingjie Yang, Dr Xuan-Ce Wang, Dr David Wacey, Dr Olivier Alard and Dr Kate Selway, have completed or are working on projects relevant to CCFS goals. The CCFS Future Fellows all continue to make significant contributions to CCFS, either directly or as external collaborators and Associates.

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

EARLY CAREER RESEARCHERS (ECR)

The second primary goal of CCFS (see *p. 4*) concerns the recruitment, development and mentoring of Early Career Research (ECR) staff "*for the development of the next generation of Australia's geoscientists*".

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

Early Career Researchers

- Dr Raphael Baumgartner - UWA
- Dr Stefano Caruso - UNSW
- Dr Montgarri Castillo-Oliver - MQ
- Dr Chunfei Chen - MQ
- Dr Isra Ezad- MQ
- Dr Guillaume Florin - MQ
- Dr Michael Förster - MQ
- Dr Yoann Gréau - MQ
- Dr Johannes Hammerli - UWA
- Dr Uwe Kirscher - CU
- Dr Hugo Olierook - CU
- Dr Beñat Oliveira Bravo - MQ
- Dr Lei Wu - CU

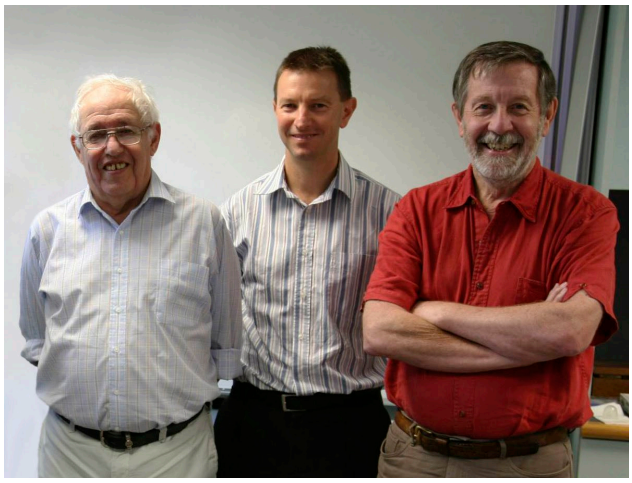
Future Fellow and ECR profiles can be accessed from the "*Participants*" section of our previous reports (http://www.ccfs.mq.edu.au/AnnualReport/Index.html).

VALE

Lev Natapov

We have lost a scholar and a gentleman. Lev Natapov (b. 1931) was the Chief Geologist of Aerogeologia, the Russian equivalent of a national geological survey, when he visited his daughter in Sydney in 1993 and was introduced by Felix Kaminsky as a man who could help us understand the geological setting of the Siberian kimberlites. He did not speak much English at that time, but he could draw great maps and diagrams! On his retirement in 1998, he and his wife Iskra moved to Sydney and Lev came to GEMOC and asked if he could be of help. His encyclopaedic knowledge of geology and tectonics (and all sorts of mineral deposits) became central to the development of the GLAM project. Lev had a remarkable memory and a fantastic ability to condense stacks of monographs and papers into the maps and data needed for GLAM's delineation of lithospheric domains. He worked closely with Graham Begg and GEMOC/CCFS on this project until ill health forced his retirement in 2018.

Lev was famous as one of a small group of Russian scientists who argued the case for plate tectonics in Russia, where the concept was officially rejected. On the fall of the Soviet Union, he and two colleagues published their work in an invited monograph of the American Geophysical Union (Zonenshain, Kuzmin & Natapov 1990; Geology of the USSR: A plate-tectonic synthesis). As a polymath and scholar, Lev contributed to the cultural life of the Russian community in Sydney in many ways, including authorship of 7-8 books and many articles on aspects of Russian and Australian culture, even including Australian colonial architecture. He was a remarkable man, a great scientist and a good friend, and we will be greatly missed.



Lev Natapov (Left) with colleagues Graham Begg and Bill Griffin.

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. 12*) 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 targeted the research goals through to 2019, providing a new focus and realigned strategies to deliver vital new knowledge about Australia's geological evolution to guide smart new mineral exploration. They have provided the basis for continuing mature research strands underpinned by two Technology Development Programs designed to deliver more leading-edge geochemical breakthroughs, capitalising on the outstanding geochemical instrumental infrastructure across CCFS.

Projects are detailed in *Flagship Programs*.

Independently funded basic research projects are listed in *Appendix 1*.

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**, Kilburn, Martin, Alard, Huang, Giuliani Gréau, Castillo-Oliver, Lu (ECRs) Dai, Takenaka de Oliveira, Greene (PhDs)
2. Genesis, transfer and focus of fluids and metals Themes 2 and 3 Fluid Fluxes	**Fiorentini**, Foley, O'Reilly, Griffin, Reddy, Lu, Bagas, Kilburn, Loucks Fougerouse, Gonzalez, Hammerli, LaFlamme, Parra-Avila (ECRs) Bennet, Bownan, Cherdantseva, Choi, Chong, Jara, Mafra, Poole, Vernes (PhDs)
3. Modelling fluid and melt flow in mantle and crust Themes 2 and 3 Earth's Architecture and Fluid Fluxes	**O'Neill**, Afonso, Yang, Li, Foley, Clark, S. Zhang, O'Reilly, Griffin, Shcheka Chen, Förster, Gao, Jiang, Oliveira Bravo (ECRs) Lanati, Liu, Manassero, Pinter, Wasilev, Wang, Wu, Zhang (PhDs)
4. Atmospheric, environmental and biological evolution Theme 1 Earth's Architecture and Fluid Fluxes	**Van Kranendonk**, Fiorentini, Foley, Kirkland, Kilburn, Alard, Baumgartner, Caruso, LaFlamme (ECRs) Barlow, Djokic, Nomchong, Soares, Tadbri, Teece (PhDs)
5. Australia's Proterozoic record in a global context Themes 2 and 3 Earth's Architecture	**Li**, Pisarevsky, Wang, Wingate, O'Reilly, Griffin, Belousova, McCuaig, Mitchell, Kirscher, Yao (ECRs) Y. Liu, Martin, Nordsvan, Volante (PhDs)
6. Fluid regimes and composition of early Earth Themes 1 and 3 Earth's Architecture and Fluid Fluxes	**Wilde**, Nemchin, Martin, O'Neill
7. Precambrian architecture and crustal evolution in WA Themes 1, 2 and 3 Earth's Architecture	**Gessner**, Kirkland, Belousova, Gréau, Yuan, Wingate, Tyler, Lu Wu (ECR)

TECHNOLOGY DEVELOPMENT

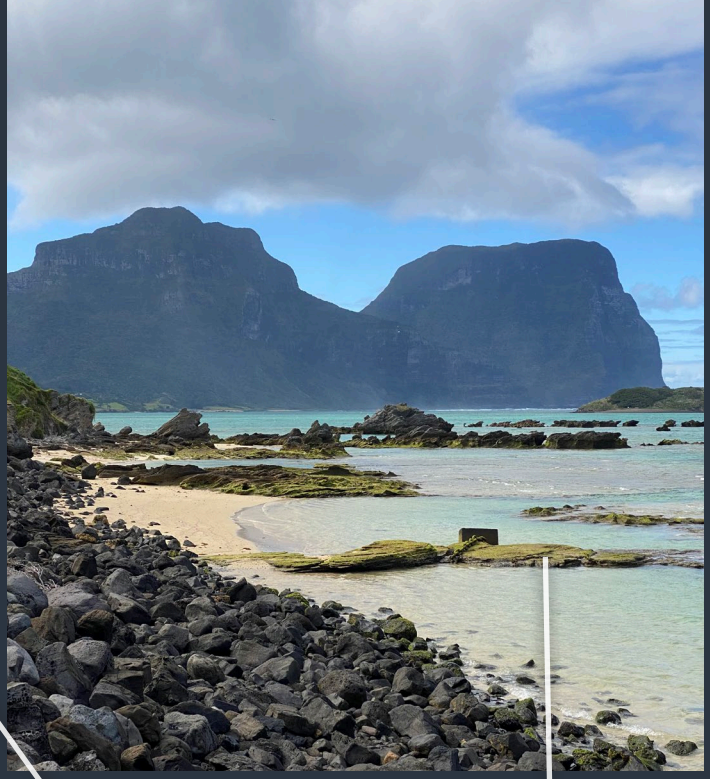
Cameca Ion microprobe development Themes 1, 2 and 3 Earth's Architecture and Fluid Fluxes	**Kilburn**, Martin, Fiorentini, Griffin, LaFlamme, Reddy Students of CIs and ECRs utilising the Ion Probe Facility are active in the program
GAU multi-instrument development Themes 1, 2 and 3 Earth's Architecture and Fluid Fluxes	**Alard**, Griffin, O'Reilly, Gréau, Kilburn, Martin, Huang Students of CIs and ECRs utilising the MQGA Facility are active in the program

Where out of this world is CCFS?

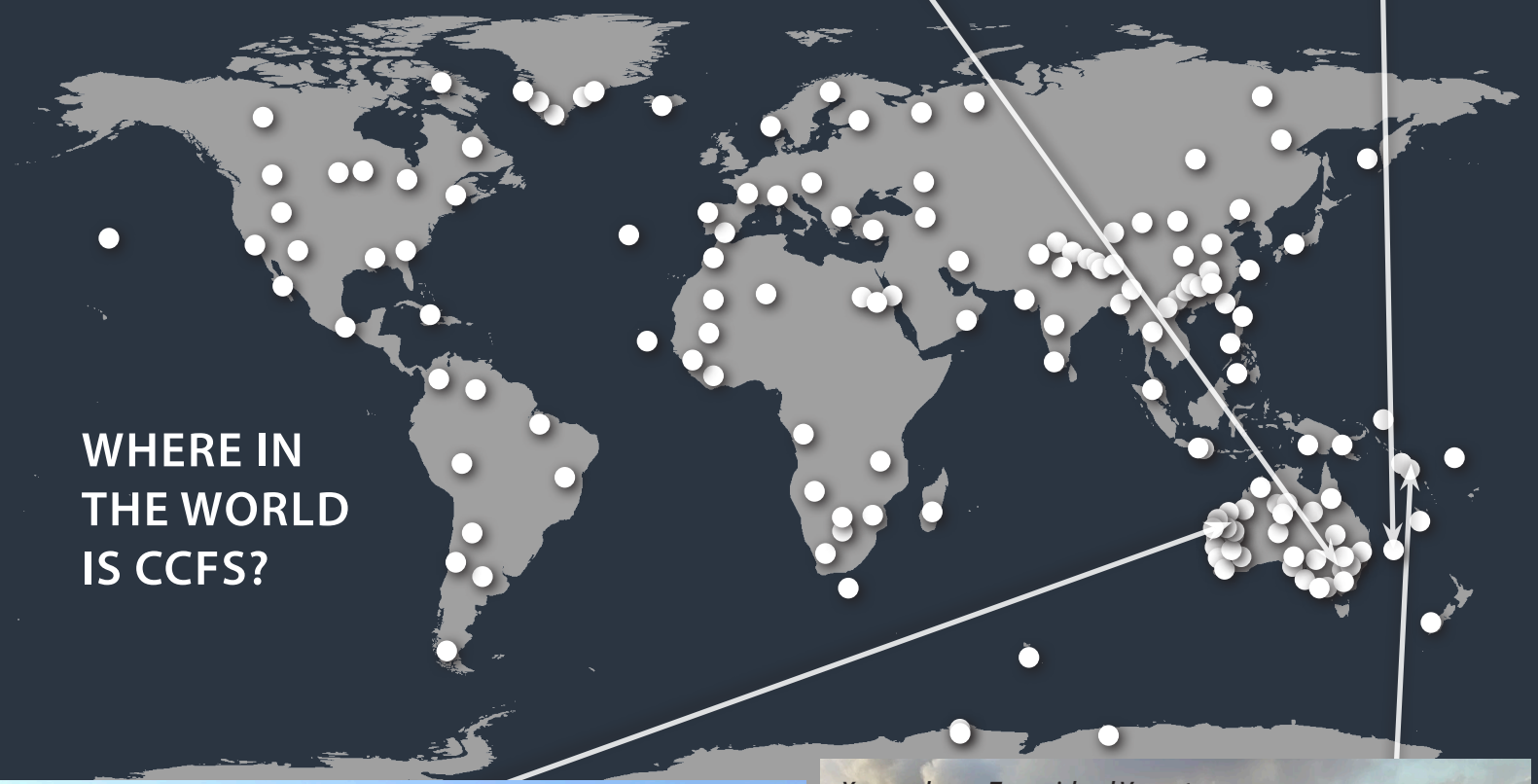
As part of our quest to better understand the processes that led to the formation of the early Earth, CCFS has been investigating the early history of the Moon, Mars and Venus.

Moon Mars Venus

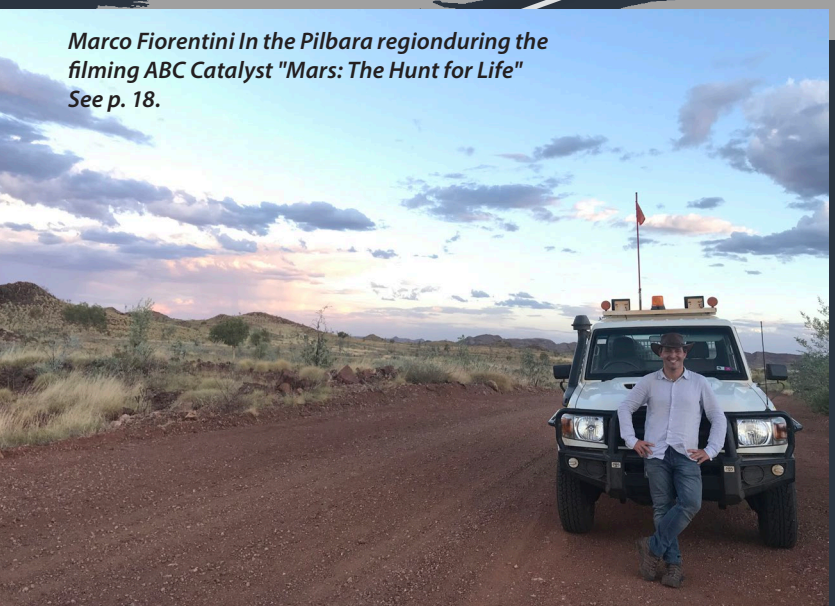
Leucitite vents at Tullibigeal, NSW (photo, Anthony Lanati)



Lord Howe Island (photo Elena Belousova)



WHERE IN THE WORLD IS CCFS?



Marco Fiorentini In the Pilbara regionduring the filming ABC Catalyst "Mars: The Hunt for Life"
See p. 18.

Yasur volcano, Tanna island Vanuatu (photo Elena Belousova)

Communications 2020

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 2020 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 2020 are given in Appendix 3.

The 153 CCFS publications that were published in 2020 are predominantly 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 has a LinkedIn Group - Join the conversation at http://www.linkedin.com/groups/6969996

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2020

CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at 11 peak geophysical, metallogenic, geodynamic and geochemical conferences and workshops as convenors, invited speakers, or presenters, with 60 presentations including:

- AUGEN Field Meeting, SCAR2020 - Science Council of Antarctic Research, Launceston, Hobart, 29-31 January and 31 July-11 August 2020
- Workshop: Emergence of Life, Munich, Bremen, and Italy, 15-21 February 2020
- Australia Earth Sciences Convention Conference Abstracts, Tasmania, Australia, 21 February 2020
- Prospectors and Developers Association of Canada Convention, Toronto, Canada, 1-4 March 2020
- International Geological Conference Abstracts, Delhi, India, March 2-8 2020
- EGU General Assembly, Online, 4-8 May 2020
- Goldschmidt Virtual 2020, 21-26 June 2020
- 6th International Archean Symposium, Perth, Australia, 14-16 July 2020
- 2020 Eresearch Australasia Online Conference, 19-23 October 2020
- Short Course on Magmatic Sulfide Mineral Systems, UWA-CSIRO, 17 November 2020
- AGU Fall Meeting, Online Everywhere, 1-17 December 2020

CONFERENCE/WORKSHOP ROLES

WORKSHOP: EMERGENCE OF LIFE MUNICH, BREMEN, AND ITALY, 15-21 FEBRUARY 2020

Invited Speaker: Martin Van Kranandonk

AUGEN FIELD MEETING, SCAR2020 - SCIENCE COUNCIL OF ANTARCTIC RESEARCH, LAUNCESTON, HOBART, 29-31 JANUARY & 31 JULY-11 AUGUST 2020

Session Co-Convenor: Nathan Daczko
Session: Antarctica and its neighbours in supercontinent cycles

A full list of abstracts for Conferences and Workshops attended is given in Appendix 4 and on the CCFS website.

CONFERENCE/WORKSHOP ROLES *cont...*

IGCP 648 VIRTUAL SEMINAR SERIES ONLINE MAY-AUG, SEPT-DEC 2020	*Co-Organiser and Host:* Zheng-Xing Li Weekly seminars by various contributors of diverse backgrounds. More information and recordings at http://geodynamics.curtin.edu.au/igcp-648-virtual-seminar-series/
SHORT COURSE ON MAGMATIC SULFIDE MINERAL SYSTEMS, UWA-CSIRO 17 NOVEMBER 2020	*Organiser:* Marco Fiorentini
AGU FALL MEETING, ONLINE EVERYWHERE, 1-17 DECEMBER 2020	*Co-Convenor, Co-Chair:* Huaiyu Yuan Session: T029 *"Tethyan Dynamics I"* Session: T025 *"Tethyan Dynamics II Posters"*

ESTEEM

AWARDS

Participant	Activity
Sue O'Reilly	NSW Premier's prize for "*Excellence in Mathematics, Earth Sciences, Chemistry or Physics*" https://www.chiefscientist.nsw.gov.au/events/nsw-premiers-prizes-for-science-and-engineering/2020-category-winners 
Nathan Daczko, Michael Rampe, Peter Reeves	2020 VC's Learning and Teaching Awards, Highly Commended Finalist
Nathan Daczko, Michael Rampe, Peter Reeves	2020 Faculty of Science and Engineering Awards, Teaching Excellence, Highly Commended

AWARDS *cont...*

Participant	Activity
Kim Jessop, **Nathan Daczko**, Sandra Piazolo	2020 Stillwell Award (The Geological Society of Australia, for best paper in Australian Journal of Earth Sciences 2019)

For Postgraduate awards see the "*Postgraduate*" section *p. 33.*

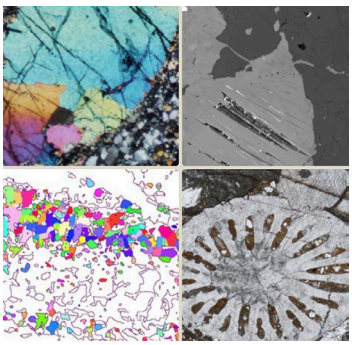
2020 NEW APPOINTMENTS AND POSITIONS

Zheng-Xiang Li	Principal Project Leader - IGCP 648: Supercontinent Cycles and Global Geodynamics Member of the Overseas Advisory Committee, China State Council
Yongjun Lu	Secretary of the 6th International Archean Symposium (6IAS), Perth 2020 Treasurer, Specialist Group in Geochemistry, Mineralogy & Petrology (SGGMP), Geological Society of Australia Mentor, Society of Economic Geologists (SEG)
Craig O'Neill	Member of the Australian Academy of Science National Committee for Earth Sciences
Sue O'Reilly	Member Executive Committee, UNCOVER national initiative (Auspices of the Australian Academy of Science) Chair, Academy of Science National Committee for Earth Sciences, and Decadal Plan preparation Member of Council, Australian Academy of Science Elected Member of Executive Committee, Australian Academy of Sciences from 2018 Co-Chair inaugural Australian Academy of Science Task Force for "*Equity and Diversity*" Australian Member, IUGG Nominations Committee Project Leader - IGCP 622: "*Orogenic architecture and crustal growth from accretion to collision*" Chair, Equity and Diversity Reference Group, Australian Academy of Science
Martin Van Kranendonk	Mars2020 Sample Return team member

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	O'Reilly, Wilde
American Journal of Science	Wilde (Assoc. Ed.)
Cogent Geosciences	O'Neill
Earth and Planetary Physics (EPP)	Yang
Exploration Geophysics	Selway, Yang
Geodynamics & Tectonophysics	Pisarevsky
Geodynamics	Yuan (Assoc. Ed.)
Geol. Society of America Bulletin	Li (Assoc. Ed.)
Geophysical Journal International	Afonso
Geosphere	Yuan
Journal of Earth Sciences	Li
Lithos	Foley, Griffin
Mineralium Deposita	Fiorentini (Assoc. Ed.)
Nature Scientific Reports	Daczko, Jacob, Li

EDITORIAL APPOINTMENTS	
Precambrian Research	Pisarevsky
Russian Geology and Geophysics	Pisarevsky
Science China - Solid Earth	Yuan
Scientific Reports	Li
Solid Earth Sciences	Griffin
Tectonophysics	Li (Co-editor in chief)

OUTREACH

Forum	Participant/s	Date
Virtual petrography https://imagematrix.science.mq.edu.au/ 	Nathan Daczko	2020
CSIRO STEM Professional in School program	Luc Doucet, Zheng Xiang Li	2020
AusEarthEd resources - Rock Detectives - Sydney Harbour Bridge and Sydney Sandstone Promary School. Sydney Science Week - 10 videos channel https://www.youtube.com/channel/UCrnZ3_G0x2sCy3PJcbaedoA /videos	Nathan Daczko	March 2020
AusEarthEd-PACE project: rounding	Nathan Daczko	April-May 2020
TESEP-PACE project: petrographic descriptions of samples in the TESEP rock kit	Nathan Daczko	April-May 2020
Virtual field trips - Primary schools https://sites.google.com/view/mapping-bingie/ https://sites.google.com/mq.edu.au/outcropanalysis/ https://sites.google.com/view/sydney-chinatown/home 	Nathan Daczko	March-Aug 2020
Early signs of life preserved in Paleoarchean hot spring deposits from the Pilbara and the search for life elsewhere	Tara Djokic	5 June 2020
Ancient carbon rocketing us into a renewable future - Virtual Seminar Macquarie University	Marco Fiorentini	18 Sep 2020
Year 4 Geology Awareness Program, Year 4 students Cottesloe Primary School (WA)	Marco Fiorentini	15 Sept 2020
TerraneChron®: Past, Present, Future - Invited seminar, ANU	Elena Belousova	22 October 2020
TerraneChron®: Past, Present, Future - Invited seminar, University of Adelaide	Elena Belousova	23 October 2020
AGN Webinar 4: MQU TerraneChron Taking the pulse of Earth's Lithosphere https://www.youtube.com/watch?v=as111oj-NA0 	Sue O'Reilly, Olivier Alard, Elena Belousova, Yoanne Greau, Guillaume Florin, Lauren Gorojovsky	28 Oct 2020
IGCP 648 Virtual Seminar Series - Weekly seminars by various contributors of diverse backgrounds. More information and recordings at http://geodynamics.curtin.edu.au/igcp-648-virtual-seminar-series/	Zheng Xiang Li, Co-organiser and Host	May-Aug, Sept-Dec 2020

OUTREACH *cont...*

Forum	Participant/s	Date
Work on the Early Earth and Mars carried out as part of Flagship Program 4 (*see p. 27*) was featured on ABC Catalyst TV show "*Mars: The Hunt for Life*" and in an article on ABC National News: https://iview.abc.net.au/video/SC2002H003S00 https://www.abc.net.au/news/2021-03-08/mars-nasa-perseverance-life-australandscapes-catalyst/13188052	Maro Fiorentini, Stefano Caruso	2020

Filming in the Pilbara: Marco Fiorentini, Greg Quicke (ABC presenter) and Stefano Caruso (below) explore the Dresser Formation on the hunt for stromatolites (right).

MEDIA

Activity	Participant/s	Date, Forum	Web address
Carmeltazite recognised as a new and rare mineral	Bill Griffin	7/1/19, Mining weekly	http://www.miningweekly.com/article/carmeltazite-recognised-as-a-new-and-rare-mineral-2019-01-07
Crust-mantle interaction: reactive melt ascent through the lower arc crust	Nathan Daczko	YouTube	https://www.youtube.com/watch?v=jSEOJYWRs8w
Geologists probe ancient African volcanoes in WA	Marco Fiorentini	Impact, UWA	https://www.uwa.edu.au/news/article/2020/november/geologists-probe-ancient-african-volcanoes-in-wa

MEDIA *cont...*

Activity	Participant/s	Date, Forum	Web address
Detrimental effects of coupled dissolution-precipitation on geochronology	Nathan Daczko	YouTube	https://www.youtube.com/watch?v=aYSse3o60ZE
Phosphine in the atmosphere of Venus which could uncover potential signs of life	Bruce Schaefer	2SER The Daily	Radio
Remixed mantle suggests early start of plate tectonics	Zheng Xiang Li, Hamed Gamal El Dien	12/06/2020, Phys.Org, ScienceDaily, EurekaAlert!	https://phys.org/news/2020-06-remixed-mantle-early-plate-tectonics.html https://www.sciencedaily.com/releases/2020/06/200612111430.htm https://www.eurekalert.org/pub_releases/2020-06/cu-rms061120.php
New research opens debate up about plate tectonics date	Zheng Xiang Li, Hamed Gamal El Dien	17/06/2020, The Canning Examiner	https://view.publitas.com/examiner-newspapers/canning-examiner-newspapers-17th-june-2020/page/2-3
Uncovering Earth	Zheng Xiang Li, Luc Doucet	30/06/2020, Phys.org	https://www.eurekalert.org/pub_releases/2020-06/cu-rms061120.php06-uncovering-earth.html
New Curtin research uncovers the two 'faces' of the Earth	Zheng Xiang Li, Luc Doucet	30/06/2020, The National Tribune, Eu-rekAlert	https://www.nationaltribune.com.au/new-curtin-research-uncovers-two-faces-of-earth/ https://www.eurekalert.org/pub_releases/2020-06/cu-ncr063020.php
Uncovering the two faces of Earth	Hugo Olierook	6/2020, Nature News&Views, Phys. Org., EurekaAlert!	https://www.nature.com/articles/s41561-020-0605-2 https://phys.org/news/2020-06-uncovering-earth.html https://www.techexplorist.com/two-faces-earth/33434/
ABC National radio The Science Show *"The importance of Pilbara stromatolites and their preservation"*	M Van Kranendonk	18/07/2020, ABC National radio	https://www.abc.net.au/radionational/programs/scienceshow/the-pilbara---used-by-ancient-people-and-nasa,-blown-up-by-rio/12463372
ABC news online, Comment on National Heritage listing of ancient geological sites	M Van Kranendonk	18/07/2020, ABC News	ABC News
In northern China, scientists have found what may be the 2 billion-year-old birthmarks of Earth's first supercontinent	Huaiyu Yuani	06/08/2020, The conversation	https://theconversation.com/in-northern-china-scientists-have-found-what-may-be-the-2-billion-year-old-birthmarks-of-earths-first-supercontinent-143846
Ancient carbon rocketing us into a renewable future	Marco Fiorentini	28/08/0020, Impact, UWA	https://www.uwa.edu.au/news/Article/2020/August/Ancient-carbon-rocketing-us-into-a-renewable-future
Radio interview, ABC Radio National Big Ideas; Einstein lecture "*Life among the stars*"	M Van Kranendonk	9/2020, ABC National radio	https://www.abc.net.au/radionational/programs/bigideas/life-among-the-stars/12684744

MEDIA *cont...*

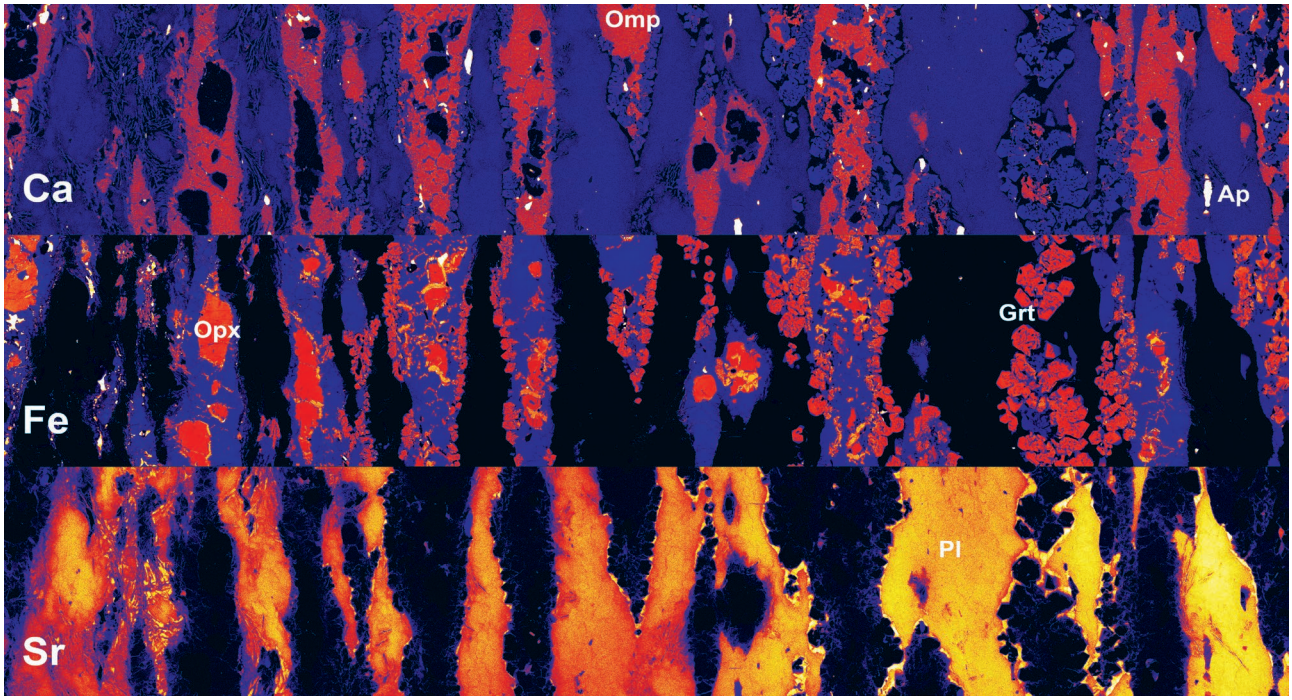
Activity	Participant/s	Date, Forum	Web address
Radio interview, ABC Radio National Science Show *"The North Pole"*	Martin Van Kranendonk	10/2020, ABC National radio	https://www.abc.net.au/radionational/programs/scienceshow/the-north-pole,-gentle-robots-and-the-future-of-ai/12745404
Please explain: Why is NASA returning to the Moon?	Craig O'Neill	16/10/2020, MQ Lighthouse	https://lighthouse.mq.edu.au/article/please-explain/october-2020/please-explain-why-is-nasa-returning-to-the-moon
NASA finds water on the Moon, raising hopes for exploration and habitation	Craig O'Neill	27/10/2020, ABC News	https://www.abc.net.au/news/science/2020-10-27/water-molecules-discovered-on-moon-using-nasa-flying-telescope/12806148
Magma '*conveyor belt*' fuelled world's longest erupting supervolcanoes	Hugo Olierook	11/2020, Science Alert, Phys. Org., EurekaAlert!	https://www.sciencealert.com/a-huge-magma-conveyor-belt-fuelled-the-world-s-longest-burst-of-supervolcanoes https://phys.org/news/2020-11-magma-conveyor-belt-fuelled-world.html https://www.eurekalert.org/pub_releases/2020-11/cu-mb110320.php

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. The global COVID-19 pandemic left little opportunity fo for face to face interaction in 2020. Despite these difficulties, collaboration continued remotely via video conferencing and webinars.

Australian and international visitors are listed in Appendix 5.

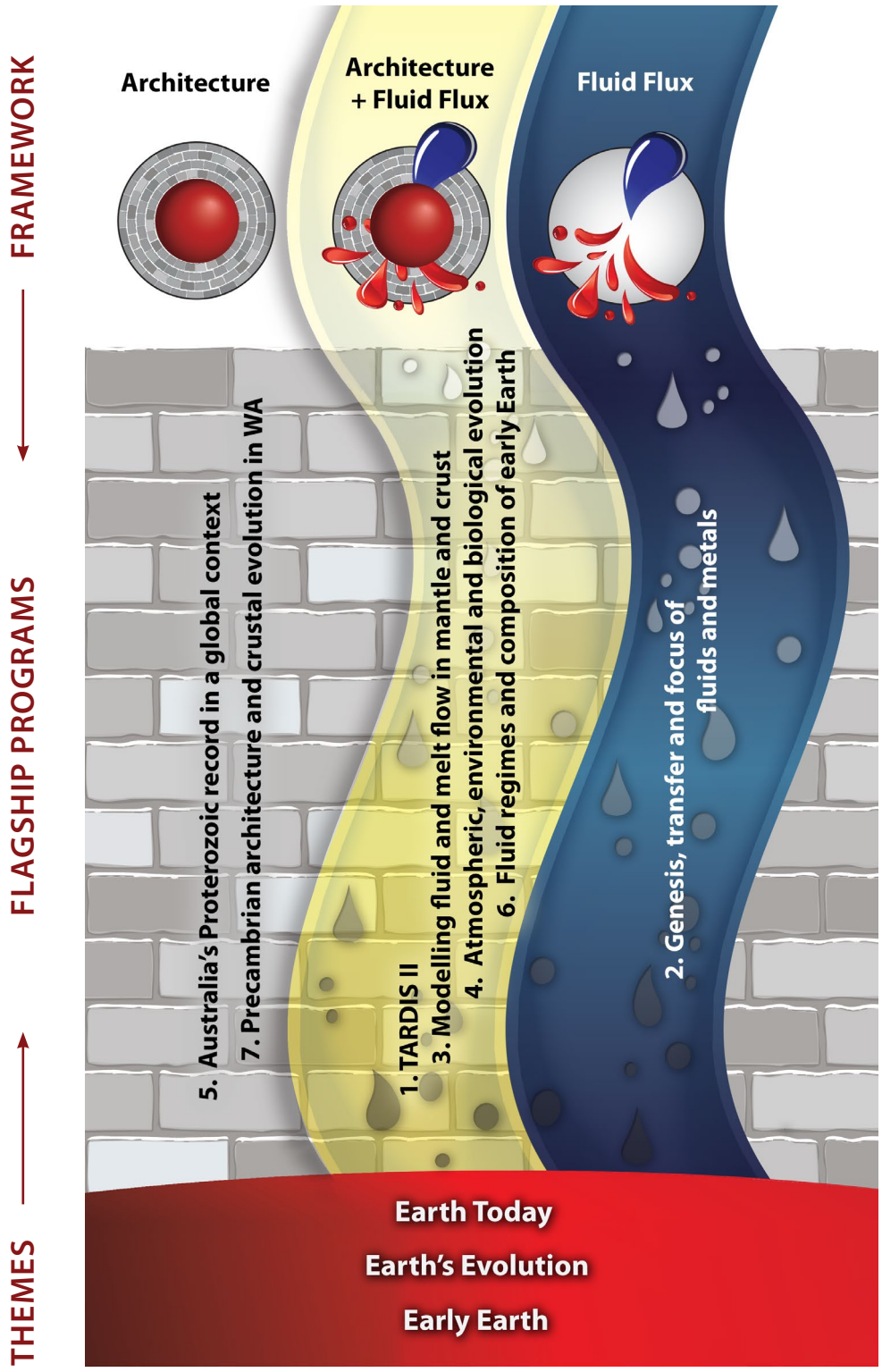
They have participated in collaborative research, technology exchange, seminars, discussions and joint publications and collaboration in postgraduate programs. For More information see the section on *International Links*.



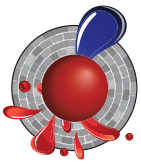
Australian Synchrotron XFM microchemical maps of zoned (left to right) Omphacite Granulite from Fiordland, New Zealand (Nathan Daczko).

Flagship Programs

Following the conceptual framework outlined on *page 4,* these Flagship Programs 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.



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



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

AIMS

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

2020 REPORT

The TARDIS project team continued in 2020 to carry out research on significant questions including those relating to kimberlite genesis, the petrogenesis of super-reduced magmatic systems, the evolution of the North China Craton, magmatism and tectonics in the Tethyan collisional belt, and the mantle beneath the Pannonian Basin in Hungary.

Kimberlites

Montgarri Castillo-Oliver, Andre Giuliani and coworkers completed a longitudinal study of carbon isotopes in kimberlites worldwide (CCFS publication #1421), concluding that a major Early Phanerozoic shift to isotopically lighter carbon reflects the beginning of subduction of organic carbon into the deep Earth. The topic is controversial and the paper is still out to review at the time of this report.

We were part of a large group collaborating with PhD student M. Kilgore (#1515) who measured the hydrogen contents in xenoliths from the Lac de Gras kimberlites of N Canada and linked the variations to the metasomatic profile previously established by GEMOC/CCFS research. Further information on the metasomatic fluids was provided by Zedgenizov et al. (#1536) who analysed the composition of diamond-forming high-density fluids in the Siberian SCLM.

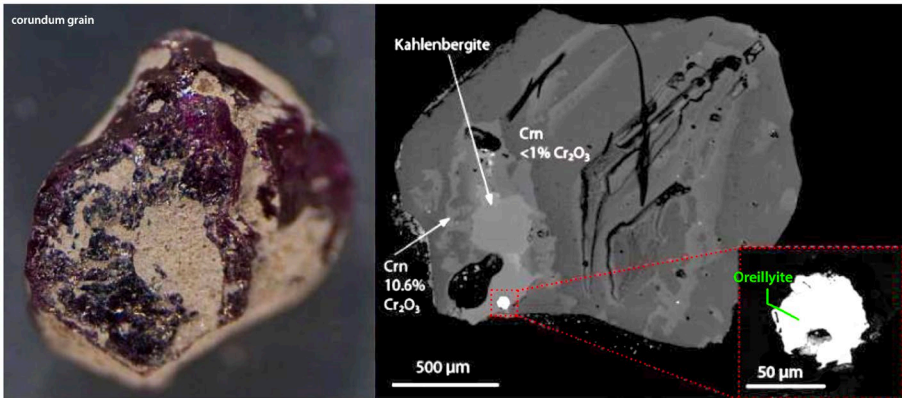
Xenoliths from kimberlites and the Deccan Traps in the Dharwar Craton of India, integrated with geophysical data, documented (#1548) the strong effect of the Traps magmatism on the composition and stability of the western part of the Dharwar cratonic root.

In related work, Perchuk et al. published a paper in *Nature* (#1531) that used dynamic modelling to develop a new model for the generation of the cratonic keels in early Archean time. This model was inspired and validated by comparison with the 4D Lithosphere Mapping profiles of SCLM stratigraphy built up by GEMOC/CCFS research over 20 years.

Ultra-reduced magmatic assemblages, Mt Carmel, Israel

Significant progress was made in this subproject this year. Oliviera et al. (#1533) used numerical modelling of zoning profiles in Carmel Sapphire aggregates to show the growth of skeletal corundum in an initially open system. The calculations showed that the entire mineral system represented in these aggregates evolved over a period of days to weeks, probably in conduits filled with rapidly moving melts and volatiles.

Two new minerals, kishonite (VH_2) and oreillyite (Cr_2N) (*see https://www.auscope.org.au/news-features/oreillyite*) were described (#1542), the latter named after Suzanne O'Reilly, director of CCFS (*see figure below*). Another paper (#1427) established the siderophile behaviour of boron under reducing conditions, while a third documented the evidence for solar-nebula oxygen fugacities in V0-bearing xenoliths.



Oreillyite was discovered in a corundum grain (left) within a sample of volcanic ejecta from Mount Carmel in Northern Israel. Right; Scanning electron microscope (SEM) image showing the Oreillyite inclusion (Bindi et al. 2020).

Huang et al. (#1492) described the mineral inclusions in SiC (moissanite) from Mt Carmel and Siberian kimberlites, establishing that most SiC in such occurrences forms from immiscible metallic melts at high temperature and very low oxygen fugacity. Two other papers in American Mineralogist documented the behaviour of chromium in reducing conditions and Al-rich melts (#1532), and the occurrence and genesis of the immiscible metallic melts in the Mt Carmel material

(in press 3/21). The two remaining papers in this project are in preparation, and some further analytical work was carried out in 2020 despite the pandemic.

North China Craton (NCC)

Work in 2020 focused on the evolution and nature of the lower crust beneath the craton and adjacent areas. Hongkun Dai continued his work on basalts and xenoliths from the Langshan area on the northern edge of the NCC, publishing a major paper in *Journal of Petrology* (#1633), while three more papers (including an invited paper in *Earth Science Reviews* (#1561) from this project are in press in major journals). Wang et al. (#1642) documented the presence of Eoarchean crust in the adjacent Central Asian Orogenic Belt, a major Proterozoic orogen.

Pannonian Basin

The Nógrád-Gömör Volcanic Field (NGVF), in the northern Pannonian Basin in Central Europe is one of five key localities where the lithospheric mantle of the Carpathian-Pannonian region can be studied using peridotite xenoliths hosted in late Miocene to Pleistocene alkali basalts. Liptai et al. built on a major study (#1361) that documented the regional distribution of microstructural characteristics in the xenoliths. Using a combination of FIB-SEM sequential sequencing and LA-ICPMS they have analysed silicate melt inclusions in the minerals of spinel peridotite xenoliths, providing new insights into the nature of the metasomatising agent that has modified the composition of the xenoliths. The paper is in press in American Mineralogist (#1530).

Tethyan Belt and other collisional orogens

Work in 2020 focused on the evolution of the petrological and tectonic evolution of the continental crust of northern Gondwana, now found in accretionary terranes in both Iran and Tibet.

Hadi Moghadam extended his long series of publications on the crustal and tectonic evolution of the Tethyan Belt in Iran (#1504, 1505, 1513, 1544). Sarshar et al. (#1513) investigated the hidden Cadomian crust in SE Zagros using exotic blocks entrained in salt diapirs. Esmaeili et al. (#1419) used amphibolites in the Makran accretionary complex to unravel permo-Triassic Neo-Tethyan evolution.

Two papers on the origin and role of pyroxenites in subduction wedges used material from W Victoria (#1387) and NW Spain (#1410).

Bo Xu and coworkers completed a series of four papers dealing with the nature and distribution of volatile phases in Cu-Au porphyry deposits in southern Tibet, and the broader controls of crustal and mantle architecture in this region. Two have been published (#1485, 1541), and two are under review. Xiong et al. 1386) investigated the effects of sulfides in Tibetan ophiolites on the stability of the Re-Os system, with implications for the interpretation of Re-Os ages (see also #1512).

WORKPLAN 2021

Work will continue on each of the projects addressed above. Most of the work in the Kimberlites and related rocks, the Ultra-reduced magmatic assemblages, Mt Carmel, Israel and the North China Craton will be focused on finalising these projects to the stage envisaged and forecast by the end of 2021. This will include writing up the remaining results and concepts for publication in high-ranked journals.

Tethyan Belt: Work will continue on the magmatic and structural evolution of the Tethyan Belt in Iran, continuing a very successful synthesis of the development of the northern edge of Gondwana, the detachment of a series of microcontinents, and their amalgamation to the European continent. Work in Tibet will start a new strand focussing on understanding the origin of previously collected samples in the Kangjinla region and implications for the tectonic history. This is in collaboration with CCFS PhD student Hongkun Dai and other colleagues from the School of Earth Sciences, China University of Geosciences, Wuhan (China).

A new phase of the TARDIS Project will commence in 2021. One of the new directions is funded by ARC DP grant DP210102196, titled *"The link between cratonic roots, redox state, and mantle geodynamic."* This project aims to understand the role of Earth's redox state on the geodynamic evolution of continental cratonic roots. Cratonic roots form strong, buoyant rafts upon which Australia's oldest crust and mineral deposits survived. Cratons preserve a record of planetary-scale chemical shifts, including the rise of surface oxygen, but it is unclear how these redox shifts themselves affected lithospheric processes. This project integrates new developments in geochemistry, geophysics, and geodynamics, to map the geochemical state and structure of cratonic roots, aiding mineral exploration, and also shedding light on the processes that modify, mineralise, and sometimes destroy cratonic roots.

A consortium of CCFS researchers, with international and industry partners, has applied for an Australian Government Australia-China Science and Research Fund Joint Research Centre titled *"Deep Exploration for Critical Minerals: Accelerating a Sustainable Future"*.

The scheme outcome was to be announced in February 2021 but has been delayed. If successful, this project will commence in 2021, springboarding from CCFS new findings to result in making the deep Earth beneath Australia and China transparent. Geophysical arrays will be deployed regionally, coinciding with geochemical mapping using new analytical technologies. Unparalleled rich datasets characterising the hidden uppermost 300 km of the Earth that controls formation and location of ore deposits will reveal in 4 dimensions (deep space and time), Earth structures and processes not previously accessible. This new knowledge will enrich our understanding of Earth's 4.6 billion year evolution, and directly benefit mineral exploration targeting.

Continuing support from Minerals Targeting International will fund a new aspect of the ongoing GLAM (Global Llihospheric Architecture Mapping) project *"Archean mantle and plate tectonics: the seismic record of arc magmatism"*.

In collaboration with colleagues from the University of Sydney, CCFS researchers have sought ARC DP funding for 2022 for a project titled *"Mapping mineral systems of deep Australia"* aimed at enabling mineral resource discoveries by calibrating geophysical surveys using geochemical and petrophysical properties measured on mantle samples brought to the surface by recent volcanoes. National geophysical surveys deliver images of geophysical gradients in the deeper part of the Australian continent. The interpretation of these gradients in geological terms and in terms of economic mineral systems is the key to unlock deep exploration success. This project will turn Australia's investment in National geophysical surveys into new discoveries of base metals. The benefit stems from enabling the transition to a clean economy which requires a much broader range of critical minerals and a larger quantity of base metals.

Fieldwork in Western Australia was the focus of activities given the inability to travel overseas.

Published outputs for 2020

CCFS Publications: #1381, 1383, 1386, 1387, 1410, 1419, 1421, 1423, 1427, 1485, 1488, 1489, 1492, 1499, 1502, 1503, 1504, 1505, 1506, 1512, 1513, 1515, 1521, 1525, 1530, 1531, 1532, 1533, 1536, 1541, 1542, 1544, 1558, 1561, 1633, 1642

2. GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

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

AIMS

This program embodies a holistic approach to ore deposit research, acknowledging that the genesis of mineral occurrences requires the conjunction in time and space of three main independent parameters: fertility, lithosphere-scale architecture, and favourable transient geodynamics. In this context, the integrated studies in this Flagship program address the critical link between metal source fertility and four-dimensional evolution of multi-scale fluid pathways that ensure efficient mass and fluid flux transfer between the mantle and the upper crust. Our studies test the hypothesis that the genesis of sizeable mineral deposits is the end product of self-organised critical systems operating from the scale of the planet all the way to the very focused environments where ore deposits can form. This Flagship Program is not commodity-focused but rather looks at the basic commonalities among various mineral systems to unravel the main constraints in the formation of ore systems.

2020 REPORT

In 2020, despite the disruptions related to the COVID pandemic, this Flagship Project progressed well, generating world-class results published in prestigious journals, attracting media attention, and seeding foundations for future strategic partnerships with industry. Work mainly focused on establishing the cycle of volatiles and metals at the scale of the lithosphere: Dr Eunjoo Choi received her PhD in early 2020, documenting Proterozoic magmatism in the Yilgarn Craton as a probe to unravel the first-order control on its metallogenic fertility and endowment. Mr Jason Bennett, Mr Greg Poole and Constanza Jara submitted their PhD studies and are expected to defend in mid-2021. Past and ongoing projects have significantly contributed to and engaged industry and generated new projects on various mineral systems in collaboration with industry:

- ARC LP190100785 *"Experimental Constraints on the Genesis of Gold-rich Ore Deposits"*. The project, in collaboration with AngloGold Ashanti, Newmont, Anglo American and Rio Tinto will provide a new set of tools to explore for gold-rich ore deposits in Australia and globally. By integrating geochemical studies with cutting-edge experiments carried out at three Australian universities in strategic partnership with industry, the outcomes of this project will provide much needed knowledge to predict the locations of large gold-rich deposits that are concealed beneath vast expanses of the Australian continent. The new results will translate into smarter exploration practice, significantly enhancing success in targeting ore deposits that are rich in high-value metal and display the smallest have a small environmental

footprint, to underpin the sustainability of our nation into the future. The project involves PhD student Carolina Mafra based at UWA.

- The High Grade Hypogene Porphyry (HGHP) project is funded by BHP as a collection of research initiatives (spread between separate institutions including UWA) designed to investigate the primary geologic controls on enhanced grade porphyry mineralisation. It is designed to identify new genetic and economic parameters for giant high grade hypogene systems in order to develop detection tools that can be employed at all scales of observation and at all stages of the exploration process. In order to achieve this, an '*all of mineral system*' approach has been identified as a key overarching principle. The project, as a whole, aims to establish the combination of mineral system elements that contribute to known high grade hypogene systems.
- In addition, in collaboration with IGO, work has focused on the characterisation of the geochemical and isotopic signature of mafic and ultramafic rocks in the Proterozoic Albany-Fraser Belt, Yilgarn Craton, Western Australia. In 2020, the work mainly aimed at unravelling the significance of garnet as a potential resistate mineral indicator. Further work in 2021 will also involve PhD student Joshua Chong, who will focus on the role of carbon as a catalyst for metal transport across the lithosphere.
- A new project at Boddington involving PhD student Nathan Bowman commenced in 2020, with significant funding and logistical support from Newmont. The project aims at unravelling the geochronological and geodynamic constraints on the genesis of one of the largest and most poorly understood Archean gold systems.
- A new project with BlueJay mining pls on Disko Island (Greenland) and Impact Minerals Ltd in western New South Wales (Australia) also started in 2020. The project involves PhD student Maria Cherdantseva, who investigates the role of volatiles in the transport of magmatic sulfides across the lithosphere.
- In 2020, the MRIWA Yilgarn2020 project made significant progress, with PhD student Anne Virnes leading the way in the study of multiple sulfur isotope systematics applied to komatiite systems.

In 2020, overseas fieldwork activities had to stop for logistical reasons. However, fieldwork related to the research activities of this Flagship Project continued in Australia, with work focused in New South Wales and Western Australia, mainly along the Fraser Belt and the Agnew-Wiluna Belt. The goal is to gradually re-start fieldwork activities globally in late 2021 and from 2022 onwards.

WORKPLAN 2021

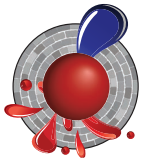
Work in 2021 will be carried out within the framework of a number of ongoing PhD projects, mainly funded by ARC or industry, and the work of ECRs at UWA. The main focus will be sampling and analysis for the key industry-funded projects that started in 2020. Strategic partnerships with overseas institutions will be strengthened, with the potential to engage Master students in other countries who could carry out sampling at specific locations. An example is the involvement of Masters students from the University of Bologna (Italy), who will be working in the framework of ARC LP190100785. A new strategic project on the role of carbon in the transport of metals in collaboration with the University of Leicester is currently being designed to be discussed with interested companies in mid-2021. This project would build on the results from CCFS Flagship Program 2 over the past decade and embody the legacy of significant research excellence that was generated.

Published outputs for 2020

CCFS Publications: #1175, 1384, 1408, 1409, 1431, 1487, 1508, 1516, 1520, 1551, 1552, 1648

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.

2020 REPORT

The major outcomes from this program have been the development and expansion of Litmod and its subsidiary codes, the completion of the first 3D probabilistic inversion method for MT data and the development of a new multi-phase multi-component reactive formalisms to handle complex physiochemical processes.

The science outcomes from these developments in the past year include

i) The first fully probabilistic method to invert stand-alone 3D MT data and joint seismic+MT data for the thermochemical structure of the lithosphere, presented in Manassero et al. 2020 (CCFS publication #1653).

ii) The development of a platform for modelling multi-phase multi-component reactive transport and its application to elucidating chemical-energy-mechanical feedbacks during magmatism. A new paper by Bravo et al. (CCFS publication #1510) presents a conceptual and numerical model to study the dynamics and nonlinear feedbacks inherent in mantle magmatism and to make quantitative comparisons between petrological and geochemical datasets (*fig. 1).*

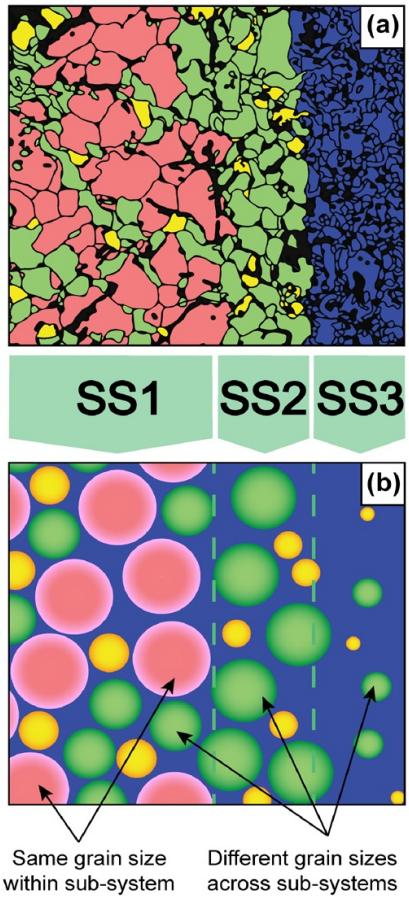


Figure 1. Schematic illustration of the diffusional re-equilibration model. (a) Mineral grains within a representative volume (spatially rearranged for convenience). (b) Individual grains are approximated as spheres. If there is melt present in the subsystem, the grains are assumed to be fully embedded in melt and keep the spherical shape. Different types of mineral grains will in general have different grain sizes that will evolve according to P-T-cb conditions (e.g. Ol, Cpx, Opx). Same type of minerals within each subsystem (e.g. every Ol grain within ss1) is modelled with a uniform grain size; however, different grain-size models are allowed across subsystems (e.g. Ol gains in ss1 and ss2 evolve according to different models).

(From Oliveira et al 2020 Journal of Petrology, https://doi.org/10.1093/petrology/egaa067.)

iii) Improved seismic models of the structure of the Chinese and Spanish lithospheres. Results were published in Zhang et al. (#1655) and Fullea et al. (#1656)

iv) First application of the litmod approach to the Australian lithosphere for large-scale exploration purposes. Results were published in Haynes et al. (#1654)

v) The development of ultra-fast 3D Stokes solvers for probabilistic inversion approaches for dynamic topography and mantle flow. Results were published in Galabert et al. (#1652)

The high-pressure experimental laboratory is in full swing under the auspices of Laboratory manager Slava Shcheka, with three post-doctoral researchers and several HDR students conducting experiments as part of their thesis studies. Many of the projects have looked at interactions between melts of crustal rocks when they react with mantle peridotites, whereas others are investigating melt compositions produced from mantle rocks. The sedimentary materials included in the experiments concentrate on likely major contributors to material in subduction zones. Michael Förster has been looking at reactions with marine sediments, whereas Chunfei Chen is investigating the behaviour of carbonates. Researchers have tended to use average compositions of sediments in their experiments, which include just small proportions of carbonates (<10%). Chunfei's investigations make the point that most carbonates are subducted as thick packages of nearly pure chalk or limestones, whose melting properties are poorly known.

Several HDR students successfully completed their theses this year: Zsanett Pintér investigated melt compositions produced from mantle peridotite that contains CO_2 and H_2O mixtures, whereas Zairong Liu investigated melting with CH_4-H_2O mixtures corresponding to more reduced conditions at low mantle pressures of around 2 GPa. Chengyuan Wang is producing multiple publications from his study of the lithospheric evolution of the Trans-North China orogen, and Mingdi Gao has completed his work on interactions in collision zones.

WORKPLAN 2021

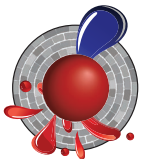
Work will continue in 2021 towards developing the next generation of tools for Earth Science simulations - in particular, novel techniques to model the interaction of fluid flow with solid geodynamic process from the crust to lithosphere,and deeper mantle.

The Australian Laureate project *"Deep Earth Cycles of Carbon, Water and Nitrogen"* continues into its third year. Current experimental projects include reaction experiments between crustal rocks and mantle in subduction zones (Chutian Shu, Chunfei Chen), the extension of partial melting experiments on peridotites with CO_2 and H_2O (Isra Ezad), investigations of the role of grain size on melt mobility (Michael Förster and Juan Carlos Afonso), melting of sulphur-bearing pyroxenites as possible sources of Cu-porphyries and shoshonites (Anthony Lanati), halogen partitioning between hydrous minerals and melts (Isra Ezad and Matthew Phillips), and the partitioning of nitrogen between hydrous minerals, fluids and melts (Michael Förster). Chutian is also investigating melting of hydrous pyroxenites in the mantle wedge above subducting plates and assessing which melts could be produced from them.

Published outputs for 2020

CCFS Publications: #1363, 1379, 1385, 1395, 1393, 1394, 1408, 1410, 1417, 1420, 1488, 1510, 1552, 1553, 1554, 1557, 1560, 1562, 1564, 1615, 1616, 1617, 1648, 1644, 1625, 1653, 1654, 1655, 1656

4. ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION



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

AIMS

We investigate how the evolution of life and ore deposits were linked to the changing whole-Earth system, focusing on planetary driving forces that affected all the different shells of the planet, to develop a 4-dimensional conceptual framework of Earth evolution. Given the broadly comparable petrological evolution of Earth and Mars, we also aim to put forward new working hypotheses on how life and mineral systems may have formed and evolved on the red planet and are involved in NASA's Mars2020 landing site selection process.

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

2020 REPORT

In 2020, this Flagship Project continued its focus on identifying proof of biogenicity for the oldest evidence of life on Earth, as well as understanding more about the environments that it inhabited, as well as studying the rise of eukaryotes in rocks from Western Australia.

Work mainly focused on two main areas in Western Australia: the 3.53-2.83 Ga Pilbara Craton and the c. 2.4 Ga Turee Creek Group of the Mount Bruce Supergroup, the succession that unconformably overlies the Pilbara basement.

In the Pilbara Craton, research continued to focus on the oldest, most convincing evidence of life on Earth as preserved in the 3.48 Ga North Pole Chert Member of the Dresser Formation, Warrawoona Group. Research conducted by Dr Raphael Baumgartner, a UNSW post-doctoral research fellow funded by the CSIRO in Perth, published three papers that help further prove the biogenicity of ancient stromatolite fossils from this unit. In his first paper, Baumgartner et al. (CCFS publication #1487) performed scanning electron microscopy, Raman spectroscopy, high resolution elemental mapping using Synchrotron Radiation X-ray Fluorescence Microscopy, and Laser ablation inductively coupled plasma mass spectrometry on samples of sulfidised stromatolites from fresh drillcore in order to define variations in geochemistry within stromatolite layering (Fig. 1). This study identified cyclical variations in arsenic, zinc, and nickel that point towards precipitation of metals by

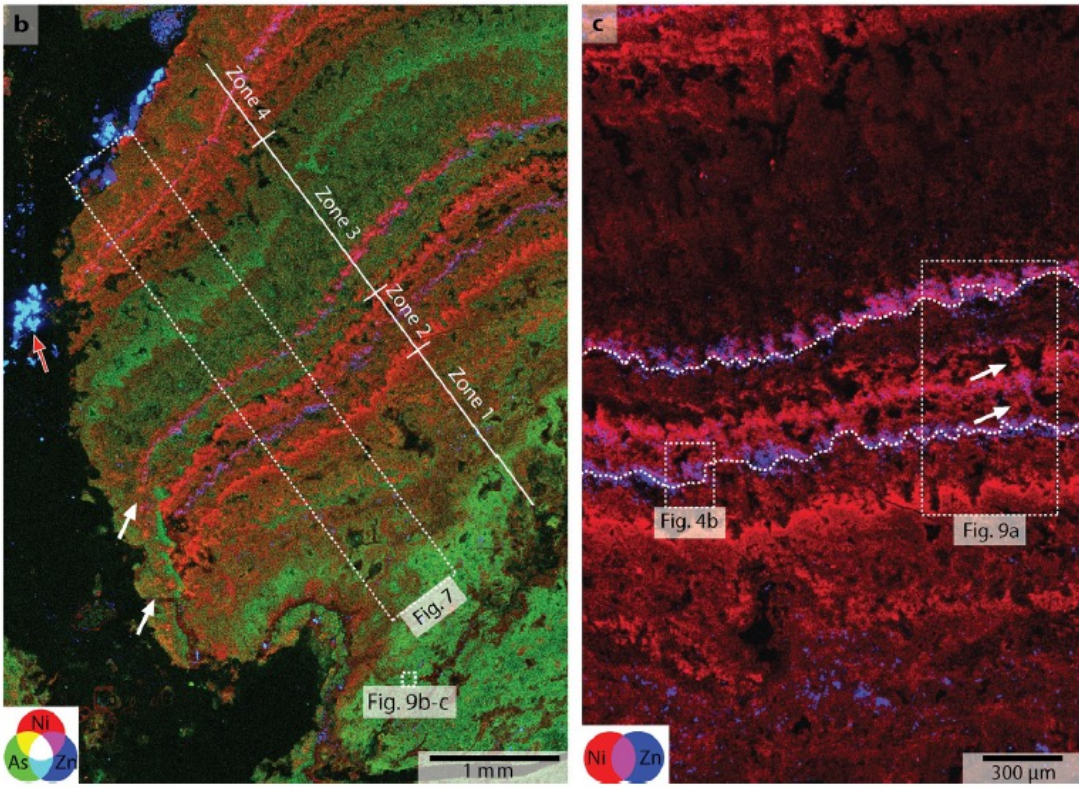


Figure 1. Elemental distribution maps of Dresser Formation stromatolites. B) Elemental distribution map of Ni, As and Zn, showing a laminated sulfide column within coarsely crystalline barite (black; compare with Fig. 2a). An overgrowth relationship within the internal fine-scale lamination of this sulfide column is indicated (white arrows). Note the dispersed sphalerite grains (red arrow) in adjacent barite, and the strong enrichments of As in the lower, more irregular and less laminated, part of this stromatolite column. C) Elemental map showing the distribution of Ni and Zn in the central part of the laminated sulfide column. Microdigitate enrichments of Ni (white arrows) and wrinkly laminations of Zn (white lines) are indicated. From Baumgartner et al. (#1487).

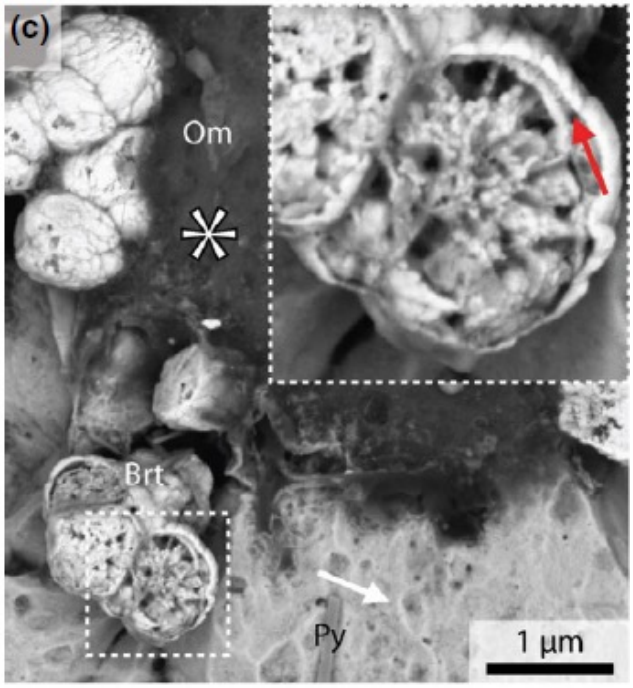


Figure 2. Assemblage of micro-spherulitic barite and organic matter. The white arrow indicates nano-porous pyrite enriched in organic matter. The arrow in the inset indicates the outer shell of a barite micro-spherulite. The asterisk indicates the location of Raman Spectroscopy analysis of organic matter (see paper for more informaiton). From Baumgartner et al. (2020b).

microbial activity, likely predominantly sulfate-reducing bacteria and/or anoxygenic photosynthesisers.

In his second paper, Baumgartner et al. (#1651) identified microspherulitic barite mineralisation within organic matter remnants trapped inside the sulfidised Dresser stromatolites (Fig. 2). These tiny (1 µm) microspheres of barite contrast dramatically with the coarse barite crystals that are so common throughout the North Pole Chert Member and derive from hydrothermal solutions. The microspherulitic barite is identical to that found in modern settings where microbial activity has induced crystallisation from the seawater, such that its presence in the ancient Dresser rocks is strong support for biological activity.

In the third paper, Baumgartner et al. (#1431) investigate biogenicity through *in situ* sulfur isotope analysis of the various phases of pyrite within the sulfidised stromatolites identified in Baumgartner et al. (#1397). The $\delta^{34}S$ shifts (up to ~17‰) generated by sulfate reduction are consistent with both thermochemical reactions and influence of sulfate-cycling microbes, the latter which may have facilitated rapid pyrite precipitation and preservation of microbial remains that are entombed within the petrogenetically earliest pyrite generation of stromatolites. Collectively, the data are consistent with ancient stromatolite growth in proximity to shallow marine hydrothermal vents, where hydrothermal fluids contributed to sulfidisation that may have been further influenced by sulfur-cycling microbes.

Further research was conducted on the Dresser Formation by both Dr Stefano Caruso, a UNSW post-doctoral fellow, and by Sahand Tadbiri, resulting from his MSc degree work at UNSW. Stefano conducted detailed geochemical and XRD research on the hydrothermal alteration assemblages that characterise the footwall of the Dresser Formation in metabasaltic rocks that host a dense network of black chert±barite±pyrite±chalcedony veins that represent the fossilised fluid conduits during cycling of warm to hot fluids through the crust. Previous work suggested that the distribution of varied mineral assemblages was zoned in a vertical manner beneath the dresser Formation, but Stefano's research shows that the mineral assemblages are distributed around the major veins, which were the source for the heat and fluid that caused the alteration. This work is being written up for publication in 2021.

Sahand's project also looked at the hydrothermal veins, but from the viewpoint of their structural distribution and sequence of emplacement. Tadbiri and van Kranendonk (#1517) identified four main sets of hydrothermal veins that were emplaced during uplift and subsequent collapse of an active volcanic caldera that hosted the stromatolites of the North Pole Chert Member. The veins define a conjugate, to more complex, structural pattern around the North Pole Dome that fits very well with known examples of more recent calderas and with sandbox models of caldera formation. Veins were emplaced within radial and concentric faults and/or fractures associated with caldera formation, but ceased after the caldera collapse except within long-lived extensional growth faults.

Dresser research also featured prominently in a chapter for a Springer book entitled *"Mars Enigmas",* which will be published in 2021 (Van Kranendonk et al., in press). This chapter summarises the environments where early life is found in the ancient Pilbara rocks (3.5-2.75 Ga) and includes nine distinct habitats, all of which can be used as analogues for where to search for life on Mars.

In addition, 2020 saw the publication of the second of three special issues of the journal Astrobiology (V. 20, No. 4) guest edited by Prof M. Van Kranendonk, on hot spring research. Specifically, these special issues focus on aspects of hot spring research that will aid in the search for life on Mars, and they include studies on everything from hot spring geochemistry, to geological facies of sinter deposits, to microbial communities and their fossilised remnants, and include authors from within the CCFS. One paper in the second issue by Teece et al. (2020) describes the discovery of preserved biomolecules from fossilised hot springs in New Zealand. Another by Ruff et al. (#1362) describes the case for siliceous sinter at Home Plate in Gusev Crater on Mars. Others develop the hot spring model for the origin of life, describe trace element enrichments in fossil microbes from hot spring sinter, outline the microbial origin of palisade fabric in sinter, and characterising the mineral assemblages of hot spring environments and how this applies to Mars orbital data.

The other main field of research is on the evolution and adaptation of life to the Great Oxidation event in a well

preserved microbialite reef complex from the 2.4 Ga Turee Creek Group of Western Australia. Ms Georgia Soares (UNSW) submitted her PhD thesis on *"An early attempt at complexity: branching siliceous structures in the 2.4 Ga Turee Creek Group"*, which described novel macroscopic fossils that appear to have characteristics more in line with an eukaryotic lineage than a prokaryotic origin. These branching organic Structures are distinct from any previously documented form of microbialite and are characterised by siliceous core zones within an otherwise entirely carbonate environment. The results of this study augment previous discoveries of complex microfossils in the same unit by Barlow and van Kranendonk (#1340). Nomchong and Van Kranendonk (#1415) describe the oldest documented thrombolites on Earth from this same unit, again highlighting an early onset of complexity of life.

WORKPLAN 2021

Work in 2021 will be carried out within the framework of a number of ongoing PhD projects, and post-doctoral research programs mainly funded by ARC. Dr Stefano Caruso will complete his study of the Dresser hydrothermal alteration, and Brendan Nomchong will submit his PhD on the petrography and environmental setting of the Turee Creek microbialite reef complex. Prof Van Kranendonk will continue his work on the Dresser Formation and begin his collaboration with Prof Tony Kemp (UWA) on the environmental conditions of early Earth from isotope tracers. Additional fieldwork will be undertaken at the Dresser Formation (Covid-willing), with a particular focus this time on conservation of the ancient stromatolite sites.

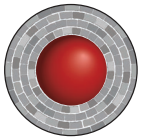
The third issue on hot spring research will be published in the Journal of Astrobiology (V. 21, No. 1), which includes three papers from the van Kranendonk research group.

Published outputs for 2020

CCFS Publications: #1415, 1431, 1487, 1517, 1591, 1649, 1651

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.

2020 REPORT

Numerous new findings, supported by Li's ARC Laureate Fellow project, were published in 2020. Work continued on the paleogeographic evolution of Australia in the Precambrian during 2020 utilising palaeomagnetism and geological evidence (including detrital zircon geochronology). The new palaeomagnetic poles from the 2.62 Ga and 1.39 Ga mafic dyke swarms of the Yilgarn Craton, a significant portion of Yebo Liu's PhD work was published. Palaeomagnetic results obtained from northern WA and the North Australian Craton were published to elucidate the Paleoproterozoic assembly of proto-Australia. An additional publication describing a modified SWEAT configuration of Australia and Laurentia during Nuna is also forthcoming.

New global paleogeographic reconstructions that stretch into the Paleoproterozoic were continually reported and published throughout 2020 (*see CCFS publications below*).

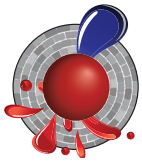
This project ended in 2020.

Published outputs for 2020

CCFS Publications: #1424, 1476, 1490, 1511, 1524, 1526, 1529, 1537, 1538, 1546, 1573, 1574, 1575, 1577, 1583, 1584, 1585, 1593, 1594, 1595, 1596, 1597, 1598, 1600, 1601, 1602, 1603, 1604, 1605, 1606, 1607, 1609, 1610, 1611

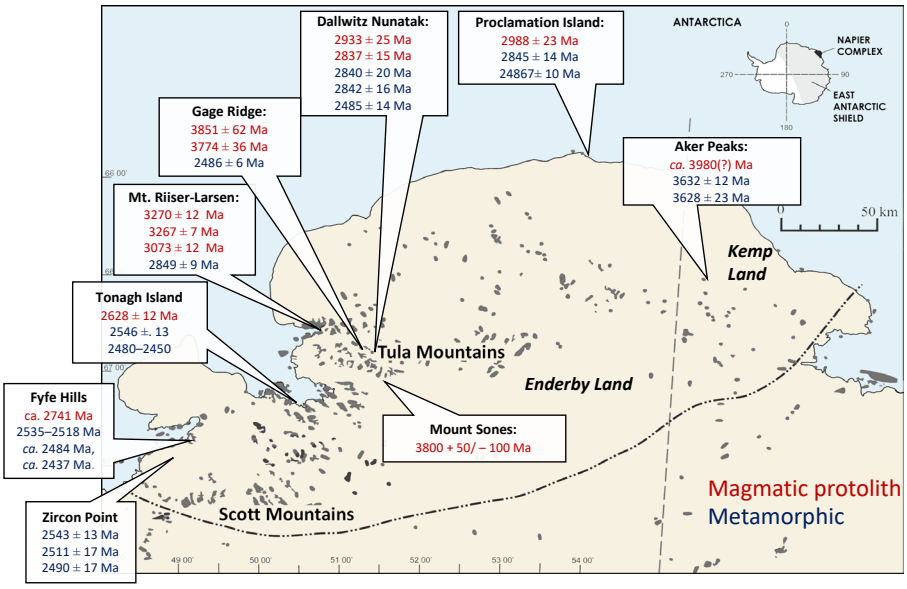
6. FLUID REGIMES AND THE COMPOSITION OF EARLY EARTH

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 record events in the first 500 million years of Earth's history since no rocks have survived from this period and no other minerals have been established as Hadean in age. There is growing evidence from the study of these zircon crystals that the Earth stabilised rapidly after accretion and that both solid rock and liquid water were present within 150 million years of its formation. This program uses the geochemical signatures of zircon crystals from all known Hadean and early Archean localities, together with geochemistry of the oldest known rocks and the application of geophysical and geochemical modelling, to establish how the first crust formed, why it was destroyed and the role fluids played in this process. The changes that took place throughout the Archean are being evaluated as crustal processes evolved and plate tectonics became the dominant regime. A key



Outcrops in Enderby and Kemp Lands (modified after Sheraton *et al.* 1987)

Synthesis of published ages from across the Napier Complex, Antarctica. Adapted from Krol et al. Goldschmidt 2020.

component is determining the interaction between the mantle and the evolving crust. In addition, work undertaken on Martian meteorites and lunar samples is providing further constraints on the early history of the Solar System, especially the role played by fluids.

2020 REPORT

Work in 2020 was severely disrupted by COVID-19. This impacted in several ways. It meant the cancellation of fieldwork in the Windmill Hills, Antarctica, and fieldwork in both Greenland and Labrador was likewise cancelled. It also caused a delay in commencing an Australian Antarctic Division research project on legacy samples stored with Geoscience Australia due to interstate border restrictions, as well as an ARC grant to utilise Sr and Ca systematics of ancient crustal rocks and minerals to constrain the evolution of the Earth's primordial mantle and oceans.

However, not all was doom and gloom! Sufficient samples were available from previous work on Antarctica, Labrador, Greenland and Jack Hills for some work to continue. Unfortunately, closure of laboratories for several months at partner institutions in Europe further delayed progress on these projects.

New work was mainly focused on the ancient rocks in the Ukrainian Shield with Curtin post-doctoral fellow Dr Leonid Shumlyanskyy. This led to several local geology papers and abstracts published in Ukrainian journals and a submission to Precambrian Research (now accepted) on the Eoarchean rocks of the Dniester-Bouh Domain of the Ukrainian Shield. Here, enderbites and mafic granulites formed at 3.79 Ga and at 3.5 Ga, but were affected by a range of subsequent metamorphic events between 3.0 and 2.7 Ga.

Further investigation of the Hadean and Eoarchean zircons from Jack Hills resulted in the publication of a trace element study of a suite of zircons ranging in age from 3.3 to 4.3 Ga undertaken with Prof Simon Turner at Macquarie University and published in Nature Communications. The key finding was that there was no variation in trace element systematics across the Hadean/Archean boundary at 4.0 Ga, with modelling suggesting the protolith of these zircons was consistent with andesite formed in modern subduction settings; implying an early onset of plate tectonics on Earth. In addition, lead nanospheres were identified in several new localities around the world, in association with former CCFS Marie Curie fellow Monika Kusiak from Poland and Dr Richard Wirth from Potsdam, Germany and the results have been written up for publication.

Further investigations on the 3.72 Ga gneisses in the Tarim Craton with former CCFS post-doctoral fellow, Associate Professor Rongfeng Ge from Nanjing University, led to the identification that they have decoupled, but weakly sub-chondritic, Nd and Hf isotopes, similar to ancient gneisses from Greenland. They were also affected by metamorphic events at 3.56 and 2.0 Ga. The paper was published in Earth and Planetary Science Letters in early 2020. A new study of gneisses in the southwest Tarim Craton has identified Mesoarchean rocks as old as 3.2 Ga, and further work is in progress.

The Lu-Hf investigation of ancient zircon crystals from Aker Peaks in Kemp Land, Antarctica, has now been completed and the paper prepared for publication. Also in Antarctica, new data from the eastern Tula Mountains in the Napier Complex, collected by Piotr Krol (PhD student of Monika Kusiak), revealed ancient TTG gneiss protoliths with ages of 3.75-3.56, associated with granitic gneisses 2.9-2.8 Ga in age. Geochemical data indicate gneisses of both age groups provide evidence of both medium/high-pressure and low-pressure melting; the results were published in Gondwana Research.

Two studies of the Dharwar Craton in India were published in 2020. Evidence for multi-stage crustal growth in the Archean of the Eastern Dharwar Craton was revealed by a comprehensive field, petrological, geochemical and isotopic study, with four episodes of magmatism identified between 3.36-3.20 Ga and 2.57-2.52 Ga; the latter identical to the main Neoarchean magmatism in the North China Craton. This work was published by Jayananda et al. in Gondwana Research. A detailed study of the late Archean Dharwar Supergroup by Krapež et al. in Earth-

Science Reviews established a rift stage from 2.77-2.72 Ga and the development of a two-stage back-arc basin sequence from 2.61-2.58 Ga and 2.58-2.54 Ga, respectively.

Lunar work in 2020 was focused on re-investigating the nature of the rocks at the Apollo landing sites. This included examining shocked zircon in the lunar highlands, obtained from clasts at the Apollo 16 site. Work also continued on investigating lunar meteorites, with special emphasis on their Pb systematics. Work on Martian meteorites included the oxygen analysis of phosphates by SIMS and also the implication of Pb isotopic data to understanding the Martian mantle. A specific investigation of 4.2 Ga Martian zircon was also undertaken, and the results applied to understanding the nature of the internal structure and geodynamics of Mars; this study was published in the Proceeding of the National Academy of the United States of America.

WORKPLAN 2021

This will in part depend on the lifting of COVID-19 restrictions and the ability to undertake international travel.

Work in Australia will remain focused on zircon from Jack Hills, especially the Hadean population. This will include a Zr isotope study in association with Simon Turner at Macquarie.

An atom probe investigation of lead (Pb) nanospheres in ancient zircons from the Napier Complex, Antarctica, will continue in order to precisely determine their distribution and isotopic composition. The full extent of Eoarchean rocks across the Napier Complex will be investigated using both the legacy collection at Geoscience Australia and samples housed at the University of Tasmania.

Work will continue on samples collected from Isua, West Greenland, in 2019, and on samples collected from Labrador in 2017. Work on the Eoarchean-Mesoarchean rocks of the Tarim Craton in China will likewise continue.

An investigation of the Eoarchean and Hadean zircons in the Singhbhum Craton in India will continue in association with Dr Rajat Mazumder in Oman.

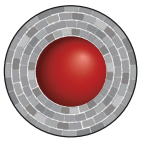
Work will continue on both lunar rocks and Martian meteorite samples with the aim of constraining the age of the oldest crust and the precise timing of events in the early solar system.

Published outputs for 2020

CCFS Publications: #1538, 1618, 1619, 1620, 1623, 1624, 1626, 1627, 1628, 1629, 1630, 1631, 1632, 1634, 1635, 1636, 1637, 1638, 1640, 1643, 1644, 1645, 1647, 1650, 1651, 1625, 1639

7. PRECAMBRIAN ARCHITECTURE AND CRUSTAL EVOLUTION IN WA

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

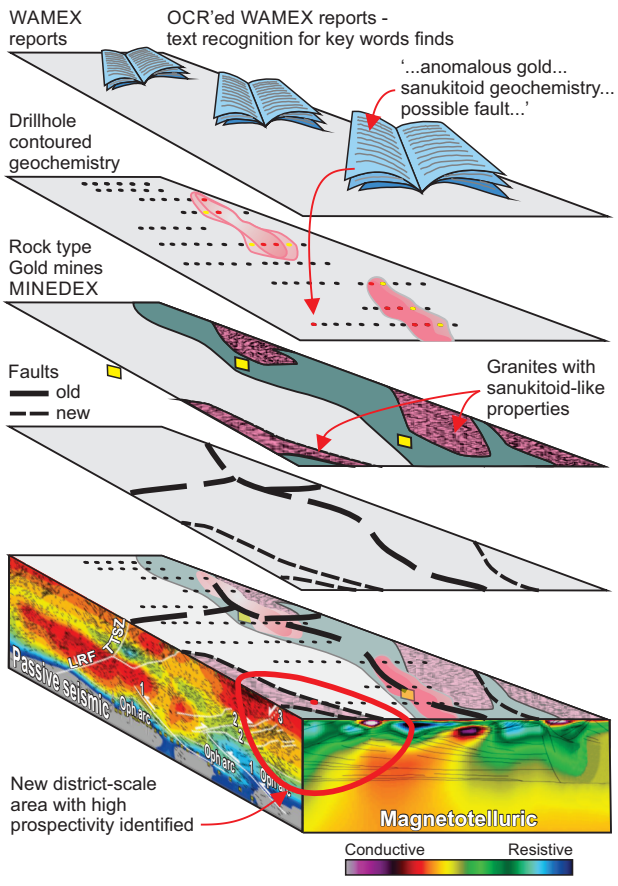


AIMS

The enormous size and limited outcrop of the Neoarchean Yilgarn Craton and the Proterozoic orogens around its margins are detrimental to a deep understanding of what controls the distribution of mineral resources and which geodynamic processes were involved in the tectonic assembly of the Australian continent. The principal aim of this program is to combine geological, geochemical and geophysical techniques to propose a 3D structural model of the lithosphere of the Yilgarn Craton and its margins. This aim is predominantly addressed through passive source seismic experiments and integrated analysis of Hf-isotope data.

2020 REPORT / WORKPLAN 2021

As a response to the COVID-19 pandemic and as part of the West Australian Government economic recovery plan, the Geological Survey of Western Australia (GSWA) reprioritised its 2020-21 work program. The focus shifted from fieldwork intensive acquisition of new data to delivering new interpretive datasets in key regions of the State to accelerate understanding of the region's geology and mineral prospectivity. These regions include the Southwest



Schematic representation of integrated datasets for the Southwest and Far-East Yilgarn Craton regions.

and Far-Eastern Yilgarn Craton, for which a large number of new digital layer and related products are planned to be released in the second half of 2021.

Prior to COVID-19 travel restrictions, Klaus Gessner attended the annual meeting of the Prospector & Developers Association of Canada (PDAC) and visited the Geological Survey of Canada (GSC), with which GSWA is collaborating on an international innovative 3-D geological modelling and data integration project. Klaus delivered an invited scientific paper at PDAC featuring the geology and critical mineral resources of Western Australia and presented a paper as part of the GSC Logan Club Lecture Series on the tectonic evolution of the Yilgarn Craton.

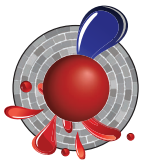
Published outputs for 2020

CCFS Publications: #1434, 1579, 1580, 1581

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.



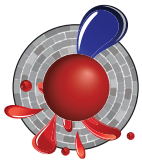
AIMS

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.

See "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:

- Implementation of a new Pb isotope column chemistry protocol
- Laser Ablation Trace Element Imaging with Aerosol Rapid Introduction System (ARIS) and (Teledyne CETAC Excite 193nm laser with ARIS and HDIP +)
- Ultra trace elements by LA-H-ICPMS
- *In situ* Rb-Sr geochronology, analytical technique and application field
- *In situ* Rb-Sr in Glauconite, dating and fingerprinting sediment diagenesis
- Pushing *in situ* Rb-Sr geochronology: going younger than 20 Ma. (Teledyne CETAC G2 193nm laser - Agilent 8900QQQ ICP-MS/MS)
- Characterisation and development of reference materials for *in situ* Rb-Sr dating using tandem LA-ICP-MS (Teledyne CETAC G2 193nm laser + Agilent 8900QQQ ICP-MS/MS)
- *In situ* Halogens quantification by tandem ICP-MS
- *In situ* sulfur isotope determination in sulfides using tandem LA-ICP-MS
- *In situ* low level chalcogenids tandem ICP-MS
- *In situ* split-stream measurement of trace elements and Re-Os isotopes in sulfides using LA-MC-ICPMS and Daly detectors (Teledyne CETAC G2 193nm laser + Nu Instrument Plasma II MC-ICP-MS)
- *In situ* strontium isotopes in phosphate/carbonate/silicate by LA-fs-MC-ICPMS (Teledyne CETAC femtosecond 198nm laser + Nu Instrument Plasma II MC-ICP-MS)
- *In situ* Zirconium Isotopes

See "Technology Development"

CCFS postgraduates

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 2012-2019. 26 papers with CCFS postgraduates as authors were published in high-profile international journals in 2020 including *Nature Sientific Reports, American Mineralogist, Chemical Geology, JAAS, Contributions to Mineralogy and Petrology, Precambrian Research, Lithos, Tectonics, Journal of Metamorphic Geology* and *Journal of Geophysical Research*. 15 presentations were also given at international conferences (see *Appendix 4*).

2020 HIGHLIGHTS

Eunjoo Choi was awarded David Groves Prize for Postgraduate Research in Geology, UWA, in July 2020.

Anthony Lanati was awarded a Deutscher Akademischer Austauschdienst (DAAD, German Academic Exchange Service) Cotutelle Scholarship. *Pictured below.*

Hamed Gamal El Dien received the Curtin Chancellor's commendation.

Anthony running a Mica-Pyroxenite melting experiment with the Yellow piston-cylinder as part of his DAAD funded cotutelle with the Institut für Mineralogie,Westfälische Wilhelms-Universität Münster (Photo: Paul Pangritzfor).

COMPLETED

Cameron Adams (PhD): Integrating petrophysical, lithogeochemical, and mineralogical data to understand the physical properties of altered mafic and ultramafic rocks: implications for geophysical exploration (UWA 2020)

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

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

David Barbosa da Silva (PhD): The microchemical and microstructural evolution of fluid and melt transfer in deep crustal shear zones (MQ 2019)

Erica Barlow (PhD): Microfossils of the Paleoproterozoic Turee Creek Group: Biological evolution resulting from atmospheric change? (UNSW 2019)

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

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

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

Richard Blake (MPhil): Determining recent organic contamination in ancient rocks (UNSW 2019)

Eleanore Blereau (PhD): Petrochronology of the ultrahigh-temperature (UHT) metamorphic Rogland-Vest Agder Sector, southwestern Norway (CU 2017)

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

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

Stefano Caruso (PhD): Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems (UWA 2019)

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

Julian Chard (PhD): Petrochronology of accessory minerals related to metamorphism and fluid-flow events in the Albany-Fraser Orogen and Eucla basement, Western Australia (CU 2020)

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

Eunjoo Choi (PhD): Alkaline magmatism as a probe into the lithospheric mantle (UWA 2020)

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

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

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

Jane Collins (PhD): The structural evolution and mineralisation history of the Flying Fox komatiite-hosted Ni-Cu-PGE sulfide deposit, Forrestania Greenstone Belt, Western Australia (UWA 2013)

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

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

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

Andrei de Souza (MSc): Petrogenesis and isotopic constraints on the emplacement of discordant ultramafic pipes in the eastern Bushveld Igneous Complex, South Africa (UWA 2019)

Gregory Dering (PhD): Dynamics and emplacement mechanisms of mafic magma networks with implications for intrusion-hosted magmatic Ni-Cu-PGE sulfide deposits (UWA 2019)

Tara Djokic (PhD): Lithofacies and Biofacies analysis of Earth's oldest subaerial hot spring deposits from the ca. 3.5 Ga Dresser Formation, Pilbara Craton, Western Australia (UNSW 2020)

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

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

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

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

Michael Förster (PhD): Experimental melting of rocks of ultramafic and sedimentary origin in accretionary orogens (MQ 2019)

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

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

Hamed Gamal El Dien (PhD): Geochemical Records Linking Plate Tectonics with Mantle Dynamics: Neoproterozoic and Beyond (CU 2021)

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

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

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

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

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

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

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

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

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

Kui Han (PhD): Modelling the physical properties of multi-phase aggregates from the single phases (MQ 2020)

Michael Hartnady (PhD): Crustal evolution of the Albany-Fraser Orogen (CU 2019)

Hadrien Henry (PhD): Mantle pyroxenites: Deformation and seismic properties (MQ 2018)

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)

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

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

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

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

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

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

Erwann Lebrun (PhD): 4D structural modelling and hydrothermal evolution of the sediment hosted Siguiri gold deposit (Guinea) and implication on Paleoproterozoic gold targeting in West Africa (UWA 2015)

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

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

Guoliang Li (PhD): Joint inversion of multiple seismic data for Basin structures (MQ 2020)

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

Shaijie Li (PhD): Isotopic dating oil generation and charge events in Canning (Australia) and Sichuan (China) (CU 2019)

Nora Liptai (PhD): Geochemical and physical properties and evolution of the lithospheric mantle beneath the Nógrád-Gömör Volcanic Field (Northern Pannonian Basin, Central Europe) (MQ 2018)

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)

Yebo Liu (PhD): Paleomagnetism of Proterozoic igneous rocks in Australia and East Antarctica: implications for pre-Pangea supercontinents and supercontinent cycle (CU 2020)

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

Zairong Liu (PhD): Identifying source rocks and oxidation states in southern Australian volcanic rocks (MQ 2020)

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

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)

Maria Constanza Manassero (PhD): A reduced order approach for probabilistic inversions of 3D magnetotelluric data (MQ 2020)

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

Macquarie postgrads and postdocs escape Sydney for a lesson in panning for zircons with Elena Belousova.

Erin Martin (PhD): Understanding Neoproterozoic geodynamics through Hafnium isotopes in zircon (CU 2020)

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

Samuel Matthews (PhD): Novel applications of gravity gradiometry for the detection and monitoring of sequestered CO_2 (MQ 2019)

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

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

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

Josh Shea at the lower pit of the Griffith Quarry.

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)

Stephanie Montalvo Delgado (PhD): Development and application of atom probe tomography to complex zircon grains (CU 2020)

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

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

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

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

Adam Nordsvan (PhD): Sedimentology and provenance of the NE Australian Proterozoic basins to understand the supercontinent Nuna (CU, 2020)

Beñat Oliveira Bravo (PhD): Multicomponent and multiphase reactive flows in the Earth's mantle (MQ 2017)

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

Matthew Pankhurst (PhD): Geodynamic significance of shoshonitic magmatism within the Andean Altiplano (MQ 2013)

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

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

Zsanett Pintér (PhD): The composition of melts in the incipient melting regime (MQ 2020)

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

Valerie Roy (MSc): Hydrogeological and hydrogeochemical study of the Peak Hill-Horseshoe Deposit, Capricorn Orogen to identify mineral system footprints (UWA 2018)

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)

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

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

Camilla Stark (PhD): Decoding mafic dykes in the southern Yilgarn Craton: Significance to Australia's positions in the supercontinent-superplume cycle (CU 2018)

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

Catherine Stuart (PhD): Melt migration in the lower crust by porous melt flow (MQ 2018)

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

Sahand Tadbiri (MSc): The geometry and kinematics of hydrothermal veins in the c. 3.5 Ga Dresser Formation, North Pole Dome, Western Australia (UNSW 2019)

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

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

Romain Tilhac (PhD): Petrology and geochemistry of pyroxenites from the Cabo Ortegal Complex, Spain (MQ 2017)

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

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

Rick Verberne (PhD): Trace element distribution and mass transfer processes in Rutile (CU 2020)

Silvia Volante (PhD): Palaeo- to Mesoproterozoic structural and metamorphic evolution of NE Australia and implications for the assembly of the supercontinent Nuna: Multi-scale analytical approach to decrypt ancient signatures (CU 2020)

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

Alexander Walker (PhD): Sulphur isotope and trace element signatures within mineralised occurrences in the Fraser Zone, Western Australia (CU 2020)

Chengyuan Wang (PhD): Modification of mantle lithosphere: reaction between recycled carbonate melt and mantle peridotite (MQ 2020)

Kai Wang (PhD): Adjoint tomography of surface wave observables from ambient seismic noise (MQ 2018)

Chong Wang (PhD): Paleogeographic reconstruction of the North China Craton in the supercontinent Nuna/Columbia: paleomagnetic and geological constraints; CIPRS (CU 2020)

Qian Wang (PhD): A geological traverse across the Jack Hills Metasedimentary Belt, Western Australia: isotopic constraints on the distribution of Proterozoic rocks and the evolution of Hadean crust (CU 2015)

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

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

Shucheng Wu (PhD): The geodynamic setting of the Western Junggar region during the Late Paleozoic: evidence from seismic tomography (MQ 2019)

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

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

Bo Xu (PhD): Mantle-derived igneous rocks from Southern Tibet: Nature and evolution of the lithospheric mantle and implications for mineralisation from subduction to collision (MQ 2019)

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

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

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

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

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

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

CONTINUING

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

Jason Bennett (PhD): On the geochemistry of cassiterite (UWA, submitted 2020)

Nathan Bowman (PhD): The architecture and genesis of the Archean Wandoo Deposit at Newmont Boddington Goldmine. (UWA, commenced 2020)

Vili Boykova Grigorova PhD): Development of an apparatus for the study of liquids and melts up to megabar pressures; *iMQRTP* (MQ, commenced 2019)

Maria Cherdantseva (PhD): The role of volatiles in the genesis of nickel-sulfide mineral systems; *CIPRS* (UWA, commenced 2019)

Joshua Chong (PhD): The role of carbon as a catalyst for metal transport across the lithosphere (UWA commenced 2020)

Hongkun Dai (PhD): Nature and evolution of the northwest North China Craton; *iMQRES* (MQ, commenced 2018) *Pictured right.*

Hongkun Dai

Benedikt Demmert (PhD): Modelling the effect of minority components in biominerals via biomimetic mineralisation; CTIMRTPS (MQ, submitted 2020)

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

Jean-Antoine Gazi (PhD): The effect of the distribution of elements in the solar system on the formation and evolution of planetary bodies *RTP* (MQ, commenced 2019)

Hindol Ghatak (PhD): Role of fluids in facilitating the intracontinential Alice Springs Orogeny; *iMQRTP* (MQ, commenced 2017) *See photo p. 39.*

Lauren Gorojovsky (PhD): Volatile Chalcophile Element Cycling Between Earth's Mantle and Exospheres; *RTP* (MQ, commenced 2020) *See photo p. 44.*

Stephanie Greene (PhD): Evolution of the lithospheric mantle sampled by the Jericho kimberlite, northern Slave craton, Canada; *IMRTPS* (MQ, commenced 2017)

Ananuer Halimulati (PhD): Abundance, Speciation and distribution of volatile elements in the SCLM; *MQRTP* (MQ, commenced 2017)

Gonzalo Henriquez (PhD): Improving zircon morphology and chemistry as a tool for assessing and ranking the prospectivity for Cu porphyry deposits in greenfield terranes; *Industry - BHP Billiton* (UWA, submitted 2020)

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

Constanza Jara Barra (PhD): Gold pathways: in the El Indio Belt, Chile-Argentina (UWA, submitted 2020)

Anthony Lanati (PhD): Petrology, geochemistry and origin of the shoshonites; *RTP, DAAD Cotutelle* (MQ, commenced 2018)

Anthony Lanati taking observations of the southernmost mound "The Dyke", Jugiong, NSW.

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 (MQ submitted 2020)

Jiangyu Li (PhD): Thermal history of Proterozoic NE Australia: Insights into Nuna assembly and breakup; *CIPRS, CSC* (CU, submitted 2020)

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

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

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

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

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

Brendan Nomchong (PhD): Depositional environment of the c. 2.4 Ga Turee Creek Group, Western Australia; *RTP* (UNSW, submitted 2021)

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

Sarath Patabendigedara (PhD): Quantifying the effects of surface and bulk proton transport in mantle materials (MQ, submitted 2020)

Greg Poole (PhD): Permian magmatism in an early Andean metallogenic belt, Cordillera Frontal, Argentina; *APA* (UWA, submitted 2020)

Carla Raymond (PhD): Archaeometric investigations of Egyptian artefacts using novel techniques; *MRTPS* (MQ, commenced 2018)

Matthew Rowe (PhD): late Archaean granitic magmatism related to cratonisation and gold mineralisation in the Yilgarn Craton; *The Robert and Maude Gledden Postgraduate Research Scholarship, GSWA* (UWA, commenced 2017)

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

Joshua Shea (PhD): Identifying non-peridotite components in the eastern Australian sub-lithosphereic mantle; *RTPS* (MQ, commenced 2019 *See photo pp. 36, 55.*

Chutian Shu (PhD): The role of hydrous pyroxenite in producing primary and intermediate arc magmas; *CTIMRTPS* (MQ, commenced 2019)

Georgia Soares (PhD): Evolution of complex life and the Great Oxidation Event; *RTP* (UNSW, submitted 2020)

Luke Steller (PhD): Movement and concentration of essential pre-biotic elements (with a focus on boron) in both ancient and modern hot spring systems (UNSW, commenced 2019)

Dennis Sugiono (PhD): Sulfur isotope application on the Kanowna Belle Deposit; *RTP-IPRS, Northern Star (Kanowna) Pty Ltd* (UWA, commenced 2017)

Lynthener Bianca Takenaka de Oliveira (PhD): Origin and composition of the subcontinental lithospheric mantle (SCLM) along the lineament of 125 Azimuth, Brazil
iMQRES (MQ, commenced 2019)

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

Anne Vernes (PhD): Understanding camp-scale crustal architecture and its effect on the channelisation of komatiite lava and Ni-Cu-PGE ore deposition (UWA, commenced 2019)

Marina Veter (PhD): Calibration of geochemical *"scouts"* for mantle processes; *IRTPS* (MQ, submitted 2020)

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

Macquarie University PhD student Hindol Ghatak (left-front) conducting fieldwork in Central Australia with his supervisors (Nathan Daczko left-back) and Tom Raimondo (cameraman, Univ. of SA), and students from The University of Adelaide and the University of South Australia (right).

Infrastructure and technology development

CCFS links three internationally recognised concentrations of analytical geochemistry infrastructure: GEMOC's Geochemical Analysis Unit (Macquarie University, reorganised in 2016 as MQGA) and the associated Computing Cluster, the Centre for Microscopy, Characterisation and Analysis (UWA/Curtin) and the John de Laeter Centre of Mass Spectrometry. All are nodes for the NCRIS AuScope and Characterisation Capabilities, and have complementary instrumentation and laboratories. In addition, Curtin and UWA share a leading facility for paleomagnetic studies, and facilities for experimental mineralogy and petrology are being built up at Macquarie and Curtin.

CCFS/GEMOC INFRASTRUCTURE, LABORATORIES AND INSTRUMENTATION

The analytical instrumentation and support facilities of the Macquarie University GeoAnalytical facilities contain:

- 2 Cameca SX-100 electron microprobes
- a Zeiss EVO MA15 Scanning electron microscope (with Oxford Instruments Aztec Synergy EDS/EBSD and Horiba HCLUE spectral cathodoluminescence detector)
- JOEL benchtop Scanning electron microscope
- A Nanomin FEI Field Emission SEM
- Micro XRF M4 Tornado from Bruecker
- three Agilent quadrupole ICPMS (industry collaboration; one 7500cs; two 7700cx)
- two Nu Plasma multi-collector ICPMS
- a triple quad (Q3) ICPMS 8900
- a Nu Plasma II multi-collector ICPMS
- a Nu Attom high-resolution single-collector sector field ICPMS
- 2 Thermo Finnigan Triton TIMS
- a Photon Analyte LSX213nm laser ablation system
- a Photon Machines Excite Excimer laser ablation system
- a Photon Machines Analyte G2 Excimer laser ablation system
- a Photon Machines Analyte198 Femtosecond laser ablation system
- Thermo Fisher Neptune Plus MC-ICPMS
- a PANalytical Axios 1kW XRF with rocker-furnace sample preparation equipment
- a Vario El Cube CHNS elemental analyser
- AEuro EA3000 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
- MP-AES (Microwave Plasma Mass Spectrometer)
- MAT 253+ Isotope Ratio Mass Spectrometer with IBEX
- 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. (see *https://www.youtube.com/watch?v=as111oj-NA0*)

THE GEMOC FACILITY FOR INTEGRATED MICROANALYSIS (FIM) AND GEOCHRONOLGY

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

This facility is focused on *in situ* imaging and microanalysis of trace elements and isotopic ratios in minerals, rocks and fluids. A wide range of *in situ* geochronological analytical capabilities has backup from traditional solution methodologies.

Major instruments were replaced or upgraded, many by joint ventures with national partners including Teledyne Cetac technologies, Nu Instruments, AMETEK and ThermoFisher Scientific.

EQUIPMENT FOR HIGH-PRESSURE EXPERIMENTATION

The new high-pressure laboratory contains two rapid-quench piston-cylinder apparatuses (GUKO Sondermaschinenbau) and three multi-anvil apparatuses, including one new 1000 ton press with a Walker module (Voggenreiter GmbH). Two older piston-cylinder apparatuses set up by Prof Trevor Green in the old high-pressure laboratory are still functional. There is also a Griggs

deformation apparatus, a one-atmosphere quench apparatus and a diamond-anvil cell apparatus.

Current projects are investigating the melting curves and melt compositions produced from peridotites with mixed volatile components, and from pyroxenites containing hydrous phases such as amphiboles and micas. The melting of sedimentary rocks, including limestones, is being investigated in combination with reaction experiments that juxtapose sediments with mantle peridotites. Other experimental projects are looking at trace element mobility in fluids, the partitioning of nitrogen, fluorine and chlorine, and the dissolution of zircons in silicate melts.

PROGRESS IN 2020:

1. Sample Preparation Facilities

In 2020 the MQGA Sample Preparation Facility was fully refurbished, providing a high-quality sample preparation precinct including nine laboratories covering ≈250 m^2. The facility accommodates the processing of large rocks down to (sub-)micrometric minerals. Instrumentation includes the SelFrag (see below), magnetic separators, heavy liquid separation and hydroseparation processing. The facility also includes fully equipped lapidary laboratories to produce high quality polished blocks and thin sections and an extensive range of crushing and milling apparatus.

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, the 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.

We envision that this facility will develop into a research node for sample preparation, mainly, but not strictly limited to mineral separation through collaborative projects with academia and industry. Indeed, there is opportunity for improvement and novel approaches to sample preparation by combining existing technologies and/or new technology.

In the coming decades, critical minerals will be required for a sustainable national (and global) future. This expected reduction in target size and abundance of these critical minerals will require enhanced mineral separation techniques. Concentration by hydro-separation, a capability of the sample preparation facility, is done with almost no loss of mineral grains and with a mineral concentration factor varying (mineral specific) between 100 to 10,000 times the original proportions of minerals. The combination of electrostatic pulse disaggregation (EPD: SelFrag) and hydro separation techniques enable the recovery of rare minerals, with abundances down to few parts per million (i.e. ≈0.0001 vol.%) in very fine fractions (Ø < 1 µm). Preliminary work is being carried out by Montgarri Castillo-Oliver (*pictured below left*).

2. Whole-rock analysis

2.1.1. In November 2012, a PANalytical Axios 1 kW X-ray Fluorescence (XRF) Spectrometer was installed and is used routinely to measure whole-rock major element compositions on fused glass discs and trace-element concentrations on pressed-powder pellets. In 2013 the sample preparation equipment was upgraded and included a new furnace to make high-quality cast glass beads. The major element calibration was modified in 2015 to extend the spectrum of rock types that could be analysed to include Fe-rich samples such as iron ores and laterites. This year the PANalytical was refurbished to maintain high accuracy and precision. Round-robin tests (GeoPT) show the PANalytica Axios is performing very well.

2.1.2. The high-performance CHNS elemental analyser from Elementar (Vario El Cube), fitted with an extra IR-detector for low-level sulfur analysis, is now in operation and is providing high quality S analyses for projects involving Re-Os isotopic analysis. It also analyses the distribution and abundance of volatile elements in the Earth's mantle (PhD student Halimulati Ananuer, ECR Michael Förster). An extensive suite of reference materials (n≈43), with variable matrix and composition, has been measured, and the results were presented at the Geoanalysis Conference (held at Macquarie University in July 2018). The Elementar analyser yields remarkably accurate and reproducible measurements for C, H, and S at low levels for relatively small samples (i.e. ≈20 mg). Refurbishment of a second Elemental analyser (Euro Vector) is underway. This instrument will be dedicated to the measurement of small samples (i.e. <20 mg)

Montgarri Castillo-Oliver using the MQGA Sample Preparation Facility.

2.2. Whole-rock solution analysis
An Agilent 7500cs ICPMS produces trace-element analyses of dissolved rock samples for the projects

of CCFS/GEMOC researchers and students and external users, supplementing the data from the XRF. We are testing the performance of the Nu Attom for ultratrace element measurements. The ICPMS dedicated to solution analysis is also used to support the development of 'non-traditional' stable isotopes with the refinement of separation techniques and analytical protocols. Further solution work is caried out on the QQQ Agilent 8900 ICP-MS to assess the precise concentration of elements with reduced interferences from specific matrixes, especially in organic rich matrixes. Thanks to our ongoing collaboration with Teledyne Cetac, we are now testing new auto/micro-samplers for the measurement of ultra-trace elements and challenging elements (e.g. halogens) in mono-grain aliquots.

3. Spectroscopy

3.1. Fourier Transform Infrared Spectroscopy: The spectroscopy infrastructure includes an FTIR microscope (ThermoFisher iN10 FTIR microscope; 2008) and a confocal laser Raman microscope (co-funded by the Macquarie University Strategic Infrastructure Scheme (MQSIS), 2014 and Future Fellowship funding to Professor Dorrit Jacob). The FTIR is used to measure H abundance in a range of nominally anhydrous minerals (e.g. olivine, pyroxene, garnet) and H and N contents in diamond. 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.

3.2. Raman Spectroscopy
The Raman spectrometer continues to serve the CCFS, the Department and the Faculty. In 2019 the system's capabilities were extended with the loan of a liquid nitrogen cold stage from the Department of Physics. The instrument continued to grow its user base across the Faculty of Science and Engineering at Macquarie University with users from Chemistry, Physics, Biology, Environmental Sciences as well as users from the Faculty of Arts, Department of Ancient History and the Museum of Ancient Cultures.

2020-21 research and applications of Raman Spectrometry included:

- Earth and Planetary Science, analysis of sulfate speciation in glasses (Dr Oliver Alard and Lauren Gorojovsky)
- Earth and Planetary Science, amphibole characterisation and quantification of volatile content (Dr Oliver Alard and Ananuer Halimulati)
- Earth and Planetary Science, characterisation of experimental petrology run products, which are now abundantly produced by Prof S. Foley's laureate team
- Forensics applications, namely ink characterisation on Egyptian papyrus (Prof Damian Gore and Assoc Prof Malcolm Choat)
- Chemistry, surface enhanced Raman spectroscopy (SERS) of nano particle interactions in serum (Dr Alfonso Garcia-Bennett and Inga Kuschnerus)
- Physics and Astronomy, Photoluminescence/ Raman characterisation of UV Laser irradiated diamond surfaces. (Mojtaba Moshkani)
- Physics and Astronomy, localised dehydroxylation in Muscovite using single ultrafast (fs) laser pulse. (Saurabh Awasthi)
- Physics and Astronomy, analysis of diamond seeded silicon surfaces and structural analysis of diamond thin films grown at low substrate temperature by microwave plasma chemical vapour deposition (MPCVD) (Fatima Zahra)
- Archaeology, oxide and corrosion analysis of ancient lead scrolls (Prof Simon Clark and Carla Raymond)
- Archaeology, identification of pigments used in Egyptian Mummy Carapace (Dr Karin Sowada and Dr Ronika Powers)
- Archaeology, pigment analysis of Amarna Blue used in Egyptian pottery (Prof Martin Bommas, Dr Tim Murphy, and Penelope Edwell)

4. *In situ* Spectrometry and imaging

4.1. CCFS and AuScope have provided significant funding support and scientific expertise to purchase a Scanning X-ray spectrometer (M4 Tornado Bruecker) to enable fast scanning and mapping of thin sections and blocks, thus providing a wider and more complete spatial framework for *in situ* analysis. The acquisition and running of this instrument is a joint venture with Professor Damien Gore (Dept. Earth and Environmental Sciences). The versatility of this instrument has attracted significant interest from most faculties across Macquarie University, including Arts, and is heavily used by MRes and PhD students. Dr Timothy Murphy is leading a group developing new approaches with this instrument in geosciences and beyond.

4.2. Scanning Electron microscopy: The Zeiss EVO SEM, equipped with an EBSD detector, is still performing well and is used in a variety of studies extending beyond geology. A Horiba H-CLUE CL monochromator was installed on the Zeiss EVO SEM in January 2016. The monochromator system provides spatially resolved quantitative cathodoluminescence spectra, which allow identification of emitters (e.g. REE in zircons), crystal lattice vacancies (e.g. in diamond) and crystallographic information on how specific elements are incorporated in the mineral crystal lattices (e.g. Mn in aragonite). The instrumentation is acquiring a growing group of users and is currently part of projects in biomineralisation (HDR student Laura Otter/Prof Dorrit Jacob), diamond growth (Professor Dorrit Jacob) and zircon characterisation (Honorary Associate Dr Christoph Lenz/Dr Elena Belousova).

The unique Nanomin FEI Field Emission scanning electron microscope is used to (i) identify micro- to nano-meter mineral species, (ii) to assess recovery and representativity (qualitatively and quantitatively) as well as (iii) characterise geochemistry. This approach will allow the production of a new map of occurrence,

abundance and chemistry of indicator and critical minerals across the Australian continent, which in turn will be fed into the AGN database, providing the community with an innovative and powerful tool for mineral exploration

4.3. Electron Microprobe: Dr Timothy Murphy oversees the 2 SX100 electron microprobes nicknamed "Norm" and "Taz". These two instruments are equipped with 5 WDS spectrometers and a Bruker EDS spectrometer. One instrument is fitted with an anti-contamination stage and Cathodoluminescence Light pipe, while the other was updated with the "Probe" software (J. Donovan). Together these two instruments, despite their respective ages, provide a robust platform for quantitative *in situ* measurement and chemical mapping of minerals for high-spatial resolution and precise thermo-barometry as well as the chemical characterisation required for further *in situ* trace element analysis in our laser ablation ICPMS facilities.

4.4. Laser-ablation ICPMS microprobe (LAM): Dr Yi-Jen Lai manages the extensive LA-ICPMS and MC-ICPMS instrument park available at Macquarie. AuScope Research Associate Yoann Gréau provides invaluable technical help and expertise. In 2019 CCFS technical and research staff Romain Tilhac and Hadrien Henry provided generous assistance for users. This was continued by Yoann Gréau and Montgarri Castillo-Oliver in 2020.

The Photon Machines Excite/G2 laser system and Agilent 7700 ICPMS are used for *in situ* trace element analyses and U-Pb geochronology. An extremely mobile 213 nm Laser (LSX213, Teldyne) has been purchased to ensure service continuity. The facility is used by Macquarie PhD thesis projects, international visitors, Masters Research students and several in-house funded research projects and industry collaborations. Projects include the analysis of minerals from mantle-derived peridotites, pyroxenites and chromitites, meteorites, unusual types of ultra-reduced phases from volcanic sources and ultra-high pressure terranes, high-grade metamorphic rocks and biominerals.

Yi-Jen Lai and collaborators have launched an initiative aiming to develop LA-ICP-MS trace-element imaging. These techniques were applied in biological samples (e.g. skin) and archaeological samples (e.g. cattle's teeth). Thanks to an enhanced collaboration with Teledyne – PhotonMachine, an Aerosol Rapid Introduction System (ARIS) was recently installed on the Excite Excimer laser ablation system. As expected, the integration of the ARIS system has greatly reduced wash-out time and enhanced resolution which together have led to enhanced trace element mapping capabilities.

The recent developments of Laser-ablation ICPMS microprobe applications include a multi-proxy approach for U-Pb dating of U-containing minerals (zircon, apatite, rutile, etc) to capture a more complete geological history. A particular focus Is the apatite U-Pb dating and improving standardisation (calibration standard) procedure. The Integrated zircon/apatite dating approach aims to resolve the current problems by providing

Isra Ezad using the SX100 electron microprobe known as "Norm". Isra joined CCFS in 2020 as an ECR working with Steve Foley's Laureate team on partial melting experiments on peridotites with CO_2 and H_2O.

valuable geochronological data for low-temperature events (e.g. mid–low-T, metamorphic, hydrothermal events) and rock types (mafic, ultramafic, metasomatic) that lack zircons.

With the addition of trace gases such as N_2 and H_2 in the ablation gas, Olivier Alard and collaborators have obtained a significant increase in terms of sensitivity (counts per ppb multiplied by 2) and a noticeable decrease in detection limit. This breakthrough allows researchers to investigate: (i) olivine trace element abundances (i.e. higher sensitivity means complete REE patterns can now be obtained), (ii) ultratrace element concentrations and distributions between silicates, sulfides and oxides of rarely investigated elements such as metalloids from the d- and p-blocks elements (e.g. Sn, Sb, Cd, Mo, W…). This technique is now being applied by Marina Vetter (PhD), S. Foley and S. Demouchy (CNRS, Géoscience Montpellier) and has been published in Contributions to Mineralogy and Petrology, Demouchy and Alard, 2021 (CCFS publication #1567). This approach has also opened new avenues of research for notoriously difficult to analyse elements i.e. the Halogens (F, Cl, Br, I).

The new Q3-ICPMS (Agilent 8900) was installed in December 2017 and is co-located with the upgraded Nu-Plasma HR. The development of *in situ* Rb-Sr analysis is well underway. Preliminary results were presented by Lauren Gorojovsky and Olivier Alard *(pictured p. 44)* at the Goldschmidt conference in August 2019 (Barcelona, Spain) and are now published Gorojovsky and Alard, 2020, JAAS (#1522). In-house reference materials have been characterised to extend the range of material (matrix) analysed. Further applications of *in situ* Rb-Sr dating are being developed. Dr O. Alard, Dr Stefan Loehr, Mehrmoush Rafei (PhD) and collaborators from Adelaide University are assessing the geochronological potential of glauconite in sedimentary rocks. The team led by Olivier Alard is also working on other developments for the precise (interference-free) measurement of chalcophile and siderophile

Lauren Gorojovsky and Olivier Alard with Q3-ICPMS (Agilent 8900).

elements for precise S-Se and Te analyses by LA-ICPMS in submarine glasses. Lauren Gorojovsky developed this approach during her MRes with great success. She is now pursuing this research in her PhD.

MQGA performed extremely well in the international round-robin proficiency test for *in situ* trace element measurements (G-PROBE, top 10) and had remarkable results in term of accuracy and precision in geochronology (Top 5 in G-CHRON proficiency testing).

5. Mass Spectrometry - isotopes

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

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

Montgarri Castillo-Oliver and Yoann Gréau have refined the measurement of *in situ* Sr isotopes in carbonate and clinopyroxene by LA-MC-ICPMS. New developments are underway for the in-situ measurement of Sr isotopes in phosphates for Earth sciences (apatite, E. Belousova) and for Archaeological Sciences (dentine and bone). The *in situ* measurement of U-Pb isotopes in zircon using a combination of the femtosecond laser system and the Nu Plasma II was a world first, with preliminary results first reported at the Goldschmidt Conference in Prague, August 2015 (N.J. Pearson et al.).

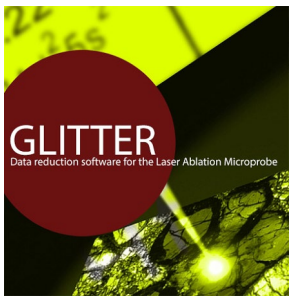
The LAM MC-ICPMS is the vehicle to deliver *in situ* high-precision ratio measurements including the analysis of Lu-Hf isotopes in zircon as a major part of *TerraneChron®* (see http://www.gemoc.mq.edu.au/TerraneChron.html). In 2015 a third Photon Machines excimer laser microprobe was installed and co-located with the Nu Plasma HR 034. The interface was upgraded, increasing sensitivity between 1.5 and 2 times, and this contributed to an overall improvement in signal stability, as well as precision of single measurements and long-term reproducibility. This setting significantly improved access and turn over for *in situ* Lu-Hf in zircon which is a key part of the *TerraneChron®* methodology. *TerraneChron®* applications continued and were up-scaled in 2020 with the involvement of Dr Montgarri Castillo-Oliver to meet the increasing demand for this powerful tool for understanding the evolution of Earth's crust, for isotopic mapping and paleogeophysics, and geochemical remote sensing for the exploration industry *(see p.50).*

An UPS and new Daly detectors were installed on the Nu Plasma II MC-ICPMS in early 2020. The larger dynamic range offer more flexibility and stability, especially for *in situ* techniques requiring simultaneous measurement of abundant and rare isotopes such as *in situ* Re-Os. CCFS/GEMOC remains one of the few facilities with the capability to perform *in situ* Re-Os dating of single grains of Fe-Ni sulfides and alloys in mantle-derived rocks. CCFS Research Associate Dr Yoann Gréau and Dr Olivier Alard, have recently made good progress in method development. A novel split-stream approach has been established, involving the simultaneous measurement of Re-Os isotopes on the Nu plasma II and siderophile and chalcophile trace elements on the Agilent 7700. Preliminary results for this world first were presented at the Goldschmidt 2019 conference in Barcelona. Future Fellow Olivier Alard is undertaking studies on worldwide mantle sulfides. The project integrates *in situ* Platinum Group Elements, Re-Os and S isotopes obtained using the newly established Laser splitting system (MU) and ion probe (CAMECA 1280, CMCA Perth) respectively, in collaboration with CCFS Research Associate Laure Martin (UWA). This project pushes the concept of analytical integration to a new level. Planned applications are (i) combined U-Pb and Lu-Hf characterisation of zircons and (ii) simultaneous measurements of Sr isotopes and trace elements in silicates and carbonates. New technique strategies involving splitting with the Q3-ICPMS are also being investigated.

6 Software and Database

6.1. GLITTER (GEMOC Laser ICPMS Total Trace Element Reduction) software is our online interactive program for quantitative trace element and isotopic analysis and features dynamically linked graphics and analysis tables. This package provides real-time interactive data reduction for LAM-ICPMS analysis, allowing inspection and evaluation of each result before the next analysis spot is chosen. GLITTER's capabilities include

the online reduction of U-Pb data. Sales of GLITTER are handled by AccessMQ, and GEMOC provides customer service and technical backup. During 2020 a further 6 licences of GLITTER were sold, bringing the total number in use to more than 300 worldwide, predominantly in Earth sciences applications but with growing usage in forensics and materials science.



Dr Will Powell continued in his role in GLITTER technical support and software development through 2019 on a consultancy basis, following his resignation and relocation to Rio Tinto (Melbourne) in early 2016. The current GLITTER release is version 4.4.5 and is available without charge to existing customers. GLITTER 5.0 is currently in development, undergoing beta testing by the GLITTER team, and is due for release in 2021. The update will include Ratio/Ratio plots, enhanced sample and standard search functions, segmented external calibration modelling and P/A factor dataset integration and plotting. (*see http://www.glitter-gemoc.com/*)

6.2. AGN database: CCFS is a part of a consortium of Earth Science facilities aiming to develop national geochemistry research infrastructure and increase end-user access to Australian laboratory facilities. Established in 2019, the AuScope Geochemistry Network (AGN, https://www.auscope.org.au/agn) is implementing a national geoscience database, capturing legacy and real-time geochemical datasets aligned with FAIR (Findable, Accessible, Interoperable and Reusable) principles. This will enable the co-registration of multiple digital datasets (e.g., geophysical, geochemical, physical state and property, time) in multidimensional space for unprecedented imaging of Earth characteristics.

Guillaume Florin and Yoann Gréau have been developing data templates for data masks specific to *in situ* U-Pb and Lu-Hf in zircon analysed by LA-(MC)-ICP-MS. The masks will help collect all the necessary "Level 1" data and sample metadata to be uploaded on the AGN AusGeochem platform. They have been working in conjunction with an Expert Advisory Group comprising of representatives from the University of Tasmania, the University of Melbourne, the University of South Australia, GSWA and Macquarie University. The Expert Advisory Group have also been discussing the analytics and graphical outputs to be generated by the AusGeochem platform. Guillaume Florin is writing a Python code to bulk collate Hf data from the various mass-spectrometer into CSV files readily uploadable onto AusGeochem, streamlining the data input process.

The AGN has an ongoing webinar series, the 3rd webinar featuring Macquarie University. AGN webinars and conference presentations are available on the AGN YouTube channel: https://www.youtube.com/channel/UC0zzzc6_mrJEEdCS_G4HYgg.

AuScope AuScope Geochemistry Network (AGN)

7. Computer cluster

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

CMCA TECHNOLOGY DEVELOPMENT AND INSTRUMENTATION

The University of Western Australia's Centre for Microscopy, Characterisation and Analysis (CMCA) is a $50M core facility providing analytical solutions across a diverse array of scientific research. The world-class facilities and associated technical and academic expertise are the focus of micro-analytical and characterisation activities within Western Australia, while strong links and collaborations have earned the CMCA an excellent national and international reputation. The CMCA incorporates the Western Australian Centre for Microscopy, and is a node of the NCRIS Characterisation capabilities, the National Imaging Facility (NIF) and the Australian Microscopy and Microanalysis Research Facility (AMMRF). It is also associated with the NCRIS funded Australian National Fabrication Facility (ANFF), and AuScope, which have made a substantial contribution to facilities run by CMCA.

CMCA capabilities:

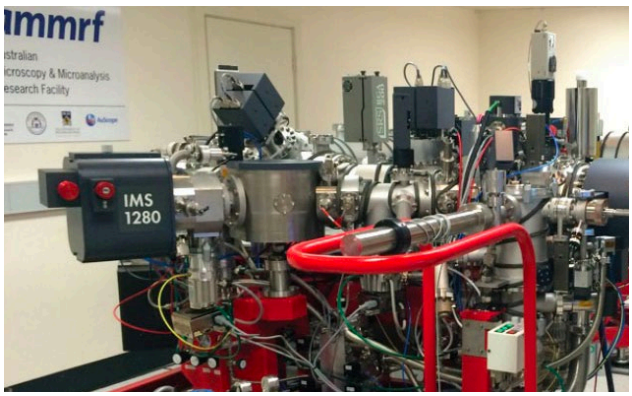
- Secondary Ion Mass Spectrometry (CAMECA IMS 1280 and CAMECA NanoSIMS 50 and NanoSIMS 50L)
- Electron probe microanalysis (2xJEOL JXA 8530F)
- Focused ion beam (FEI Helios)
- Transmission electron microscopy (FEI Titan, JEOL 2100)
- Scanning electron microscopy (FEI Verios XHR, Zeiss 1555, Tescan Vega3)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

- Optical and confocal microscopy
- Biological sample cryo-preparation and ultramicrotomy

THE AMMRF FLAGSHIP ION PROBE FACILITY

The CAMECA SIMS 1280 and NanoSIMS 50 are flagship instruments of the AMMRF. The AMMRF Flagship Ion Probe Facility offers state-of-the-art secondary ion mass spectrometry (SIMS) capabilities to the Australian and international research communities, allowing *in situ*, high-precision isotopic and elemental analyses and secondary ion imaging on a wide range of samples.

The SIMS1280 large-geometry ion probe, installed in 2009, was co-funded by the University, the State Government of Western Australia, and the Federal Government's Department of Innovation, Industry, Science and Research (DIISR) under the "*Characterisation*" (AMMRF) and "*Structure and Evolution of the Australian Continent*" (AuScope) capabilities of the National Collaborative Research Infrastructure Strategy (NCRIS). The NanoSIMS 50, installed in 2003, was funded through the Federal Government's NCRIS-precursor, the Major National Research Facility scheme (NANO-MNRF). UWA's Ion Probe Facility can currently lay claim to being the best-equipped SIMS lab in the world, as no other facility has two NanoSIMS alongside an IMS1280.



CAMECA SIMS 1280.

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 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.

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

PROGRESS IN 2020:

The Ion Probe Facility has continued to contribute to various projects in the context of CCFS. Both 1280 and NanoSIMS laboratories contributed to individual projects in Earth Sciences, originating from CCFS partners, other Australian research institutes and overseas.

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 based at Curtin University and is the core research infrastructure centre for the Faculty of Science and Engineering. The centre houses advanced instrumentation for high-resolution imaging and analysis of natural and man-made materials. By the end of 2021, the JdLC will host $46M in research infrastructure supporting research in: geosciences (geochronology, thermochronology and isotope studies); environmental science; isotope metrology; forensic science; economic geology (minerals and petroleum); marine science; and nuclear science.

The JdLC will soon be home to new equipment vital for gaining a better understanding of the Earth and its place in the Universe after receiving $8.2 million in federal (AuScope) and state government (GSWA) funding. A new Large Geometry Ion Microprobe (LGIM) will be installed at the John de Laeter Research Centre at Curtin to replace a Sensitive High Resolution Ion MicroProbe (SHRIMP), which has been a JdLC flagship platform for 27 years. The new LGIM instrument will be a CAMECA 1300HR3 ion microprobe, which will operate with support from both GSWA and the AuScope Earth Composition and Evolution Program which includes Curtin University, The University of Melbourne and Macquarie University.

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

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

https://jdlc.curtin.edu.au/facilities/sensitive-high-resolution-ion-micro-probe-facility/

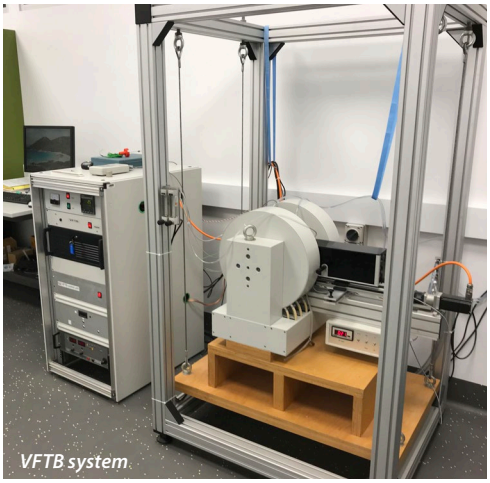
WESTERN AUSTRALIA PALEOMAGNETIC AND ROCK-MAGNETIC FACILITY

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

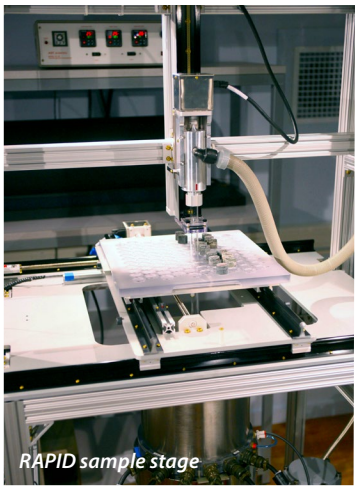
Inside the Shielded Room

A significant component of the facility is the magnetically shielded room (constructed in mid-2015 by Dr Gary Scott's Lodestar Magnetics team) which provides a 20m2 laboratory space with ambient magnetic fields less than 0.5% of the local geomagnetic field. Within this shielded room are: a 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system), an AGICO JR-6A spinner magnetometer, and ASC TD-48SC and MAGNETIC MEASUREMENTS thermal demagnetisers. An earlier model 2G 755 cryogenic magnetometer is undergoing further repair and will be installed into the shielded room in the future.

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



VFTB system



RAPID sample stage

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

- a 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories (including; AF coils, susceptibility meter, ARM and IRM modules)
- an earlier model 2G 755 cryogenic magnetometer upgraded to a 4K DC SQUID system (this system is currently undergoing additional repairs)
- an AGICO JR-6A spinner magnetometer
- 1x MMTD80, 2x MMTD18 and a TD-48-SC thermal demagnetiser
- a Petersen Instruments Variable Field Translation Balance (VFTB)
- an AGICO MFK-1FA Kappabridge with K-T capacity
- a MAGNETIC MEASUREMENTS MMPM5 pulse magnetiser

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

A national workshop on paleomagnetism, rock magnetism and their applications to tectonics, paleoclimate research, and Earth resource exploration has been postponed due to the COVID-19 pandemic. This will be reconvened once the pandemic is over, and will include a tour of the facilities along with training on the operation of all instruments for potential users of the laboratory.

Industry interaction

INDUSTRY INTERACTION AND TECHNOLOGY TRANSFER ACTIVITIES

CCFS has a strategic goal to interact closely with the mineral exploration industry at both the research and the teaching/training levels. The research results of the Centre's work are transferred to industry and to the scientific community in several ways:

- collaborative industry-supported 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).

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

ACTIVITIES IN 2020

- Several new geochronology and geochemistry projects with the minerals industry, including FMG, Atlas Iron, Anglo American, Breaker Resources, Latitude 66 Cobalt and Regis Resources, commenced.
- *TerraneChron*® studies (*see p. 50* and http://www.gemoc.mq.edu.au/TerraneChron.html) have enjoyed continued uptake by a significant segment of the global mineral exploration industry. This methodology, currently unique to CCFS/GEMOC, requires the integration of data from three instruments (electron microprobe, LAM-ICPMS and LAM-MC-ICPMS) and delivers fast, cost-effective information on the tectonic history of regional terranes (http://www.gemoc.mq.edu.au/TerraneChron.html). The unique, extensive database (over 32,000 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry. Associate Professor Elena Belousova delivered

CCFS supports the national UNCOVER initiative: CCFS Chief and Associate Investigators, collaborating researchers and Board members have been instrumental in shaping UNCOVER Australia and the 2017 AMIRA "Undercover Roadmap" (ROADMAP). Indeed the 4-D Lithosphere Mapping approach, established by GEMOC and CCFS with industry partners, forms the robust conceptual basis for UNCOVER, contributed significantly to the AMIRA Roadmap process, and has become part of the vernacular in smart exploration strategies. ***http://www.uncoverminerals.org.au/***

several invited presentations in 2020 titled *TerraneChron®*'s trajectory 2000-2030.

- The CCFS collaboration with Shefa Yamim (A.T.M.) Ltd. (Akko, Israel) continued in 2020. As part of the collaboration the mineral Carmeltazite was discovered in pockets of trapped melt in corundum xenocrysts from the Cretaceous Mt Carmel volcanics of northern Israel by CCFS's Bill Griffin, Sarah Gain, Luca Bindi (Università degli Studi di Firenze, Italy), Vered Toledo (Shefa Yamim Ltd., Israel), Fernando Cámara (Università degli Studi di Milano, Italy), Martin Saunders (UWA) and Sue Y. O'Reilly. In 2020, two new minerals, kishonite (VH_2) and oreillyite (Cr_2N) (*see https://www.auscope.org.au/news-features/oreillyite*) were described (*CCFS Publication #1542*), the latter named after Suzanne O'Reilly, Director of CCFS.
- The popular annual event, GSWA Open Day 2020, was held on Friday, 21 February at the Esplanade Hotel in Fremantle. The event showcased the latest geological information and major activities of the GSWA.
- The "*LAMP*" (Lithosphere Architecture Mapping in Phanerozoic orogens) project was originally funded 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.

  A project "*Archean mantle and plate tectonics: the seismic record of arc magmatism*" continued in 2020. The multi-disciplinary project (geophysics, geochemistry and modelling) will examine the robustness of global horizontal-Vs tomographic models. The project also aims to characterise the seismic signature of subduction zones in ancient terranes. The role of subduction processes in the formation of mineral deposits (e.g. Cu, Au) in these ancient terranes, now undercover, is critical for future mineral exploration.

  Dr Begg visited CCFS/GEMOC several times in 2020 as part of the close collaborative working pattern for this project.
- In the project "*Developing thermochemical models of Australia's lithosphere*" funded by GA, researchers from GA and CCFS are using and further developing the LitMod inversion platform to study the deep architecture and thermochemical structure of the Australian continent using recently acquired datasets from the AusLAMP and AusArray national initiatives. This represents one of the largest probabilistic inversions ever attempted, which required the development of efficient multi-algorithm techniques and parallel software infrastructure.
- Industry partners provided mentoring and both logistical and financial support for CCFS postgraduate research projects in 2020.

  Through a Cotutelle PhD, the Geological Survey of Brazil (CPRM) is collaborating by providing samples for Lynthener Takenaka de Oliveira's PhD project, including mineral concentrates, diamonds and thin sections. The collaboration also allows access to internal geochemistry datasets, geophysical and geological maps, software licences and collaboration with other researchers from the company on data treatment, interpretation and scientific writing.

  A project funded by Northern Star Resources provides funding for Dennis Sugiono's PhD project, including a PhD scholarship as well as additional funding for analytical costs and travel.

  Other participating organisations include BHP Billiton (BHP Chile Inc.), Barrick Exploration (Compania Minera Barrick Chile Ltd.), Teck Resources Ltd, CSIRO, ANSTO and MRIWA. See *CCFS postgraduates* (*p. 33*) for a full list of postgraduate projects.
- BHP partnered with UNSW's Big Questions Institute through M Van Kranendonk to support outreach activities to attract students into STEM; research on Life on Mars, conservation of Pilbara stromatolites.
- In 2020, interaction continued with BHP on the utilisation of detrital minerals in the exploration for porphyry systems. The project involves a PhD student (Gonzalo Henriquez) and long-term CCFS collaborator Bob Loucks. This work has laid a robust foundation for the establishment of a new 3-year BHP-funded project that started in late 2020 in collaboration with the University of Bristol, UK.
- A new multi-sponsored MRIWA project (M 530 Yilgarn 2020) has continued in 2020. The project aims to constrain the multi-scale controls on the metal endowment of the Yilgarn Craton. A lot of this work is underpinned by science that was developed throughout CCFS.
- Ongoing engagement with IGO aims to develop a predictive understanding of the genesis of chonoliths that contain magmatic nickel-sulfide mineralisation. The work is focused at the Nova-Bollinger Nickel Deposit, in the Albany-Fraser Belt of Western Australia.
- Industry visitors spent varying periods at Macquarie, Curtin and UWA (CET) in 2020 to discuss our research and technology development (see visitor list, *Appendix 5*). This face-to-face interaction has proved highly effective both for CCFS researchers and industry colleagues.
- 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 2020 (see Abstracts, *Appendix 4*).

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.

CCFS industry collaborative projects are designed to develop the strategic aspects and applications stemming from the fundamental research programs; many are based on understanding the architecture of the lithosphere and the nature of Earth's geodynamic processes that have controlled the evolution of the lithosphere and its important discontinuities. The basic research strands that have given rise to strategic applications include the use of geochemical data integrated with tectonic analyses and large-scale datasets (including geophysical) to understand the relationship between lithosphere domains and large-scale mineralisation. The use of sulfides to date mantle events, and the characterisation of crustal terrane development using U-Pb dating and Hf isotopic compositions of zircons (*TerraneChron®*) have been developed as regional isotopic mapping tools for integration with geophysical modelling. This integrated approach has been widely adopted by a significant proportion of the mineral exploration industry and has resulted in the granting of licence to use methodologies developed.

Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP)	***Linkage Project (LP170100233)*** ***Industry Collaborators: CSIRO, Geological Survey of NSW, Geological Survey of South Australia, Geoscience Australia, Northern Territory Geological Survey*** ***CIs: Regenauer-Lieb, Afonso, Clark, Thiel, Czarnota, Poulet, Jones, Walsh*** ***Summary:*** This project aims to provide a newly developed science approach to the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP). AusLAMP provides unparalleled geophysical information aimed at unravelling the tectonic history of the Australian continent and its mineral potential. The project will use thermodynamically based geodynamic simulators to jointly analyse and quantify intraplate deformation. This will illuminate the cause of driving fluid flow through the lithosphere, mineralisation phenomena, their datasets and geometries, and dynamic aspects of the processes driving mineral systems.
Mitigating 3D geological risk in resources management	***Linkage Project (LP170100985)*** ***Industry Collaborators: AUSCOPE, British Geological Survey, Department of Planning and Environment, Geological Survey of Canada, Geological Survey of South Australia, GSWA, Geoscience Australia, Northern Territory Geological Survey, Research for Integrative Numerical Geology, Georessources - Université de Lorraine, RWTH Aachen University of Technology, Germany*** ***CIs: Ailleres, Jessell, de Kemp, Caumon, Wellmann, Armit, Droniou, Lindsay, Cui, Betts, Cruden, Kemp, Gessner, Spampinato, Harrison, Kessler*** ***Summary:*** The project aims to develop technologies to mitigate 3D geological risk in resources management. The project is expected to create new knowledge and methods in the field of 3D geological modelling through the innovative application of mathematical methods, structural geology concepts and cutting-edge probabilistic programming. The expected outcomes are an enhanced capability to model the subsurface, characterise model uncertainty and test multiple geological scenarios. This enhanced capability is extremely important for the future of Australia's subsurface management; including urban geology and our continuously growing sustainable resources industry (including water).
Enhanced 3-D seismic structure for Southwest Australia	***Linkage Project (LP180101118)*** ***Industry Collaborators: Geological Survey of Western Australia; Geoscience Australia; Department of Fire and Emergency Service*** ***CIs: Miller, Kennett, Yuan, Allen, Gray, Gessner*** ***Summary:*** The aim of this project is to develop a geophysically relevant proton conduction model for the Earth's upper mantle. This will allow the robust interpretation of conductivity maps of the interior of the Earth and the discovery of major new mineral deposits. This advance will be achieved through four major initiatives based on recently developed experimental and computational facilities. This project will develop new methods for determining rock conductivities and subsurface mapping from combined datasets. We will obtain new insights into the structure and dynamics of the upper mantle as well as providing key data necessary for a national effort aimed at reestablishing Australia as a primary target for mineral exploration.
Archean mantle and plate tectonics: the seismic record of arc magmatism	***Industry Collaborator: Minerals Targeting International (PI G. Begg)*** ***CIs: Griffin, O'Reilly, Begg*** ***Summary:*** This multi-disciplinary project (geophysics, geochemistry and modelling) will examine the robustness of global horizontal-Vs tomographic models. The project also aims to characterise the seismic signature of subduction zones in ancient terranes. The role of subduction processes in the formation of mineral deposits (e.g. Cu, Au) in these ancient terranes, now undercover, is critical for future mineral exploration.

Multiple sulfur isotope systematics of the Kanowna Belle Gold deposit	***Industry Collaborator: Northern Star Resources Ltd*** ***CIs: LaFlamme, Thébaud, Fiorentini*** ***Summary:*** This study aims to 1) resolve the paragenetic sequence of veins in relation to the mineralisation, intrusions and structural episodes of the Kanowna Belle deposit, Western Australia, 2) apply the quadruple sulfur isotope techniques in conjunction to the vein paragenesis and structural events to understand the evolution, possible source changes of hydrothermal fluids and their relationship to the tectonic framework changes in Archean orogenic gold deposits, and 3) carry out in-depth mineral scale quadruple sulfur isotope analysis incorporated with other geochemical analyses to interpret how gold is transported and precipitated in Archean orogenic gold systems.
Genesis of the Nova Nickel Deposit	***Industry Collaborator: IGO Independence Group*** ***CIs: Barnes, Fiorentini*** ***Summary:*** This study aims to determine the multiple sulfur isotope architecture of the Nova-Bollinger deposit in the Albany-Fraser Belt of Western Australia by spatially mapping tracer S isotopes across the orebody as well as country rocks.
Improving zircon morphology and chemistry as a tool for assessing and ranking the relative prospectivity for Cu porphyry deposits in "*greenfield*" terrains	***Industry Collaborator: BHP Billiton*** ***CIs: Fiorentini, Loucks*** ***Summary:*** A substantial exploration and research problem remains outstanding: although all porphyry copper ore-forming magmas are adakites (distinguished from ordinary calc-alkalic arc magmas by high Sr/Y ratio and spoon-profile rare-earth-element patterns), many adakites are apparently unmineralised or have weak, subeconomic copper mineralisation. Then, how do we distinguish a hydrothermally altered adakitic igneous complex that is weakly mineralised or barren from a hydrothermally altered adakitic igneous complex that is likely to contain a major copper deposit? This study is set to address this very question.
Yilgarn 2020	***Supported by MRIWA M530*** ***Industry Collaborators: Gold Road Resources, BHP Billiton Nickel West, Newmont, Northern Star Resources Limited, Saracen, Evolution Mining*** ***CI: Thebaud, Aitken, Jessell, Occhipinti, Dentith, Hagemann, Kemp, Fiorentini, Smithies, Lu, Gessner*** ***Summary:*** Yilgarn 2020 is a 3-year research-intensive program that integrates priority research and technology activities with complementary data compilation and targeted data acquisition. The research project is articulated into three modules ranging from regional- to camp- and deposit-scale studies applied to both well-mineralised, and less well-endowed areas. The combination of studies conducted on both mineralised and less mineralised areas is critical to evaluate and test the robustness of perceived mineralisation controls derived from the study of well-mineralised domains.
Tectonic evolution and amalgamation of continental, arc and arc-related terranes of Northern Thailand	***Industry Collaborator: Auldana*** ***CIs: George, Fiorentini, Parra Avila*** ***Summary:*** This project centres on the characterisation of volcanic and sedimentary records to unravel the records of convergence and amalgamation of the continental arcs and terranes of north-eastern Thailand. Furthermore, it addresses the closure of an oceanic basin (Nan Suture Zone) between the Sukothai and Indochina Terrane. Current tectonic models will be tested, and improved models will be developed. Unfolding the geologic history of this region is relevant to the development of valuable petroleum and mineral resources in Northern Thailand.

International links

BACKGROUND

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

FORMAL MEMORANDUM OF UNDERSTANDING (MOU)

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

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

COTUTELLE MOU

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

- China University of Petroleum, Beijing, China
- Durham University, United Kingdom
- Eötvös Loránd University, Hungary
- Friedrich-Alexander-University of Erlangen, Nuremberg, Germany
- Nanjing University, China
- Pierre and Marie Curie University, PARIS VI
- Peking University, China
- São Paulo University, Brazil
- University of Barcelona, Catalonia, Spain
- Universidad de la Republica, Uruguay
- Université Montpellier 2, France
- Université Paul Sabatier, France
- Université Jean Monnet, France
- University of Zaragoza, Spain

INTERNATIONAL LINKS - 2020 SELECTED HIGHLIGHTS

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

  As a result of the COVID-19 pandemic, the focus shifted from fieldwork to data interpretation.

  A related Chinese NSF proposal commenced in 2020, expands the Canning project into the Archean cratonic regions. This 4-year project will also seek opportunities to put a second Ocean Bottom Seismic Array offshore of the Canning coastal region.

- Unfortunately, the COVID-19 pandemic limited the opportunity for delegates from international institutions to visit CCFS in 2020. Visitors discussed programs including the exchange of staff, joint research activities and the exchange of students (see *Visitors list, Appendix 5*).

- A collaborative research agreement continued with the China University of Geosciences (Wuhan) with funding by the Chinese Scholarship Council (CSC). This grant provides a living allowance and travel between China and Australia for students and visiting scholars. Students and researchers funded by this project will study and work under the project's aims, integrating geological, geochemical, geophysical and experimental techniques to study the structure, composition, geodynamics and metallogeny of the deep lithosphere and beyond.

- Prof Zheng-Xiang Li continued as Co-director of the Australia-China Joint Research Centre for Tectonics and Earth

CCFS INTERNATIONAL COLLABORATIVE NETWORK

Resources (ACTER). ACTER is a joint research centre led by the Institute for Geoscience Research at Curtin University and the Institute of Geology and Geophysics of the Chinese Academy of Sciences, with participants from collaborating institutions from the two countries. CET, TIGeR and GEMOC are all Key Australian Partner Institutions (http://tectonics.curtin.edu.au/).

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

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

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

- The UNESCO-IUGS IGCP 648 project *"Supercontinent cycles and global geodynamics"* continued in 2020. 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.

  IGCP 648 annual workshop was replaced by a virtual seminar series held in Perth from May-August and September-December 2020

  For more information visit http://geodynamics.curtin.edu.au/igcp-648/

- Zheng-Xiang Li has continued his collaborative ties with researchers at the University of Liverpool, studying the evolution of the Earth's magnetic field through time.

- Marco Fiorentini continued international collaborations with:
  - University of Milan, Italy: ongoing work with Marilena Moroni and Massimo Tiepolo on the Ivrea Zone (Italy) and the role of volatiles in magmatic systems
  - Moscow State University, Russia: ongoing work with Alexey Ariskin on the genesis of Ni-Cu-PGE mineralisation in the Dovyren layered intrusion, Russia
  - Siberian Branch of the Russian Academy of Science, Irkutsk, Russia: Ongoing work to establish the nature of the volatiles in the Siberian Traps
  - University of Bologna, Italy: ongoing work on the nature of the sulfur cycle in magmatic arcs
  - University of Leicester, UK: ongoing work with David Holwell on the Ivrea Zone (Italy), the role of volatiles in magmatic systems, and the Munali Ni-Cu-PGE deposit
  - ETH, Switzerland: ongoing work with Andrea Giuliani on metasomatism of the lithospheric mantle
  - Tokyo Institute of Technology, Japan: ongoing work with Yuichiro Ueno on the multiple sulfur isotope characterisation of Archean magmatism

International visitors are listed in Appendix 5.

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.

Joshua Shea searching for an elusive outcrop at Harden, NSW (photo Anthony Lanati).

Appendix 1: Independently funded basic research projects

Independently funded research projects now provide resources for the continuation of CCFS research and play an important role in research work plans over their duration. 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 and ARC Linkage Projects, see *Industry Interaction p. 48*.

Unlocking Earth's inner secrets in deep time using palaeointensities	**Z.-X. Li**, A. Biggin: *Support by ARC DP (commenced 2020)* ***Summary:*** The geomagnetic field, generated in Earth's liquid outer core, provides Earth's biosphere and atmosphere with a critical protective shield from the bombardment of the solar wind. However, we still know little about the evolution of the geomagnetic field or the deep-time secrets it keeps. This project aims to study the varying intensity of the geomagnetic field during Earth's middle life. The results will help decipher how the Earth's core responded to evolving tectonic and dynamic systems, including the supercontinent cycles, and when Earth's solid inner core initiated. Such knowledge will help us to better understand how the Earth System evolved as a whole, and how such an evolution has led to the present day life and environment on Earth.
Plumbing the gap: a mantle solution to the enigma of bimodal arc volcanism	**N. Daczko**, **S. Foley**, H. Handley, T. Raimondo: *Support by ARC DP (commenced 2020)* ***Summary:*** Subduction zones and volcanic arcs are the most tectonically active regions on Earth and are crucial to understanding, geochemical cycles, tectonic-climate coupling, ore genesis and natural hazards. Bimodal volcanism is a long-recognised characteristic of arc crust that has never been satisfactorily explained. This project tests the new hypothesis that the two types of magmas originate from distinct mantle sources. It takes the innovative approach of integrating novel high-pressure experiments with database analysis of natural volcanic rocks, covering magmatic systems from mantle source to volcano. This project will improve our understanding of arc processes, including the association of economic metals with arc volcanism.
Testing continental growth models with calcium and strontium isotopes	T. Kemp, **S. Wilde**, **M. Van Kranendonk**, T. Elliot: *Support by ARC DP (commenced 2020)* ***Summary:*** The Project aims to chart the evolution of the Earth's primordial mantle and oceans between 3.75 and 2.8 billion years ago using calcium and strontium isotopes in ancient igneous and sedimentary rocks. A novel solution to the controversy over the timing and rate of growth of the Earth's continents is expected. Anticipated outcomes include the establishment of innovative analytical tools for tracing geological and environmental processes, and stronger collaborative links with premier research institutions abroad. The significant benefits of the Project include an enhanced understanding of the environment in which early life evolved, and fresh insight into the formation of the richly mineralised nucleus of the Australian continent.
Mantle dynamics and ore deposits	A. Cruden, **M. Fiorentini**, S. Barnes, A. Bunger, C. Jackson: *Support by ARC DP (commenced 2019)* ***Summary:*** This project aims to investigate where, how and why narrow finger-like conduits form in lithosphere-scale magma plumbing systems by a novel integration of field surveys, three-dimensional reflection seismic data, laboratory experiments and rock fracture mechanics. The project expects to generate new knowledge on the formation and location of highly valuable ore deposits of nickel, copper, cobalt and platinum group elements, which are preferentially trapped in poorly understood finger-like magma conduits.

Unveiling the fine structure of the Australian continent using ocean waves	**Y. Yang**, **J.C. Afonso**, N. Rawling, M. Ritzwoller, F. Niu: *Support by ARC DP (commenced 2019)* ***Summary:*** This project aims to develop new methods to better image lithospheric and upper-mantle structures by using noise from ubiquitous ocean waves, and then use these methods to illuminate fine-scale lithospheric-asthenospheric structures in Australia, from the surface to the upper mantle. Imaging the Earth's structure using seismic tomography is one of the most fundamental tasks of geoscience. Conventional earthquake-based seismic tomography has difficulties in deciphering fine-scale lithospheric structures. The images from this project will provide a better understanding of the nature of intraplate earthquakes and volcanoes and improve the assessment of intraplate seismic and volcanic hazards in Australia.
A terrestrial hot spring setting for the origin of life? Darwin's Warm Little Pond revisited	**M. Van Kranendonk**, **M. Fiorentini**, K.A. Campbell, D. Deamer: *Support by ARC DP (commenced 2018)* ***Summary:*** This Project aims to test the proposal that a terrestrial hot spring field could have been the setting for the origin of life, in preference to the currently favoured site at deep sea vents. This will be achieved by: 1) detailed characterisation of the only known, truly ancient, inhabited terrestrial hot spring analogue in the geological record - the 3.5 billion-year-old Dresser Formation, Western Australia; 2) comparison of this ancient analogue with active hot spring fields in New Zealand; and 3) experimental research on prebiotic organic chemistry using Dresser materials and active hot spring fluid chemistries. Results will be used to develop a terrestrial origin of life setting and assist in the search for life on Mars.
Understanding the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution	**S. Foley**: *Supported by ARC Laureate Fellowship (commencing 2019)* ***Summary:*** This project aims to understand the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution. Through improved understanding of the impact of melting on the deep earth cycles of carbon, water and nitrogen, this project intends to better understand how key elements are enriched towards economically viable concentrations. This project will generate knowledge of long-term benefit for decision-making in the minerals exploration industry and key government agencies. The project will establish a new generation of Australian scientists with a deep interdisciplinary understanding of earth sciences and pave the way for eventual unification of plate tectonics with climate systems.
How the Earth works-toward building a new tectonic paradigm	**Z.X. Li**: *Supported by ARC Laureate Fellowship (commenced 2015)* ***Summary:*** This fellowship project aims to build on the latest technological and conceptual advances to establish the patterns of Earth evolution and use this information to examine a ground-breaking geodynamic hypothesis which links cyclic plate aggregation and dispersion to deep Earth processes. Half a century after the inception of plate tectonics theory, we are still unsure how the Earth '*engine*' works, particularly the forces that drive plate tectonics. The project involves extensive national and international collaboration to potentially create a paradigm shift in our understanding of global tectonics and hopes to contribute to an understanding of the formation and distribution of Earth resources to provide a conceptual framework for their exploration.
Ultra-precise dating in Earth, planetary and archaeological science	D. Phillips, F. Jourdan, E. Matchan, A. Gleadow, Z.X. Li, P. Bland, N. Norman, M. Honda, P. Cawood, R. Weinberg, P. Vasconcelos, A. Herries, **M. Fiorentini**, **M. Wingate**: *Support by ARC LIEF (commencing 2021)* ***Summary:*** An advanced facility incorporating next generation, multi-collector mass spectrometer and ultra-clean gas line systems, capable of ultra-precise dating of Earth, planetary and archaeological material. This joint Melbourne-Curtin facility seeks to generate ultra-precise age data from ever smaller and younger samples, such as minute particles from space return missions and tiny inclusions in diamonds. The facility is expected to revolutionise noble gas dating techniques, resulting in new knowledge on solar system genesis, hominid evolution, indigenous migrations, palaeo-climate change, natural hazards and ore deposit formation, while further enhancing Australia's international leadership and competitive advantage in the discipline.

WA CRC-MC-ICPMS for Earth, Planetary and Environmental science	N. Evans, P. Bland, K. Rankenburg, **Z.X. Li**, F. Jourdan, S. Rowins, **M. Fiorentini**, M. Wingate, S. Barnes, Y. Uvarova: *Support by ARC LIEF (commenced 2020)* ***Summary:*** This application aims to provide a mass spectrometer for Australian researchers collaborating on NASA, Japanese Aerospace Exploration Agency and China National Space Administration extra-terrestrial sample return missions as they characterise unique samples of dust and rock collected from asteroids, the Moon and meteorites. The Application will also support government geoscience agencies who will generate nationally significant isotopic datasets to improve mineral exploration success, and scientists monitoring Earth's environment. Expected outcomes will ensure that Australia remains at the forefront of cosmochemistry, minerals research and environmental studies, which will provide significant benefits to our economy and society.
The Western Australia ThermoChronology Hub	M. Danisik, N. Evans, B. McInnes, **C. Kirkland**, **Z.X. Li**, **M. Fiorentini**, **M. Wingate**: *Support by ARC LIEF (commenced 2019)* ***Summary:*** This project aims to facilitate novel geochronological research in diverse areas of Earth and planetary science by providing a world-first triple-dating instrument facility. Combining three independent radiometric dating methods, the facility will undertake research to advance our understanding of the origin and evolution of the Earth and other planets and provide tools to enhance exploration for Earth's resources. Expected outcomes include the formation of a strong collaborative facility for academic, government and industry research and a further strengthening of Australia's position as an international research and education leader in the field of geochronology. It will lead to an improved understanding of the evolution of Earth's surface, and the formation and distribution of mineral and petroleum resources.
A novel ToF-SIMS facility for organic and inorganic analyses in WA	K. Grice, W. Rickard, G. Benedix, S.-P. Jiang, **S. Reddy**, **M. Kilburn**, P. Clode, D. Peyrot, D. Wacey, P. Lavery, P. Masque, R. Trengove, F. Xia, A. Deditius, G. Maker: *Support by ARC LIEF (commenced 2019)* ***Summary:*** Time-of-flight secondary ion mass spectrometry is a surface sensitive analytical technique that provides detailed elemental, isotopic and molecular information on surfaces, interfaces and thin layers with detection limits reaching in the parts-per-billion-range. The proposed facility is a next generation time-of-flight secondary ion mass spectrometer that allows parallel detection of organic and inorganic species in a given sample. Most importantly it will provide structural information of organic molecules intimately associated with minerals, meteorites, fossils, petroleum source-rocks to biochemical samples bolstering Western Australia's Earth and planetary sciences, energy, materials sciences, life science and metabolomics research.
Testing Late Cretaceous True Polar Wander on the Western Australian Margin	**Y. Liu**, **Z.-X. Li**, **R. Mitchell**: *Support by ANZIC IODP Legacy Analytical Funding (AILAF) (commenced 2020)* ***Summary:*** To test the controversial late Cretaceous true polar wander (TPW) event using palaeomagnetism on core samples from the continental margin of Western Australia.
Determining the extent and nature of the oldest crust in Antarctica	**S. Wilde**, **A. Nemchin**, M. Whitehouse, S. Harley, **M. Kusiak**, D. Dunkley: *Support by Australian Antarctic Science Grant (commenced 2019)* ***Summary:*** A large inventory of samples, collected by past Australian expeditions to Antarctica, reside with Geoscience Australia and provide a unique treasure-trove of information that can now be tapped, following major advances in knowledge and instrumentation over the past three decades. Selected samples collected from the Napier Complex in Enderby and Kemp Lands, on the western frontier of the Australian Antarctic Territory, have already provided exciting new insights into the timing and complexity of geological processes acting during the earliest stages of Earth's history. In order to further advance our understanding of this globally significant area, and to add value to a vital academic resource, this project aims to determine the extent of this most ancient terrain and to unravel the complex geological events that affected the area since its formation almost four billion years ago.

Determining the extent and nature of the oldest crust in Antarctica	**S. Wilde**, **A. Nemchin**, M. Whitehouse, S. Harley, **M. Kusiak**, D. Dunkley: *Support by Australian Antarctic Science Grant (commenced 2019)* ***Summary:*** A large inventory of samples, collected by past Australian expeditions to Antarctica, reside with Geoscience Australia and provide a unique treasure-trove of information that can now be tapped, following major advances in knowledge and instrumentation over the past three decades. Selected samples collected from the Napier Complex in Enderby and Kemp Lands, on the western frontier of the Australian Antarctic Territory, have already provided exciting new insights into the timing and complexity of geological processes acting during the earliest stages of Earth's history. In order to further advance our understanding of this globally significant area, and to add value to a vital academic resource, this project aims to determine the extent of this most ancient terrain and to unravel the complex geological events that affected the area since its formation almost four billion years ago.
Magnetotelluric analysis for Greenland and Postglacial Isostatic Evolution (MAGPIE)	C.P. Conrad, **K. Selway**, C. Gaina, R. Karlsson, K. Nisancioglu, B. Steinberger, L. Tarasov: *Support by Norwegian Research Council FRINATEK (commenced 2019)* ***Summary:*** With this project we seek to develop new constraints on rock viscosity beneath Greenland by collecting geophysical data on the ice sheet. The magnetotelluric (MT) data image the Earth's electrical conductivity, which is sensitive to the temperature and water content of mantle rocks. Because these factors also control mantle viscosity, we can use MT data to map viscosity variations beneath Greenland. These data are also sensitive to subglacial melt, which will enable us to detect extra heat added beneath Greenland by the Iceland Plume (GIA). We will develop a new numerical modelling technique for GIA that can accommodate large viscosity variations. The code will be useful to study GIA problems worldwide, but we will use it to predict GIA uplift patterns associated with the viscosity variations beneath Greenland. We will then use these much-improved GIA models to produce more accurate estimates for modern-day ice loss in Greenland.
Using geochemical and microstructural XFM mapping to identify proximal, medial and distal vectors around magma transfer zones	**N. Daczko**, **J. Munnikhuis**: *Supported by ANSTO - Australian Synchrotron Beamline Program (commenced 2019)* ***Summary:*** The Earth is composed of a layered crust overlying a relatively homogeneous mantle. This layered nature necessitates material (in the form of melts) to be transferred from the mantle to the crust. However, the types of melt migration pathways remain unclear. We aim to assess changing the degree of chemical interaction of melt pathways from a transect near a mass transfer zone from the crust-mantle transition zone using the Maia-384 detector. This study will allow for better identification of other more cryptic mass transfer zones from surrounding rocks on the km scale.
Constraining the palaeodepth evolution of the South Tasman Rise and determining its role in development of the Antarctic Circumpolar Current (ACC)	S. Loehr, J. Wittaker, **N. Daczko**, P. Hall: *Support by ANZIC IODP Legacy Analytical Funding (AILAF) (commenced 2019)* ***Summary:*** This project aims to determine the palaeodepth evolution of the South Tasman Rise, a tectonically-thinned and submerged continental block formerly part of the Tasmanian Land Bridge which connected Australia and Antarctica until the Eocene. This will provide important constraints on the opening of the Tasmanian oceanic gateway to deep water circulation, hypothesised to be a primary control on the Eocene-Oligocene climate transition, arguably the most profound climatic re-organisation of the Cenozoic. A multiproxy sediment geochemistry approach developed and validated by the authors during recent work on the East Tasman Plateau will be employed to 1) determine the palaeodepth evolution of the South Tasman Rise during the Eocene and 2) to identify the timing of initial submergence of the continental blocks in this critical region of Eocene tectonics.

Orogenesis: Assembly and Growth of Continents and Supercontinents	**S. Pisarevsky**: *Support by Ministry of Science and Higher Education of the Russian Federation (commenced 2019)* ***Summary:*** Creation of a new high-profile center to study geochronology, geochemistry and paleomagnetism at the Institute of the Earth's Crust of the Siberian Branch of the Russian Academy of Sciences.
3D Earth	**J.C. Afonso**, J. Ebbing: *Supported by European Space Agency and MQ University (commenced 2017)* ***Summary:*** The goal of this project is to establish a global 3D reference model of the crust and upper mantle based on the analysis of satellite gravity and (electro-)magnetic data in combination with seismological models and analyse the feedback between processes in Earth's deep mantle and the lithosphere. Selected case examples will provide the possibility to test these approaches on a global and regional scale. This will result in a framework for consistent models that will be used to link the crust and upper mantle to the dynamic mantle.
Australian membership of the International Ocean Discovery Program	R. Arculus, D. Cohen, S. Gallagher, P. Vasconcelos, C. Elders, J. Foden, M. Coffin, O. Nebel, H. McGregor, M. Clennell, C. Sloss, A. Heap, A. Webster, A. Kemp, **S. George**: *Supported by ARC LIEF (commenced 2016)* ***Summary:*** This project is for an Australian membership of the International Ocean Discovery Program. The Program will recover drill cores, situate observatories, and conduct down-hole experiments in all the world's oceans from lowest to highest latitudes to address fundamental questions about Earth's history and processes within four high-priority scientific themes: climate and ocean change - reading the past and informing the future; biosphere frontiers - deep life, biodiversity, and environmental forcing of ecosystems; Earth connections - deep processes and their impact on Earth's surface environment; Earth in motion - processes and hazards on a human time scale.
CWAS: China-Western Australia Seismic Survey	L. Zhao, **H. Yuan**, **GSWA**: *Supported by the Institute of Geology & Geophysics, Chinese Academy of Sciences, Beijing (commenced 2016)* ***Summary:*** Western Australia is an ideal natural laboratory for understanding the evolution of the Australian craton. To better understanding how and where the cratonic nuclei merged in the Precambrian requires high-resolution probing of the crustal and mantle structure beneath Western Australia. IGGCAS, CCFS and GWSA will install a 900-km-long dense (station spacing of 10 to 15 km) seismic profile across Western Australia from Port Hedland to the southwestern border of the Kimberly Craton, in order to: - image the crustal structure of the north edge of Pilbara craton, the Canning basin and south edge of the Kimberly craton with a high-resolution, and address the following issues: 1) deep geometry of the craton boundaries, 2) deep geometry of craton collisional belt; 3) differences of crustal structures between two cratons. - image the mantle structure of the north edge of Pilbara craton, the Canning basin and south edge of Kimberly craton and address the following questions: 1) geometry of the convergence beneath the craton boundaries, 2) characteristic difference of the upper mantle of the two cratons.

Appendix 2: Participants list

Chief Investigators

- Professor Suzanne Y. O'Reilly (Centre Director, MQ)
- Professor Simon Wilde (Node Director, CU)
- Associate Professor Marco Fiorentini (Node Director, UWA)
- Associate Professor Elena Belousova (MQ)
- Professor Simon Clark (MQ)
- Professor Stephen Foley (MQ)
- Honorary Professor William Griffin (MQ)
- Associate Professor Matthew Kilburn (CMCA, UWA)
- Professor Zheng-Xiang Li (CU)
- Associate Professor Alexander Nemchin (CU)
- Associate Professor Craig O'Neill (MQ)
- Professor Martin Van Kranendonk (UNSW)
- Associate Professor Yingjie Yang (MQ)

Associate Investigators

- Professor Juan Carlos Afonso (MQ)
- Dr Olivier Alard (MQ)
- Associate Professor Nathan Daczko (MQ)
- Dr Richard Glen (Adjunct Professor)
- Dr Masahiko Honda (ANU)
- Professor Dorrit Jacob (MQ / ANU)
- Associate Professor Mary-Alix Kaczmarek (University Paul Sabatier Toulouse III)
- Associate Professor Christopher Kirkland (CU)
- Professor Jochen Kolb (GEUS and KIT, Germany)
- Dr Yongjun Lu (GSWA at UWA)
- Dr Louis-Noel Moresi (UM)
- Professor Steven Reddy (CU)
- Associate Professor Bruce Schaefer (MQ)
- Dr Michael Wingate (GSWA)
- Professor Shijie Zhong (University of Colorado at Boulder, USA)

Partner Investigators

- Dr Ian Tyler (CCFS Leader, GSWA)
- Professor Michael Brown (University of Maryland, USA)
- Dr Klaus Gessner (GSWA)
- Professor David Mainprice (Université de Montpellier, France)
- Professor Catherine McCammon (Bayreuth University, Germany)
- Dr T. Campbell McCuaig (BHP Billiton)
- Professor Fuyuan Wu (Chinese Academy of Science, China)

Other Researchers and Research Associates

- Dr Raphael Baumgartner (UWA)
- Dr Walid Ben Mansour (MQ)
- Dr Stefano Caruso (UNSW)
- Dr Montgarri Castillo-Oliver (MQ)
- Dr Chunfei Chen (MQ)
- Dr Luc-Serge Doucet (CU)
- Dr Steven Denyszyn (UWA)
- Dr Isra Ezad (MQ)
- Dr Denis Fougerouse (CU)
- Dr Guillaume Florin (MQ)
- Dr Michael Förster (MQ)
- Dr Christopher Gonzalez (UWA)
- Dr Weronika Gorczyk (UWA)
- Dr Yoann Gréau (MQ)
- Dr Johannes Hammerli (UWA)
- Dr Jin-Xiang Huang (MQ)
- Dr Kim Jessop (MQ)
- Dr Uwe Kirscher (CU)
- Dr Monika Kusiak (ING PAN)
- Dr Laure Martin (CMCA, UWA)
- Dr Ross Mitchell (CU)
- Dr Hugo Olierook (CU)
- Dr Beñat Oliveira Bravo (MQ)
- Dr Luis Parra-Avila (UWA)
- Adjunct Professor Robert Pigeon (CU)
- Dr Sergei Pisarevsky (CU)
- Dr Amaury Pourteau (CU)
- Dr Svyatoslav Shcheka (MQ)
- Dr Nicholas Thébaud (UWA)
- Dr Lei Wu (CU)
- Dr Huaiyu Yuan (MQ at UWA)

Administrative Staff

Ms Sally-Ann Hodgekiss, Reporting & Comms. Manager (MQ)	Ms Anna Wan, Centre Admin Officer (MQ)

Professional Staff

Ms Manal Bebbington (MQ)	Dr Will Powell (MQ)
Dr Oliver Gaul (MQ)	Mr Peter Weiland (MQ)

Adjunct

Dr Steve Beresford	Dr Jingfeng Guo	Mr Richard Schodde
Dr Michael Etheridge	Dr Jon Hronsky	Dr John Vann
Professor Jim Everett	Dr Robert Loucks	Dr Peter Williams
Dr Richard Glen	Dr Franco Pirajno	Professor Xisheng Xu
Dr Richard Goldfard		

Honorary Associates

Dr John Adam	Dr Hadrien Henry	Dr Takako Satsukawa
Dr Mehmet Akbulut	Dr Jin-Xiang Huang	Dr Ed Saunders
Dr Jacques Batumike Mwandulo	Dr Christoph Lenz	Dr Hadi Shafaeimoghaddam
Dr Graham Begg	Dr Kreshimir Malitch	Dr Thomas Stachel
Professor Hannes Brueckner	Dr Vlad Malkovets	Dr Huayun Tang
Dr Mei-Fe Chu	Dr Bertrand Moine	Dr Romain Tilhac
Professor Massimo Coltorti	Dr Ria Mukherjee	Dr Kuo-Lung Wang
Professor Kent Condie	Dr Rosanna Murphy	Dr Xiao-Lei Wang
Professor Jean-Yves Cottin	Dr Lev Natapov	Dr Qing Xiong
Professor Manel Fernandez	Dr Oded Navon	Dr Jin-Hui Yang
Ms Sarah Gain	Dr Ryan Portner	Professor Jin-Hai Yu
Dr José María Gonzaléz-Jiménez	Dr Yvette Poudjom Djomani	Dr Ming Zhang
Dr Michel Grégoire	Dr William Powell	Professor Jianping Zheng

PhD Students

Mr Arash Amirian (MQ)	Mr Gonzalo Henriquez (UWA)	Mr Greg Poole (UWA)
Mr Jason Bennett (UWA)	Mr Raham Jalil (MQ)	Ms Carla Raymond (MQ)
Mr Nathan Bowman (UWA)	Ms Constanza Jara Barra (UWA)	Mr Matthew Rowe (UWA)
Mr Vili Boykova Grigorova (MQ)	Mr Anthony Lanati (MQ)	Mr Farshad Salajegheh (MQ)
Ms Maria Cherdantseva (UWA)	Mr Pablo Lara (MQ)	Mr Joshua Shea (MQ)
Mr Joshua Chong (UWA)	Mr Jiangyu Li (CU)	Mr Chutian Shu (MQ)
Mr Hongkun Dai (MQ)	Mr Shiladitya Mazumdar (MQ)	Ms Georgia Soares (UNSW)
Mr Benedikt Demmert (MQ)	Mr Keith McKenzie (MQ)	Mr Luke Steller (UNSW)
Ms Katherine Farrow (MQ)	Miss Uvana Meek (MQ)	Mr Dennis Sugiono (UWA)
Mr Jean-Antoine Gazi (MQ)	Mr Jonathan Munnikhuis (MQ)	Ms Lynthener Takenaka de Oliveira (MQ)
Mr Hindol Ghatak (MQ)	Mr Thusitha Nimalsiri (MQ)	Ms Bronwyn Teece (UNSW)
Ms Lauren Gorojovsky (MQ)	Mr Brendan Nomchong (UNSW)	Ms Anne Vernes (UWA)
Mrs Stephanie Greene (MQ)	Mr Sinan Özaydin (MQ)	Ms Marina Veter (MQ)
Ms Ananuer Halimulati (MQ)	Mr Sarath Patabendigedara (MQ)	Miss Anqi Zhang (MQ)

Appendix 3: 2020 Publications

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

1175. **Loucks, R.R., Fiorentini, M.L.** and **Henríquez, G.J.** 2020. New magmatic oxybarometer using trace elements in zircon reveals oxidation states of Hadean and Eoarchean lithosphere in four cratons. *Journal of Petrology*, *61*, *egaa034*.

1198. **Caruso, S.**, **Fiorentini, M.L.**, Barnes, J.B., **LaFlamme, C.K.** and **Martin, L.** 2020. Microchemical and sulfur isotope constraints on the magmatic and hydrothermal evolution of the Black Swan Succession, Western Australia. *Mineralium Deposita, 55, 535-553.*

1204. Sun, X., Hollings, P. and **Lu, Y.-J.** 2020. Geology and origin of the Zhunuo porphyry copper deposit, Gangdese belt, southern Tibet. *Mineralium Deposita*, *https://doi. org/10.1007/ s00126-020-00970-0*.

1358. **Baatar, B.**, **Parra-Avila, L.A.**, **Fiorentini, M.L.**, Polito, P. and Crawford, A.J. 2020. Porphyry Cu fertility of the Loch Lilly - Kars Belt, Western New South Wales, Australia. *Australian Journal of Earth Sciences, 67, 75-87.*

1372. **Bennett, J.M.**, Kemp, A.I.S. and Roberts, M.P. 2020. Microstructural controls on the chemical heterogeneity of cassiterite revealed by cathodoluminescence and elemental X-ray mapping. *American Mineralogist*, *105*, *58-76*.

1381. **Moghadam, H.S.**, Li, Q.L., **Griffin, W.L.**, Stern, R.J., Ishizuka, O., **Henry, H.**, Lucci, F., **O'Reilly, S.Y.** and Ghorbani, G. 2020. Repeated Magmatic Buildup and Deep "Hot Zones" in Continental Evolution: the Cadomian Crust of Iran. *Earth and Planetary Science Letters*, *531*, *115989*.

1383. Malitch, K.N., **Belousova, E.A.**, **Griffin, W.L.**, **Martin, L.**, Badanina, I.Yu. and Sluzhenikin, S.F. 2020. Oxygen-hafnium-neodymium isotope constraints on the origin of the Talnakh ultramafic-mafic intrusion (Noril'sk Province, Russia). *Economic Geology*, *115*, *1195- 1212*.

1384. Ariskin, A.A., Danyushevsky, L.V., **Fiorentini, M.**, Nikolaev, G.S., Kislov, E.V., Pshenitsyn, I.V., Yapaskurt, V.O. and Sobolev, S.N. 2020. Petrology, geochemistry and the origin of sulfide-bearing and PGE-mineralized troctolites from the Konnikov Zone in the Yoko-Dovyren layered intrusion. *Russian Geology and Geophysics*, *61*, *611-633*.

1386. **Xiong, Q.**, Xu, Y., González-Jiménez, J.M., Liu, J., **Alard, O.**, Zheng, J.-P., **Griffin, W.L.** and **O'Reilly, S.Y.** 2020. Sulfide in dunite channels reflects long-distance reactive migration of mid-ocean-ridge melts from mantle source to crust: A Re-Os isotopic perspective. *Earth and Planetary Science Letters*, *531*, *115969*.

1386a. **Xiong, Q.**, Xu, Y., González-Jiménez, J.M., Liu, J., **Alard, O.**, Zheng, J.-P., **Griffin, W.L.** and **O'Reilly, S.Y.** 2020. Corrigendum to "Sulfide in dunite channels reflects long-distance reactive migration of mid-ocean-ridge melts from mantle source to crust: A Re-Os isotopic perspective." [Earth and Planetary Science Letters, 531 115969]. *Earth and Planetary Science Letters*, *535*, *116136*.

1394. Temdjim, R., Njombie Wagsong, M.P., Nzakou Tsepeng, A.J. and **Foley, S.** 2020. Variation in mantle lithology and composition beneath the Ngao Bilta volcano, Adamawa Massif, Cameroon volcanic line, West-central Africa. *Geoscience Frontiers*, *11*, *665-677*.

1407. Sun, X., **Lu, Y.**, Li, Q., and Li, R. 2020. A downgoing Indian lithosphere control on along-strike variability of porphyry mineralization in the Gangdese belt of southern Tibet. *Economic Geology*, *338*, *105593*.

1408. **Choi, E.**, **Fiorentini, M.L.**, **Giuliani, A.**, **Foley, S.F.**, Maas, R. and Taylor, W.R. 2020. Subduction-related petrogenesis of Late Archean calc-alkaline lamprophyres in the Yilgarn Craton (Western Australia). *Precambrian Research*, *338*, *105550*.

1409. Le Vaillant, M., Barnes, S.J., **Mole, D.R.**, **Fiorentini, M.L.**, **Laflamm, C.**, **Denyszyn, S.W.**, Austin, J., Patterson, B., Godel, B., Hicks, J., Mao, Y.-J. and Neaud, A. 2020. Multidisciplinary study of a complex magmatic system: The Savannah Ni-Cu-Co Camp, Western Australia. *Ore Geology Reviews*, *117*, *103292*.

1410. **Tilhac, R.**, **Oliveira, B.**, **Griffin, W.L.**, **O'Reilly, S.Y.**, **Schaefer, B.F.**, **Alard, O.**, Ceuleneer, G., **Afonso, J.C.** and Grégoire, M. 2020. Reworking of old continental lithosphere: Unradiogenic Os and decoupled Hf-Nd isotopes in sub-arc mantle pyroxenites. *Lithos*, *354-355*, *105346*.

1411. **Castillo-Oliver, M.**, Melgarejo, J.C., Torró, L., Villanova-De-benavent, C., Campeny, M., Díaz-Acha, Y., Amores-Casals, S., Xu, J., Proenza, J. and Tauler, E. 2020. Sandstone- hosted uranium deposits as a possible source for critical elements: The eureka mine case, Castell- Estaó, Catalonia. *Minerals*, *10*, *34*.

1412. Halpin, J., **Daczko, N.**, Direen, N.G., Mulder, J.A., **Murphy, R.C.** and Ishihara, T. 2020. Provenance of rifted continental crust at the nexus of East Gondwana breakup. *Lithos*, *354-355*, *105363*.

1414. Piazolo, S., **Daczko, N.R.**, **Silva, D.** and Raimondo, T. 2020. Melt-present shear zones enable intracontinental orogenesis. *Geology*, *doi.org/10.1130/G47126.1*.

1415. **Nomchong, B.** and **Van Kranendonk, M.J.** 2020. Diverse thrombolites from the c. 2.4 Ga Turee Creek Group, Western Australia. *Precambrian Research*, *338*, *105593*.

1416. Patkó, L., **Liptai, N.**, Előd Aradi, L., Klébesz, R., Sendula, E., Bodnar, R.J., János Kovács, I., Hidas, K., Cesare, B., Novák, A., Trásy, B. and Szabó, C. 2020. Metasomatism- induced wehrlite formation in the upper mantle beneath the Nógrád-Gömör Volcanic Field (Northern Pannonian Basin): Evidence from xenoliths. *Geoscience Frontiers*, *11*, *943-964*.

1417. **Förster, M.W.**, Buhre, S., Xu, B., Prelević, D., Mertz-Kraus, R. and **Foley, S.F.** 2020. Two-stage origin of K-enrichment in ultrapotassic magmatism Simulated by melting of experimentally metasomatized mantle. *Minerals*, *10*, *41*.

1418. Lenz, C., **Belousova, E.** and Lumpkin, G.R. 2020. The *in-situ* quantification of structural radiation damage in zircon using laser-induced confocal photoluminescence spectroscopy. *Minerals*, *10*, *83*.

1419. Esmaeili, R., Xiao, W., **Griffin, W.L.**, Moghadam, H.S., Zhang, Z., Ebrahimi, M., Zhang, J., Wan, B., Ao, S. and Bhandari, S. 2020. Reconstructing the source and growth of the Makran Accretionary Complex: Constraints from detrital zircon U-Pb geochronology. *Tectonics*, *92*, *e2019TC005963*.

1420. Luo, Y., **Yang, Y.**, Xie, J., Yang, X., Ren, F., Zhao, K. and Xu, H. 2020. Evaluating uncertainties of phase velocity measurements from cross-correlations of ambient seismic noise. *Seismological Research Letter*, *91*, *1717-1729*.

1421. **Castillo-Oliver, M.**, **Giuliani, A.**, **Griffin, W.L.**, **O'Reilly, S.Y.**, Drysdale, R.N., Abersteiner, A., Thomassot, E. and Li, X.-H. 2020. New constraints on the source, composition and post-emplacement modification of kimberlites from *in situ* C-O-Sr isotope analyses of carbonates from the Benfontein sills (South Africa). *Contributions to Mineralogy and Petrology*, *175*, 33.

1422. **Lara, P.**, Oyhantcabal, P. and **Belousova, E.** 2020. Two distinct crustal sources for Late Neoproterozoic granitic magmatism across the Sierra Ballena Shear Zone, Dom Feliciano Belt, Uruguay: whole-rock geochemistry, zircon geochronology and Sr-Nd-Hf isotope evidence. *Precambrian Research*, *341*, *105625*.

1423. **Griffin, W.L.**, **Gain, S.E.M.**, Cámara, F., Bindi, L., Shaw, J., **Alard, O.**, Saunders, M., **Huang, J-X.**, Toledo, V. and **O'Reilly, S.Y.** 2020. Extreme reduction: Mantle-derived oxide xenoliths from a hydrogen-rich environment. *Lithos*, *358-359*, *105404*.

1424. **Olierook, H.K.H.**, Jourdan, F., Whittaker, J.M., Merle, R.E., Jiang, Q., **Pourteau, A.** and **Doucet, L.S.** 2020. Timing and causes of the mid-Cretaceous global plate reorganization event. *Earth and Planetary Science Letters*, *534*, *116071*.

1425. Zibra, I., **Lu, Y.**, Clos, F., Weinberg, R.F., Peternell, M., Wingate, M.T.D., Prause, M., Schiller, M., and **Tilhac, R.** 2020. Regional-scale polydiapirism predating the Neoarchean Yilgarn Orogeny. *Tectonophysics*, *779*, *228375*.

1427. **Griffin, W.**, **Gain, S.**, Saunders, M., Bindi, L., **Alard, O.**, Toledo, V. and **O'Reilly, S.Y.** 2020. Parageneses of TiB_2 in corundum xenoliths from Mt Carmel, Israel: Siderophile behaviour of Boron under reducing conditions. *American Mineralogist*, *105*, *1609-1621*.

1428. **Jessop, K.**, **Daczko, N.R.** and Piazolo, S. 2020. Two belts of HTLP sub-regional metamorphism in the New England Orogen, eastern Australia: occurrence and characteristics exemplified by the Wongwibinda Metamorphic Complex. *Australian Journal of Earth Sciences*, *67*, *479-507*.

1430. **Iaccheri. L.M.** and **Bagas, L.** 2020. Zircon provenances provide paleogeographic constraints on models reconstructing the Paleoproterozoic Columbia Supercontinent. *Gondwana Research*, *82*, *254-266*.

1431. **Baumgartner, R.J.**, **Caruso, S.**, **Fiorentini, M.L.**, **Van Kranendonk, M.J.**, **Martin, L.**, **Jeon, H.**, Pagès, A., Wacey, D. 2020. Sulfidization of 3.48 billion-year-old stromatolites of the Dresser Formation, Pilbara Craton: Constraints from *in-situ* sulfur isotope analysis of pyrite. *Chemical Geology*, *538*, *119488*.

1434. Markwitz, V., **Kirkland, C.L.** and **Gessner, K.** 2020. Provenance bias between detrital zircons from sandstones and river sands: A quantification approach using 3-D grain shape, composition and age. *Geoscience Frontiers*, *11*, *835-842*.

1476. **Zhang, N.**, Behn, M., Parmentier, E.M. and Kincaid, C. 2020. Melt Segregation and Depletion during Ascent of Buoyant Diapirs in Subduction Zones. *Journal of Geophysical Research: Solid Earth*, *125*, *e2019JB018203*.

1483. Xu, Y.X., Yang, B., Zhang, A.Q., Wu, S.C., Zhu, L., **Yang, Y.J.**, Wang, Q.Y. and Xia, Q.K. 2020. Magnetotelluric imaging of a fossil oceanic plate in northwestern Xinjiang, China. *Geology*, *https://doi.org/10.1130/G47053.1*.

1484. Zhao, L., Malusà, M.G., **Yuan, H.**, Paul, A., Guillot, S., Lu, Y., Stehly, L., Solarino, S., Eva, E., Lu, G., Bodin, T., CIFALPS group, AlpArray Working Group. 2020. Evidence for a serpentinized plate interface favouring continental subduction. *Nature Communications*, *11*, *2171*.

1485. Zheng, Y., Wang, L., Xue, C., Xu, B., Abdul, G., Yang, Z., Lu, Y., Zhou, L., **Griffin, W.L.** and Hou, Q. 2020. Porphyry Cu deposits linked to episodic growth of an underlying parental magma chamber. *Science China Earth Sciences*, *63*, *https://doi.org/10.1007/s11430-020-9634-2*.

1487. **Baumgartner, R.**, **Van Kranendonk, M.**, Pagès, A., **Fiorentini, M.**, Wacey, D. and Ryan C. 2020. Accumulation of transition metals and metalloids in sulfidized stromatolites of the 3.48 billion-year-old Dresser Formation, Pilbara Craton. *Precambrian Research*, *337*, *105534*.

1488. **Giuliani, A.**, Pearson, D.G., Solty, A., Dalton, H., Phillips, D., **Foley, S.F.**, Lim, E., Goemann, K., **Griffin, W.L.** and **Mitchell, R.H**. 2020. Kimberlite genesis from a common carbonate-rich primary melt modified by lithospheric mantle assimilation. *Science Advances*, *6*, *aaz0424*.

1489. Colás, V., Subías, I., González-Jiménez, J.M., Proenza, J.A., Fanlo, I., Camprubí, A., **Griffin, W.L.**, Gervilla, F., **O'Reilly, S.Y.** and Escayola, M.F. 2020. Metamorphic fingerprints of Fe-rich chroxmitites from the Eastern Pampean Ranges, Argentina. *Boletín de la Sociedad Geológica Mexicana*, *72*, *AO80420*.

1490. **Volante, S.**, **Pourteau, A.**, Collins, W.J., **Blereau, E.R.**, **Li, Z.-X.**, Smit, M., Evans, N.J., **Nordsvan, A.R.**, Spencer, C.J., McDonald, B.J., Li, J. and Günter, C. 2020. Multiple P- T-d-t paths reveal the evolution of the final Nuna assembly in northeast Australia. *Journal of Metamorphic Geology*, *38*, *593-627*.

1492. **Huang, J.-X.**, Xiong, Q., **Gain, S.E.M.**, **Griffin, W.L.**, Murphy, T.D., Shiryaev, A.A., Li, L., Toledo, V., Tomshin, M.D. and **O'Reilly, S.Y.** 2020. Immiscible metallic melts in the deep Earth: Clues from moissanite (SiC) in volcanic rocks. *Science Bulletin*, *65*, *1479-1488*.

1499. Ponthus, L., de Saint Blanquat, M., Guillaume, D., Le Romancer, M., **Pearson, N.**, **O'Reilly, S.Y.** and Grégoire, M. 2020. Plutonic processes in transitional oceanic plateau crust: structure, age and emplacement of the South Rallier du Baty laccolith, Kerguelen Islands. *Terra Nova*, *https://doi.org/10.1111/ter.12471*.

1500. Xie, J.,**Yang, Y.** and Luo, Y. 2020. Improving cross-correlations of ambient noise using a RMS-ratio selection stacking method. *Geophysical Journal International*, *222*, *989-1002*.

1501. **Gardner, R.L.**, **Piazolo, S.**, **Daczko, N.R.** and Trimby, P. 2020. Microstructures reveal multistage melt present strain localisation in mid-ocean gabbros. *Lithos*, *366-367*, *105572*.

1502. **Lu, J.G.**, **Tilhac, R.**, **Griffin, W.L.**, **Zheng, J.P.**, **Xiong, Q.**, **Oliveira, B.** and **O'Reilly, S.Y.** 2020. Lithospheric memory of subduction in mantle pyroxenite xenoliths from rift-related basalts. *Earth and Planetary Science Letters*, *544*, *116365*.

1504. Moghadam, H.S., Li, Q.-L., **Griffin, W.L.**, Stern, R.J., Massimo Chiaradia, M., Karsli, O., Ghorbani, G., **O'Reilly, S.Y.** and Pourmohsen, M. 2020. Zircon U-Pb, Geochemical and Isotopic Constraints on the Age and Origin of A- and I-type Granites and Gabbro-Diorites from NW Iran. *Lithos*, *374-375*, *105688*.

1505. Moghadam, H.S., Li, Q.-L., **Griffin, W.L.**, Karsli, O., Santos, J.F., Ottley, C.J., Ghorbani, G. and **O'Reilly, S.Y.** 2020. Tracking the birth and growth of Cimmeria: Geochronology and origins of intrusive rocks from NW Iran. *Gondwana Research*, *87*, *188-206*.

1506. Huang X.-X., Shi R.-D., Gong X.-H., Huang Q.-S., **Griffin W.L.**, **O'Reilly S.Y.** and Chen S.-S. 2020. Oceanization of the subcontinental lithospheric mantle recorded in the Yunzhug ophiolite, Central Tibetan Plateau. *Lithos*, *370-371*, *105612*.

1507. Zhao, K., **Yang, Y.**, and Luo, Y. 2020. Broadband finite frequency ambient noise tomography: A case study in the western United States using USArray stations. *Journal of Geophysical Research: Solid Earth*, *125*, *e2019JB019314*.

1508. **Gonzalez, C.M.**, **Fiorentinti, M.L.**, **Gorczyk, W.** and **Dering, G.** 2020. Numerical modeling of post-collisional carbonated alkaline magmatism: Variscan style Orogeny (the Ivrea Zone as natural laboratory). *Solid Earth Science*, *5*, *131-152*.

1509. **Wang, K.**, Jiang, C., **Yang, Y.**, Schulte-Pelkum, V. and Liu, Q. 2020. Crustal deformation in Southern California constrained by radial anisotropy from ambient noise adjoint tomography. *Geophysical Research Letters*, *47*, *e2020GL088580*.

1510. **Oliveira, B.**, **Afonso, J.C.** and **Tilhac, R.** 2020. A disequilibrium reactive transport model for mantle magmatism. *Journal of Petrology*, *61*, *egaa067*.

1511. **Li, T.**, Zhao, L., Wan. B., **Z.X. Li**, Bodin, T., Wang, K. and **Yuan, H.** 2020. New Crustal Vs model along an array in south-east China: Seismic Characters and paleo-Tethys continental amalgamation. *G-Cubed*, *21*, *e2020GC009024*.

1512. Wan, B., Yang, X., Tian, X., **Yuan, H.**, **Kirscher, U.** and **Mitchell, R.N.** 2020. Seismological evidence for the earliest 1 global subduction network at 2 Ga. *Science Advances*, *6*, *eabc5491*.

1514. Du, P., Wu, J., Li, Y., Wang, J., Han, C., Lindsay, M., **Yuan, H.**, Zhao, L. and Xiao, W. 2020. Imaging Karatungk Cu-Ni Mine in Xinjiang, western China with a passive seismic array. *Minerals*, *10*, *601*.

1515. Kilgore M.L., Peslier, A.H., Brandon, A.D., Schaffer, L.A., Morris, R.V., Graff, T.G., Agresti, D.G., **O'Reilly, S.Y.**, **Griffin, W.L.**, Pearson, D.G., Gangi, K. and Shaulis, B.J. 2020. Metasomatic control of hydrogen contents in the layered cratonic mantle lithosphere sampled by Lac de Gras xenoliths in the central Slave Craton, Canada. *Geochimica et Cosmochemica Acta*, *286*, *29-53*.

1516. **Choi, E.**, **Fiorentini, M.L.**, Hughes, H.S.R and **Giuliani, A.** 2020. Platinum-group element and Au geochemistry of Late Archean to Proterozoic calc-alkaline and alkaline magmas in the Yilgarn Craton, Western Australia. *Lithos*, *374-375*, *10571615*.

1517. **Tadbiri, S.**, and Van **Kranendonk, M.J.** 2020. Structural analysis of syn-depositional hydrothermal veins of the 3.48 Ga Dresser Formation, Pilbara Craton, Australia. *Precambrian Research*, *347*, *105844*.

1518. Soltys, A., **Giuliani, A.**, Phillip, D. and Kamenetsky, V.S. 2020. Kimberlite metasomatism of the lithosphere and the evolution of olivine in carbonate-rich melts - Evidence from the Kimberley Kimberlites (South Africa). *Journal of Petrology*, *61*, *agaa062*.

1519. **Etheridge, M.A.**, **Daczko, N.R.**, Chapman, T. and Stuart, C.A. 2020. Mechanisms of melt extraction during lower crustal partial melting. *Journal of Metamorphic Geology*, *DOI: 10.1111/jmg.12561*.

1520. **Poole, G.H.**, Kemp, A.I.S., Hagemann, S.G., **Fiorentini, M.L.**, Jeon, H., Williams, I.S. Zappettini, E.O. and Rubinstein, N.A. 2020. The petrogenesis of back-arc magmas, constrained by zircon O and Hf isotopes, in the Frontal Cordillera and Precordillera, Argentina. *Contributions to Mineralogy and Petrology*, *175*, *89*.

1521. **González Jiménez, J.M.**, Mondal, S.K., Ghosh, B., **Griffin, W.L.** and **O'Reilly, S.Y.** 2020. Re-Os isotope systematic of sulfides in chromitites and host lherzolites of the Andaman ophiolite, India. *Minerals*, *10*, *686, 1-21*.

1522. **Gorojovsky, L.** and **Alard, O.** 2020. Optimisation of laser and mass spectrometer parameters for the *in-situ* analysis of Rb/Sr ratios by LA-ICP-MS/MS. *JAAS*, *35*, *2322-2336*.

1523. Malitch, K.N., Puchtel, I.S., **Belousova, E.A.** and Badanina I.Yu. 2020. Contrasting platinum-group mineral assemblages of the Kondyor Massif (Russia): Implications for the sources of HSE in zoned-type ultramafic massifs. *Lithos*, *376-377*, *105800*.

1524. Fan, H.-P., Zhu, W.-G. and **Li, Z.-X.** 2020. Paleo- to Mesoproterozoic magmatic and tectonic evolution of the southwestern Yangtze Block, South China: new constraints from ca. 1.7-1.5 Ga mafic rocks in the Huili-Dongchuan area. *Gondwana Research*, *87*, *248-262*.

1525. Jiang, W., Yu, J.-H., Wang, X., **Griffin, W.L.**, Pham, T.H., Nguyen, D.L. and Wang, F.Q. 2020. Early Paleozoic magmatism in northern Kontum Massif, Central Vietnam: Insights into tectonic evolution of the eastern Indochina Block. *Lithos*, *376-377*, *105750*.

1527. Sun, W., Zhao, L., **Yuan, H.** and Fu, L. 2020. Sharpness of the mid-lithospheric discontinuity and craton evolution in North China. *Journal of Geophysical Research, Solid Earth*, *2019JB018594RRR*.

1529. **Volante, S.**, Collins, W.J., **Pourteau, A.**, **Li, Z.-X.**, Li, J. and **Nordsvan, A.R.** 2020. Structural evolution of a 1.6 Ga orogeny related to the final assembly of the supercontinent Nuna: coupling of episodic and progressive deformation. *Tectonics*, *39*, *10.1029/2020TC006162*.

1531. Perchuk, A.L., Gerya, T.V., Zakharov, V.S. and **Griffin, W.L.** 2020. Building cratonic keels in Precambrian plate tectonics. *Nature*, *586*, *395-401*.

1535. **Gorczyk, W.**, **Gonzalez, C.M.** and Hobbs, B. 2020. Carbon dioxide as a proxy for orogenic gold source. *Ore Geology Reviews*, *127*, *103829*.

1536. Zedgenizov, D.A., Skuzovatov, S.Y., **Griffin, W.L.**, Pomazansky, B.S., Ragozin, A.L. and Kalinina, V.V. 2020. Diamond-forming HDFs tracking episodic mantle metasomatism beneath Nyurbinskaya kimberlite pipe (Siberian craton). *Contributions to Mineralogy and Petrology*, *175*, *106*.

1537. **Volante, S.**, Collins, W.J., **Blereau, E.**, **Pourteau, A.**, Spencer, C., Evans, N., Barrote, V., **Nordsvan, A.R.**, **Li, Z.X.** and **Li, J.** 2020. Reassessing zircon-monazite thermometry with thermodynamic modelling: insights from the Georgetown igneous complex, NE Australia. *Contributions to Mineralogy and Petrology*, *175*, *110*.

1538. Wang, X.-C., **Wilde, S.A.**, **Li, Z.-X.**, Li, S. and Li, L. 2020. Do supercontinent-superplume cycles control the growth and evolution of continental crust? *Journal of Earth Science*, *31*, *1142-1169*.

1542. Bindi, L., Cámara, F., **Gain, S.E.M.**, **Griffin, W.L.**, **Huang, J.-X.**, Saunders, M. and Toledo, V. 2020. Kishonite, VH_2, and oreillyite, Cr_2N, two new minerals from the corundum xenocrysts of Mt Carmel, Northern Israel. *Minerals, 10, 1118, 1-10*.

1546. **Li, J.**, **Pourteau**, **A.**, **Li, Z.-X.**, Jourdan, F., **Nordsvan, A.R.**, Collins, W.J. and **Volante, S.** 2020. Heterogeneous Exhumation of the Mount Isa Orogen in NE Australia After 1.1 Ga Nuna Assembly: New High-Precision $^{40}Ar/^{39}Ar$ Thermochronological Constraints. *Tectonics*, *39*, *e2020TC006129*.

1551. Godefroy-Rodríguez, M., Hagemann, S., LaFlamme C. and **Fiorentini, M.** 2020. The multiple sulfur isotope architecture of the Golden Mile and Mount Charlotte deposits, Western Australia. *Mineralium Deposita*, *55*, *797-822*.

1552. **Fiorentini, M.L.**, **O'Neill, C.**, **Giuliani, A.**, **Choi, E.**, Maas, R., Pirajno, F. and **Foley, S.** 2020. Bushveld superplume drove Proterozoic magmatism and metallogenesis in Australia. *Scientific reports*, *10*, *19729*.

1553. **Wang, Y.** and **Foley, S.F.** 2020. The Role of Blueschist Stored in Shallow Lithosphere in the Generation of Postcollisional Orogenic Magmas. *Journal of Geophysical Research: Solid Earth*, *125*, *e2020JB019910*.

1554. **Wang, C.**, Lai, Y.J., **Foley, S.F.**, Liu, Y., **Belousova, E.**, Zong, K. and Hu, Z. 2020. Rutile records for the cooling history of the Trans-North China orogen from assembly to break-up of the Columbia supercontinent. *Precambrian Research*, *346*, *105763*.

1556. **O'Neill, C.**, Lowman, J. and **Wasiliev, J.** 2020. The effect of galactic chemical evolution on terrestrial exoplanet composition and tectonics. *Icarus*, *352*, *114025*.

1557. Muirhead, J.D., Fischer, T.P., Oliva, S.J., Laizer, A., van Wijk, J., Currie, C.A., Lee, H., Judd, E.J., Kazimoto, E., Sano, Y., Takahata, N., Tiberi, C., **Foley, S.F.**, Dufek, J., Reiss M.C. and Ebinger, C.J. 2020. Displaced cratonic mantle concentrates deep carbon during continental rifting. *Nature*, *582, 67-72*.

1558. **Xiong, Q.**, Xu Y., **González-jinénez, J.M.**, Liu J., **Alard, O.**, Zheng J.-P., **Griffin, W.L.** and **O'Reilly, S.Y.** 2020. Sulfide Aggregation in Ophiolitic Dunite Channels Explains Os-Isotope Mismatch between Oceanic Crust and Mantle. *Acta Geologica Sinica (English Ed.)*, *94*, *66*.

1560. **Xu, R.**, Liu, Y., **Wang, X.C.**, **Foley, S.F.**, Zhang, Y. and **Yuan, H.** 2020. Generation of continental intraplate alkali basalts and implications for deep carbon cycle. *Earth-Science Reviews*, *201*, *103073*.

1562. **Chen, C.**, **Huang, J.X.**, **Foley, S.F.**, Wang, Z., Moynier, F., Liu, Y., Dai, W. and Li, M. 2020. Compositional and pressure controls on calcium and magnesium isotope fractionation in magmatic systems. *Geochimica et Cosmochimica Acta, 290, 2020, 257-270.*

1564. **Chen. C.**, Ciazela, J., Li, W., Dai, D., Wang, Z., **Foley, S.F.**, **Li, L.**, Hu, Z. and Liu, Y. 2020. Calcium isotopic compositions of oceanic crust at various spreading rates. *Geochimica et Cosmochimica Acta*, *278, 272-288*.

1572. **Volante, S.**, **Pourteau, A.**, Collins, W.J., **Blereau, E.**, **Li, Z.-X.**, Li, J. Smit, M., Evans, N.J., **Nordsvan, A.R.**, Spencer, C.J., McDonald, B.J and Li, J. 2020. Multiple P- T-d-t paths reveal the evolution of the final Nuna assembly in northeast Australia. *Journal of Metamorphic Geology*, *38*, *593-627*.

1573. Gan, B., Diwu, C., Yan, J., Wang, T. and **Li, J.** 2020. Formation and stabilization of the Dunhuang Block, NW China: Constraints from the Late Paleoproterozoic A-type granites of the Dunhuang Complex. *Precambrian Research*, *38*, *105791*.

1574. Gan, B., Diwu, **Li, Z.**, Song, Z. and **Li, J.** 2020. Middle Cambrian granites in the Dunhuang Block, NW China mark the southernmost subduction in the Central Asian Orogen. *Lithos*, *372*, *105654*.

1575. Wang, C., Peng, P., **Li, Z.X.**, **Pisarevsky, S.**, Denyszyn, S., **Liu, Y.**, **Gamal El Dien, H.** and Su, X. 2020. The 1.24-1.21 Ga Licheng large igneous province in the North China Craton: Implications for paleogeographic reconstruction. *Journal of Geophysical Research: Solid Earth*, *125*, *e2019JB019005*.

1577. Dang, Z., Zhang, N., **Li, Z.X.**, Huang, C., Spencer, C.J. and **Liu, Y.** 2020. Weak orogenic lithosphere guides the pattern of plume-triggered supercontinent break-up. *Communications Earth & Environment*, *1*, *1-11*.

1578. Murdie, R., **Yuan**, **H.**, Dentith, M.C. and Lin, X. 2020. A passive seismic experiment in the Perth Basin, Western Australia. *Geological Survey of Western Australia, Report 208, Perth*.

1579. Murdie, R., **Gessner, K.**, Miller, M., Salmon, M., **Yuan, H.**, Whitney, J., Gray, S. and Allen, T. 2020. Geological Survey of Western Australia: SWAN takes off-a new seismic monitoring project in Western Australia. *Preview, 208, 28-29.*

1580. Doublier, M.P., Kennett, B.L.N., Fomin, T., Costelloe, R.D., Moro, P., Kohanpour, F., Calvert, A.J., Huston, D.L., Champion, D.C., Southby, Czarnota, K.C., Hickman, A.H.H., Haines, P.W., Kelsey, D.E., Martin, D.McB., Smithies, R.H., Chopping, R., Howard, H.M., **Gessner, K.** and Johnson, S.P. 2020. Basement Architecture from the Pilbara Craton to the Aileron Province: New Insights from Deep Seismic Reflection Line 18GA-KB1, Exploring for the Future. *Extended Abstracts, Geoscience Australia, DOI:10.11636/134381.*

1581. Kirilova, M., Toy, V., Sauer, K., Renard, F., **Gessner, K.**, Wirth, R., Xiao, X. and Matsumura, R. 2020. Micro-and nano-porosity of the active Alpine Fault zone, New Zealand. *Solid Earth, 11, 2425-2438.*

1582. Varga, J., Raimondo, T., **Daczko, N.R.** and Adam, J. 2020. Experimental alteration of monazite in granitic melt: variable U-Th-Pb and REE mobility during melt-mediated coupled dissolution-precipitation. *Chemical Geology*, *544*, *119602*.

1583. Agangi, A., **Reddy, S.M.**, Plavsa, D., **Olierook, H.K.H.**, Kylander-Clark, A.R.C. 2020. Compositional modification and trace element decoupling in rutile: insight from the Capricorn Orogen, Western Australia. *Precambrian Research, 345, 105772.*

1584. **Doucet, L.S.**, **Li, Z.X.**, **Gamal El Dien, H.G.**, **Pourteau, A.**, Murphy, B., Collins, W.J., Mattiel, N., **Olierook, H.K.H.**, Spencer, C.J. and **Mitchell, R.N.** 2020. Distinct formation history for deep-mantle domains reflected in geochemical differences. *Nature Geoscience*, *13*, *511-515*.

1585. Jiang, Q., Jourdan, F., **Olierook, H.K.H.**, Merle, R. E. and Whittaker, J. M. 2020. Longest continuously erupting large igneous province driven by plume-ridge interaction. *Geology 49, 206-210.*

1591. Fischer-Gödde, M., Elfers, B-M., Münker, C., Szilas, K., Maier, W.D., Messling, N., Morishita, T., **Van Kranendonk**, M., Smithies, R.H. 2020. Ru isotope vestige of Earth's pre-late veneer mantle preserved in Archean rocks. *Nature, 579, 240-244. doi. org/10.1038/s41586-020-2069-3.*

1593. **Gamal El Dien, H.G.**, **Doucet, L.S.**, **Murphy, B.** and **Li, Z.X.** 2020. Geochemical evidence for a widespread mantle re-enrichment 3.2 billion years ago: implications for global-scale plate tectonics. *Scientific Reports*, *10*, *9461*.

1594. Cawood, P.A., Wang, W., Zhao, T., Xu, Y., Mulder, J.A., **Pisarevsky, S.A.**, Zhang, L., Gan, C., He, H., Liu, H., Qi, L., Wang, Y., Yao, J., Zhao, G., Zhou, M.-F. and Zi, J.-W. 2020. Deconstructing South China and consequences for reconstructing Nuna and Rodinia. *Earth-Science Reviews*, *204*, *103169*.

1596. Beunon, H., Chernonozhkin, S.M., Mattielli, N., Goderis, S., **Doucet, L.S.,** Debaille, V. and Vanhaecke, F. 2020. Innovative two-step isolation of Ni prior to stable isotope ratio measurements by MC-ICP-MS: Application to igneous geological reference materials. *Journal of Analytical Atomic Spectrometry*, *35*, *2213-2223*.

1597. Yang, C., Li, X.-H., **Li, Z.-X.**, Zhu, M. and Lu, K. 2020. Provenance evolution of age-calibrated strata reveals when and how South China Block collided with Gondwana. *Geophysical Research Letters*, *47*, *e2020GL090282*.

1598. Murphy, J.B., Nance, R.D., Cawood, P.A., Collins, W.J., Dan, W., **Doucet, L.S.**, Heron, P.J., **Li, Z.-X.**, **Mitchell, R.N.**, **Pisarevsky, S.**, Pufahl, P.K., Quesada, C., Spencer, C.J., Strachan, R.A. and Wu, L. 2020. Pannotia: In defence of its existence and geodynamic significance. *Geological Society, London, Special Publications*, *503, 13-39, https://doi.org/10.1144/SP503-2020-96*.

1600. **Doucet, L.S.**, Xu, Y., Klaessens, D., Hui, H., Ionov, D.A., Mattielli, N. 2020. Decoupled water and iron enrichments in the cratonic mantle: A study on peridotite xenoliths from Tok, SE Siberian Craton. *American Mineralogist*, *105*, *803-819*.

1601. **Kirscher, U.**, Gevorgyan, H., Meliksetian, K., Navasardyan, G., Dallanave, E., Breitkreuz, C. and Bachtadse, V. 2020. Pleistocene ignimbrites of western Armenia - Paleomagnetic and magnetic anisotropy constraints on flow direction and stratigraphy. *Journal of Volcanology and Geothermal Research*, *402*, *106982*.

1602. Beunon, H., Mattielli, N., **Doucet, L.S.**, Moine, B. and Debret, B. 2020. Mantle heterogeneity through Zn systematics in oceanic basalts: Evidence for a deep carbon cycling. *Earth-Science Reviews*, *205*, *103174*.

1603. Meert, J.G., Pivarunas, A.F., Evans, D.A.D., **Pisarevsky, S.A.**, Pesonen, L.J., **Li, Z.X.**, Elming, S.-Å., Miller, S.R., Zhang, S. and Salminen, J.M. 2020. The magnificent seven: A proposal for modest revision of the Van der Voo (1990) quality index. *Tectonophysics*, *790*, *228549*.

1604. **Mitchell, R.N.**, Wu, L., Murphy, J.B. and **Li, Z.-X.** 2020. Trial by fire: Testing the paleolongitude of Pangea of competing reference frames with the African LLSVP. *Geoscience Frontiers*, *11*, *1253-1256*.

1605. **Doucet, L.S.**, Laurent, O., Ionov, D.A., Mattielli, N., Debaille, V. and Debouge, W. 2020. Archean lithospheric differentiation: Insights from Fe and Zn isotopes. *Geology*, *48*, *1028-1032*.

1606. **Nordsvan, A.R.**, **Kirscher, U.**, **Kirkland, C.L.**, Barham, M. and Brennan, D.T. 2020. Resampling (detrital) zircon age distributions for accurate multidimensional scaling solutions. *Earth-Science Reviews*, *204*, *103149*.

1607. Pourteau, A., **Doucet, L.S.**, Blereau, E.R., Volante, S., Johnson, T.E., Collins, W.J., **Li, Z.X.** and Champion, D.C. 2020. TTG generation by fluid-fluxed crustal melting: Direct evidence from the Proterozoic Georgetown Inlier, NE Australia. *Earth and Planetary Science Letters*, *550*, *116548*.

1609. Tetley, M.G., **Li, Z.-X.**, Matthews, K.J., Williams, S.E. and Müller, R.D. 2020. Decoding Earth's plate tectonic history using sparse geochemical data. *Geoscience Frontiers*, *11*, *265-276*.

1610. Vernikovskaya, A., Vernikovsky, V.A., Matushkin, N., Kadilnikov, P., Metelkin, D.V., Romanova, I., **Li, Z.-X.** and Bogdanov, E. 2020. Early Ediacaran magmatism in the Yenisei Ridge and evolution of the southwestern margin of the Siberian Craton. *Minerals*, *10*, *565*.

1611. **Doucet, L.S.**, **Li, Z.X.**, Ernst, R.E., **Kirscher, U.**, **Gamal El Dien, H.** and **Mitchell, R.N.** 2020. Coupled supercontinent-mantle plume events evidenced by oceanic plume record. *Geology*, *48*, *159-163*.

1615. He, D., Liu, Y., **Chen, C.**, **Foley, S.F.** and Ducea, M.N. 2020. Oxidization of the mantle caused by sediment recycling may contribute to the formation of iron-rich mantle melts. *Science Bulletin*, *65*, *519-521*.

1616. He, D., Liu, Y., Moynier, F., **Foley, S.F.**, **Chen, C.** 2020. Platinum group element mobilization in the mantle enhanced by recycled sedimentary carbonate. *Earth and Planetary Science Letters*, *541*, *116262*.

1617. Wang, X., Wang, Z., Cheng, H., **Foley, S.**, Xiong, L. and Hu, Z. 2020. Early cretaceous lamprophyre dyke swarms in Jiaodong Peninsula, eastern North China Craton, and implications for mantle metasomatism related to subduction. *Lithos*, *368*, *105593*.

1618. Turner, S., **Wilde, S.**, Wörner, G., **Schaefer, B.** and Lai, Y.-J. 2020. An andesitic source for Jack Hills zircon supports onset of plate tectonics in the Hadean. *Nature Communication*, *11*, *1241*.

1619. Ghazi, J.M., Moazzen, M., Rahgoshay, M. and **Wilde, S.A.** 2020. Zircon U-Pb-Hf isotopes and whole rock geochemistry of magmatic rocks from the Posht-e-Badam Block: A key to tectonomagmatic evolution of Central Iran. *Gondwana Research*, *87*, *162-187*.

1620. Stepanyuk, L.M., Shunlyanskyy, L.V., Gatsenko, V.O. and **Wilde, S.A.** 2020. The U-Pb zircon geochronology (LA-ICP-MS) of geological processes in granulites of Middle Bouh area. *Mineralogical Journal - Ukraine*, *42*, *50-68*.

1623. Liu, K., Zhang, J., Xiao, W., **Wilde, S.A.** and Alexandrov, I. 2020. A review of magmatism and deformation history along the NE Asian margin from ca. 95 to 30 Ma: Transition from the Izanagi to Pacific plate subduction in the early Cenozoic. *Earth-Science Reviews*, *209*, *103317*.

1624. Ge, R.F., Zhu, W., **Wilde, S.A.**, Wu, H.L. 2020. Remnants of Earth's oldest continental crust formed by subduction. *Acta Geologica Sinica*, *94*, *14*.

1625. Dunkley, D.J., **Kusiak, M.A.**, **Wilde, S.A.**, Whitehouse, M.J. 2020. Two Neoarchean tectonothermal events on the western edge of the North Atlantic Craton, as revealed by SIMS dating of the Saglek Block, Nain Province, Labrador. *Journal Geological Society, London*, *177*, *31-49*.

1626. Stepanyuk, L.M., Shunlyanskyy, L.V. and **Wilde, S.A.** 2020. The U-Pb Zircon geochronology (LA-ICP-MS) of geological processes in granulites of Middle Bouh area. Article 2. Rock association in the Chausove open pits. *Mineralogical Journal - Ukraine*, *42*, *84-103*.

1627. Han, W., Zhou, J.B. and **Wilde, S.A.** 2020. LA-ICPMS zircon U-Pb dating of the Heilongjiang Complex in the Luobei area: New constraints for the late Palaeozoic-Mesozoic tectonic evolution of Jiamusi Block, NE China. *Geological Journal*, *55*, *1644-1669*.

1628. Romanov, M., Sovetov, J.K., Vernikovsky, V.A., Rosenbaum, G., **Wilde, S.A.**, Vernikovskaya, A.E., Matushkin, N.Y. and Kadilnikov, P.I. 2020. Late Neoproterozoic evolution of the southwestern margin of the Siberian Craton: evidence from sedimentology, geochronology and detrital zircon analysis. *International Geology Review*, *1-24, DOI:10.1080/00206814.2020.1790044*.

1629. Li, L.X., Zi, J.W., Meng, J., Li, H.M., Rasmussen, B., Sheppard, S., **Wilde, S.A.** and Li., Y.H. 2020. Using *in situ* monazite and xenotime U-Pb geochronology to resolve the fate of the "missing" banded iron formation-hosted high-grade hematite ores of the North China craton. *Economic Geology*, *115*, *189-204*.

1630. Wu, Y., Guo, F., Wang, X.C., **Wilde, S.A.** and Fan, W. 2020. Derivation of Jurassic HIMU-like intraplate basalts from mantle transition zone in South China: New geochemical constraints from olivine-hosted melt inclusion. *Lithos*, *354-355*, *105337*.

1631. Jayananda, M., Aadhiseshan, K.R., **Kusiak, M.A.**, **Wilde, S.A.**, Sekhamo, K.U., Guitreau, M., Santosh, M. and Gireesh, R.V. 2020. Multi-stage crustal growth and Neoarchean geodynamics in the Eastern Dharwar Craton, southern India. *Gondwana Research*, *78*, *228-260*.

1632. Krapež, B., Srinivasa Sarma, D., Ram Mohan, M., McNaughton, N.J., Rasmussen, B. and **Wilde, S.A.** 2020. Tectonostratigraphy of the Late Archean Dharwar Supergroup, Dharwar Craton, India: Defining a tectonic history from spatially linked but temporally distinct intracontinental and arc-related basins. *Earth-Science Reviews*, *201*, *102966*.

1633. **Dai, H-K.**, Zheng, J., **Griffin, W.L.**, **O'Reilly, S.Y.**, **Xiong, Q.**, Ping, X-Q., Chen, F-K. and Lu, J-G. 2020. Pyroxenite xenoliths record complex melt impregnation in the deep lithosphere of the northwestern North China Craton. *Journal of Petrology, egaa079*.

1634. Ge, R., **Wilde, S.A.**, Kemp, A.I.S., Jeon, H., **Martin, L.A.J.**, Zhu, W. and Wu, H. 2020. Generation of Eoarchean continental crust from altered mafic rocks derived from a chondritic mantle: The 3.72 Ga Aktash gneisses, Tarim Craton (NW China). *Earth and Planetary Science Letters*, *538*, *116225*.

1635. Król, P., **Kusiak, M.A.**, Dunkley, D.J., **Wilde, S.A.**, Yi, K., Lee, S. and Kocjan. I. 2020. Diversity of Archean crust in the eastern Tula Mountains, Napier Complex, East Antarctica. *Gondwana Research*, *82*, *151-170*.

1636. Li, S., Wang, X.C., Li, C.F., Liu, K., **Wilde, S.A.**, Hu, S.Y., Gui, L., Liu, J. and Wu, L. 2020. First direct dating of alteration of Paleo-oil pools using rubidium-strontium pyrite geochronology. *Minerals*, *10*, *1-16*.

1637. Hu, F., Huang, W., Yang, Z., **Wilde, S.A.**, Furnes, H., Luo, M. and Zhang, K. 2020. Geochemistry and zircon U-Pb-Hf isotopes of the Mante Aobao granite porphyry at East Ujimqin Banner, Inner Mongolia: Implications for petrogenesis and tectonic setting. *Geological Magazine*, *157*, *1068-1086*.

1638. Huang, B., Kusky, T.M., Johnson, T.E., **Wilde, S.A.**, Wang, L., Polat, A. and Fu, D. 2020. Paired metamorphism in the Neoarchean: A record of accretionary-to-collisional orogenesis in the North China Craton. *Earth and Planetary Science Letters*, *543*, *116355*.

1639. Fu, D., Kusky, T.M., **Wilde, S.A.**, Windley, B.F., Polat, A., Huang, B. and Zhou, Z. 2020. Structural anatomy of the early Paleozoic Laohushan ophiolite and subduction complex: Implications for accretionary tectonics of the Proto-Tethyan North Qilian orogenic belt, northeastern Tibet. *Bulletin of the Geological Society of America*, *132*, *2175-2201*.

1640. Wu, T., Zhang, W. and **Wilde, S.A.** 2020. The origin of mafic microgranular enclaves in granitoids: Insights from *in situ* Sr isotope of plagioclases and Zr-Hf isotopes of zircons. *Chemical Geology*, *551*, *119716*.

1643. Kenny, G.G., Karlsson, A., Schmieder, M., Whitehouse, M.J., **Nemchin, A.A.** and Bellucci, J.J. 2020. Recrystallization and chemical changes in apatite in response to hypervelocity impact. *Geology, 48, 19-23*.

1644. Bellucci, J.J., Herd, C.D.K., Whitehouse, M.J., **Nemchin, A.A.**, Kenny, G.G. and Merle, R.E. 2020. Insights into the chemical diversity of the martian mantle from the Pb isotope systematics of shergottite Northwest Africa. *Chemical Geology, 545, 119638*.

1645. Costa, M.M., Jensen, N.K., Bouvier, L.C., Connelly, J.N., Mikouchi, T., Horstwood, M.S.A., Suuronan, J-P., Moynier, F., Deng, Z.B., Agranier, A., **Martin, L.A.J.**, Johnson, T.E., **Nemchin, A.A.** and Bizzarro, M. 2020. The internal structure and geodynamics of Mars inferred from a 4.2-Gyr zircon record. *Proceedings of the National Academy of the United States of America, 117, 30973-30979.*

1646. Kenny, G.G., Manttari, I., Schieder, M., Whitehouse, M.J., **Nemchin, A.A.**, Bellucci, J.J. and Merle, R.E. 2020. Age of the Saaksjarvi impact structure, Finland: reconciling the timing of small impacts in crystalline basement with regional basin development. *Journal of the Geological Society, London, 177, 1231-1243.*

1647. Merle, R.E., **Nemchin, A.A.**, Whitehouse, M.J., Snape, J.F., Kenny, G.G., Bellucci, J.J., Connelly, J.N. and Bizzarro, M. 2020. Pb-Pb ages and initial Pb isotopic composition of lunar meteorites: NWA 773 clan, NWA 4734, and Dhofar 287. *Meteoritics and Planetary Science, 55, 1808-1832.*

1648. Blanks, D.E., Holwell, D.A., **Fiorentini, M.L.**, Moroni, M., **Giuliani, A.**, Tassara, S., González-Jiménez, J.M., Boyce, A.J. and Ferrari, E. 2020. Fluxing of mantle carbon as a physical agent for metallogenic fertilization of the crust. *Nature Communications, 11, 1-11.*

1649. Bellucci, J.J., Whitehouse, M.J., **Nemchin, A.A.**, Snape, J.F. Kenny, G.G., Merle, R.E., Bland, P.A. and Benedix, G.K. 2020. Tracing martian surface interactions with the triple O isotope compositions of meteoritic phosphates. *Earth and Planetary Science Letters, 531, 115977.*

1650. Joy, K.H., Snape, J.F., **Nemchin, A.A.**, Kenny, G.G. and Merle, R.E. 2020. Timing of geological events in the lunar highlands recorded in shocked zircon-bearing clasts from Apollo 16. *Royal Society Open Science, 7, 6.*

1651. **Baumgartner, R.J.**, **Van Kranendonk, M.J.**, **Fiorentini, M.L.**, Pages, A., Wacey, D., Kong, C., Saunders, M. and Ryan, C. 2020. Formation of micro-spherulitic barite in association with organic matter within sulfidized stromatolites of the 3.48 billion-year-old Dresser Formation, Pilbara Craton. *Geobiology, 18, 415-425.*

1652. Galabert, O., Zlotnik, S., **Afonso, J.C.** and Diez, P. 2020. Fast Stokes flow solvers for geophysical-geodynamic inverse problems and sensitivity analyses based on reduced order modeling. *Journal of Geophysical Research: Solid Earth, 125, e2019JB018314.*

1653. **Manassero, M.C.**, **Afonso, J.C.**, Zyserman, F., Zlotnik, S. and Fomin, I. 2020. A reduced order approach for probabilistic inversions of 3D magnetotelluric data I: General formulation. *Geophysical Journal International, 223, 1837-1863, ggaa415.*

1654. Haynes, M., Fomin, I., **Afonso, J.C.**, Gorbatov, A., **Salajegheh, F.** 2020. Developing thermochemical models of Australia's lithosphere. *Geoscience Australia, http://pid.geoscience.gov.au/dataset/ga/134193.*

1655. Zhang, A., Guo, Z., **Afonso, J.C.**, **Yang., Y.**, Yang, B., Xu, Y., 2020. The deep thermochemical structure of the Dabie Orogenic Belt from multi-observable probabilistic inversion. *Tectonophysics, 787, https://doi.org/10.1016/j.tecto.2020.228478.*

Appendix 4: 2020 Abstract titles

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

AUSTRALIA EARTH SCIENCES CONVENTION CONFERENCE ABSTRACTS, TASMANIA, AUSTRALIA, 21 FEBRUARY 2020	Proterozoic crustal evolution of NE Australia during Nuna assembly: insights from geophysical and radiogenic isotope data **J.Y. Li**, **H.K.H. Olierook**, **Z.-X. Li**, **A.R. Nordsvan**, W.J. Collins, **A. Pourteau**, **S. Volante**, C. Elder and **L.S. Doucet**
PROSPECTORS AND DEVELOPERS ASSOCIATION OF CANADA CONVENTION, TORONTO, CANADA, 1-4 MARCH 2020	Scale integrated approach to understanding architecture and fertility in Archean cratons: Examples from Western Australia **K. Gessner**
INTERNATIONAL GEOLOGICAL CONFERENCE ABSTRACTS, DELHI, INDIA, MARCH 2-8 2020	Proterozoic tectonic evolution of NE Australia during the supercontinent Nuna assembly: new insights from geophysics and Nd isotope data reinterpretation **Y. Li**, **H.K.H. Olierook**, **Z.-X. Li**, **A.R. Nordsvan**, W.J. Collins, **A. Pourteau**, **S. Volante**, C. Elder and **L.S. Doucet**
EGU GENERAL ASSEMBLY, ONLINE, 4-8 MAY 2020	New constraints on the Sulfur isotope signature of the sub-continental lithospheric mantle wedge: *In situ* $\delta^{34}S$ analyses of pentlandite from the exhumed orogenic garnet-bearing peridotite of the Ulten Zone, Eastern Italian Alps G. Consuma, R. Braga, **M.L. Fiorentini**, **L. Martin**, P. Tropper and S. Aulbach Advances on multiobservable thermochemical tomography for the physical state of the upper mantle I. Fomin and **J. Afonso** From Rodinia to Pangea: an extroversion process driven first by plume push followed by downwelling pull, absorption and merging **Z.-X. Li**, W. Collins, **L. Wu** and **S. Pisarevsky** Modern plate tectonic cycles are inherited from Hadean mantle convection **R. N. Mitchell**, J.C. Spencer, **U. Kirscher** and **S.A. Wilde** The AuScope Geochemistry Laboratory Network A. Prent, B. McInnes, A. Gleadow, **S. O'Reilly**, S. Boone, B. Kohn, E. Matchan and T. Rawling Reconciling zircon and monazite thermometry constrains H_2O content in granitic melts **S. Volante**, W. Collins, C. Spencer, **E. Blereau**, **A. Pourteau**, V. Barrote, **A. Nordsvan**, **Z.-X. Li**, N. Evans and **J. Li** Ignimbrite flare-ups in the Central Andes: Crustal sources and processes of magma generation G. Wörner, **E. Belousova**, S. Turner, **J. Kemann**, A. K. Schmitt, A. Gerdes and S. de Silva The South China and Indochina neighbourhood in the assembled Gondwana **W. Yao**, J. Wang, C. Spencer, **E. Martin** and **Z.-X. Li**
GOLDSCHMIDT VIRTUAL 2020, 21-26 JUNE 2020	Sampling the C of the deep earth: *In situ* C-O-Sr isotopes of kimberlitic carbonates worldwide **M. Castillo-Oliver**, **A. Giuliani**, **W.L. Griffin**, **S.Y. O'Reilly**, R. Drysdale and X.-H. Li Pyroxenite xenoliths record episodic metasomatism in deep lithosphere, northwestern North China Craton **H.K. Dai**, J.P. Zheng, **W.L. Griffin**, **S.Y. O'Reilly** and Q. Xiong

GOLDSCHMIDT VIRTUAL 2020, 21-26 JUNE 2020
cont...

Incorporation of hydrogen and other atomic impurities in natural olivines
S. Demouchy and **O. Alard**

Origin and tectonic significance of the serpentinites in the Escambray Complex, Central Cuba: Geodynamic implications
D. Diaz Al, **S. Wilde** and C.A. Garcia

The petrology and sulphur isotopic composition of sulphide and sulphate in the kimberley kimberlites
A. Fitzpayne, **A. Giuliani**, N. Magalhaes, A. Soltys, **M. Fiorentini** and J. Farquhar

Use of EBSD to identify primary magmatic apatite inclusions in zircon
J. Gillespie, A. Cavosie, **A. Nemchin** and P. Kinny

Sulfur, selenium, tellurium and copper systematics in the manus back-arc basin
L. Gorojovsky, **O. Alard** and S. Turner

In situ determination of Re-Os isotopes by LA-MC-ICP-MS using daly detectors: Preliminary results
Y. Gréau, **O. Alard** and **S.Y. O'Reilly**

Extensive prekimberlitic lithosphere modification recorded in Jericho Mantle xenoliths in kimberlites, Slave Craton
S. Greene, **D. Jacob**, **S.Y. O'Reilly**, **H. Henry**, **Z. Pinter** and L. Heaman

The Wet but Dry Mantle
A. Halimulati, **O. Alard**, S. Demouchy and **S.Y. O'Reilly**

Longest continually erupting large igneous province driven by plume-ridge interaction
Q. Jiang, F. Jourdan, **H.K.K. Olierook**, R.E. Merle, M.F. Coffin and J.M. Whittaker

Deformation, metasomatism and seismic anisotropy in the lithospheric mantle beneath Taiwan Straits, Southeast Asian Margin: Constraints from mantle xenoliths
F. Kourim, K.-L. Wang, K. Michibayanchi and **S.Y. O'Reilly**

Differences in crustal ages between the Tula and Scott Mountains of Enderby Land, East Antarctica
P. Król, **M.A. Kusiak**, D.J. Dunkley, **S.A. Wilde**, K. Yi, S. Lee and M.J. Whitehouse

Pb nanospheres in metamorphic zircon
M.A. Kusiak, R. Wirth, D.J. Dunkley, L. Shumlyanskyy, M.J. Whitehouse and **S.A. Wilde**

Decoding high-K rocks: Linking magma source and metal endowment
A.W. Lanati and **S.F. Foley**

The AuScope Geochemistry Laboratory Network
B. McInnes, A. Gleadow and **S.Y. O'Reilly**

Chromitite in a Tibetan ophiolite records deep upper-mantle circulation and episodic subduction
S.Y. O'Reilly, Q. Xiong, **W.L. Griffin**, **H. Henry**, J.-P. Zheng and **N. Pearson**

A disequilibrium reactive transport model for mantle magmatism
B. Oliveira, **J.C. Afonso**, M. Klöcking and **R. Tilhac**

The AuScope Geochemistry Laboratory Network
A. Prent, B. McInnes, A. Gleadow, **S. O'Reilly**, B.P. Kohn, E. Matchan, S. Boone, **G. Florin**, H. Dalton, **Y. Greau**, **O. Alard**, T. Rawling, F. Kohlmann, M. Theile, D. Phillips and W. Noble

First zircon evidence of Hadean material in the Ukrainian Shield
L. Shumlyanskyy, **S.A. Wilde**, G. Artemenko, A. Bekker, M. Whitehouse and **A. Nemchin**

Lithosphere mapping in the south-western margin of the São Francisco Craton
L.B. Takenaka, **W.L. Griffin**, **S.Y. O'Reilly**, M. Basei, C.E. Ganade and **D. Jacob**

Hf-Nd isotope decoupling in the mantle: A brief review and new geodynamic perspectives
R. Tilhac, G.C. Begg, **S.Y. O'Reilly** and **W.L. Griffin**

Mapping the 4D lithospheric architecture of Zealandia using zircon O and Hf isotopes in plutonic rocks
R. Turnbull, J. Schwartz, **M. Fiorentini**, R. Jongens, T. Ludwig, N. Evans, B. McDonald and K. Klepeis

GOLDSCHMIDT VIRTUAL 2020, 21-26 JUNE 2020 cont...	An andesitic source for Jack Hills Zircon Argues for a Hadean Onset of Plate Tectonics S. Turner, **S. Wilde**, G. Worner, **B. Schaefer** and Y.-J. Lai All a matter of scale: The good, the bad and the ugly of zirconology **S. Wilde**, **M. Kusiak** and M. Whitehouse Ba isotope study on arc lavas and mantle peridotites with the application of 1013 ohm resistor F. Wu, **B. Schaefer**, **O. Alard** and S. Turner Complex formation processes of the Yarlung Zangbo Ophiolites (Tibet) Q. Xiong, J.-P. Zheng, H.D. Zheng, **W.L. Griffin** and **S.Y. O'Reilly** Recycled volatiles determine fertility of porphyry deposits in collisional settings B. Xu, **W.L. Griffin**, **S.Y. O'Reilly**, Z.-Q. Hou, Y. Lu, **E. Belousova**, Z.-Y. Chen and J.-F. Xu Solubility of Ru, Rh and Ir in spinel and olivine: can the Nugget Effect be Avoided? I. Zhukova, H. O'Neill, I. Campbell and **M. Fiorentini**
6TH INTERNATIONAL ARCHEAN SYMPOSIUM, PERTH, AUSTRALIA, 14-16 JULY 2020	Widespread Archean lithosphere continental foundations - Hidden from view? G.C. Begg, **W.L. Griffin**, **S.Y. O'Reilly** and **L. Natapov**
2020 ERESEARCH AUSTRALASIA ONLINE CONFERENCE, 19-23 OCTOBER	The AuScope Geochemistry Network S.C. Boone, A.M. Prent, H. Dalton, **G. Florin**, **Y. Greau**, **O. Alard**, E.L. Matchan, T. Rawling, F. Kohlmann, M. Theile, W. Noble, L. Wyborn, **S.Y. O'Reilly**, B.P. Kohn, A. Gleadow and B.I.A. McInnes
AGU FALL MEETING, ONLINE EVERYWHERE, 1-17 DECEMBER 2020	The AuScope Geochemistry Laboratory Network A. Prent, B. McInnes, A. Gleadow, **S. O'Reilly**, B.P. Kohn, E. Matchan, S. Boone, **G. Florin**, H. Dalton, **Y. Greau**, **O. Alard**, T. Rawling, F. Kohlmann, M. Theile, D. Phillips and W. Noble Tracing the origin and evolution of the lithospheric mantle beneath the Fijian Archipelago — Insights from Koro Island Peridotite Xenoliths N. Barrett, G. Pearson, H. Sommer, **S.F. Foley** and N. Kumar Making use of geological information: a perspective on challenges and opportunities from the Geological Survey of Western Australia R. Chopping, **K. Gessner** and S.P. Johnson The topography of the Iberian Peninsula: Integrated geophysical-petrological multi-data inversion for lithospheric temperature and composition J. Fullea, A.M. Negredo, M. Charco, I. Palomeras, A. Villasenor and **J.C. Afonso** Porosity reduction in post-rupture ultramylonitic fault rocks - implications for fluid transport in Archean granitic shear zones **K. Gessner**, I. Zibra, J. Liu, X. Xiao, M.A. Pearce, L. Menegon, V. Markwitz, I. Fielding and F.J. Korhonen Numerical constraints on heat flux variations and lithospheric thinning associated with passage of the Iceland plume beneath Greenland B. Heyn, C.P Conrad and **K. Selway** Imaging Australia's lithospheric architecture: Implications for our understanding of mineral systems M. Haynes, **J.C. Afonso**, K. Czarnota, D.P. Hasterok, A. Kirkby, **F. Salajegheh**, I. Fomin and A. Gorbatov New crustal Vs model along an array in South-east China: Seismic characters and paleo- Tethys continental amalgamation T. Li, L. Zhao, B. Wan, **Z.-X. Li**, T. Bodin, K. Wang and **H. Yuan** Receiver function mapping of mantle transition zone discontinuities beneath Western Alps using scaled 3-D velocity corrections D. Liu, L. Zhao, **H. Yuan** and A. Paul

AGU FALL MEETING, ONLINE EVERYWHERE, 1-17 DECEMBER 2020
cont...

Mesozoic decratonization of the North China Craton triggered by dehydration of the Pacifc Slab
L. Liu, S.S. Gao, K.H. Liu, **W.L. Griffin**, S. Li, S. Tong and J. Ning

A reduced order approach for joint probabilistic inversions of 3D magnetotelluric and surface wave data
M.C. Manassero, **J.C. Afonso**, F. Zyserman, S. Zlotnik, I. Fomin and S. Özaydin

Craton evolution: a more complex story from thermochemical imaging of the lithospheric and sub-lithospheric mantle
W.B. Mansour, **J.C. Afonso**, **S.F Foley**, **S.Y. O'Reilly**, **W.L Griffin**, **K. Selway**, A. Macdonald, N. Januszczak and **F. Salajegheh**

Interpretation of conductivity variations in magnetotelluric models of cratonic lithospheric mantle with the new open-source software MATE
S. Özaydin and **K. Selway**

Integrating magnetotelluric and seismic geophysical observations to improve upper mantle viscosity estimates beneath polar regions
F. Ramirez, **K. Selway** and C.P Conrad

Thermochemical structure of the Superior craton from multi-observable probabilistic inversion
D. Riddhi, F.A. Darbyshire, **J.C. Afonso** and K. Ali

How magnetotellurics can aid cryosphere studies: mantle rheology, GIA, surface heat flow and basal melting
K. Selway, C.P Conrad, F. Ramirez, N.B. Karlsson, M. Weerdesteijn and B. Heyn

Seismological evidence for the earliest global subduction network at 2 Ga ago
B. Wan, X. Yang, X. Tian, **H. Yuan**, **U. Kirscher** and **R.N. Mitchell**

An open-source 3D glacial isostatic adjustment modeling code using ASPECT
M.F.M. Weerdesteijn, C.P. Conrad, J. Naliboff and **K. Selway**

Appendix 5: CCFS visitors

CCFS VISITORS 2020 (Excluding participants in conferences and workshops)

VISITOR	ORGANISATION	COUNTRY
Dr Graham Begg	Minerals Targeting International, Perth, WA	Australia
Dr Huang Bo	China University of Geosciences, Wuhan	China
Dr Dong Fu	China University of Geosciences, Wuhan	China
Mr Mingdi Gao	China University of Geosciences, Wuhan	China
Dr Wei Guo	Institute of Geology and Geophysics, Chinese Adcademy of Sciences, Beijing	China
Mr Jue Hou	Institute of Geophysics, China Earthquake Administration, Beijing	China
Mr Igor Iakovlev	VS Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences	Russia
Miss Tingzi Li	Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing	China
Dr Yunshuai Li	Institute of Surface-Earth System Science, Tianjin University	China
Dr Ed Saunders	University of New England, Armidale, NSW	Australia
Mr Xuiangdong Sue	Institute of Geology and Geophysics, Chinese Adcademy of Sciences, Beijing	China
Dr Xiang Wang	China University of Geosciences, Wuhan	China
Dr Qiuhong Xie	China University of Geoscience, Beijing	China
Mr Kaizhang Yu	China University of Geosciences, Wuhan	China

Appendix 6: Research funding

GRANTS AND OTHER INCOME FOR 2020

Investigators	2020 Funding Source	Project Title	Amount
Li, Biggin	ARC Discovery Project (DP210102495)	Unlocking Earth's inner secrets in deep time using palaeointensities	$525,000
Daczko, Foley, Handley, Raimondo	ARC Discovery Project (DP200100482)	Plumbing the gap: a mantle solution to the enigma of bimodal arc volcanism	$90,000
Kemp, Wilde, Van Kranendonk, Elliot	ARC Discovery Project (DP200103298)	Testing continental growth models with calcium and strontium isotopes	$71,000
Yang, Afonso, Rawling, Ritzwoller, Niu	ARC Discovery Project (DP190102940)	Unveiling the fine structure of the Australian continent using ocean waves	$130,000
Cruden, Fiorentini, Barnes, Bunger, Jackson	ARC Discovery Project (DP190102422)	Magma dynamics and ore deposits	$100,000
Van Kranendonk, Fiorentini, Campbell, Deamer	ARC Discovery Project (DP180103204)	A terrestrial hot spring setting for the origin of life?	$96,476
Foley	ARC Australian Laureate Fellowship (FL180100134)	Understanding the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution	$612,075
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - Toward building a new tectonic paradigm	$282,953
Phillips, Jourdan, Matchan, Gleadow, Li, Bland, Norman, Honda, Cawood, Weinberg, Vasconcelos, Herries, Fiorentini, Wingate	ARC LIEF (LE210100044)	Ultra-precise dating in Earth, planetary and archaeological science	$905,654
Evans, Bland, Rankenburg, Li, Jourdan, Rowins, Fiorentini, Wingate, Barnes, Uvarova	ARC LIEF (LE200100035)	WA CRC-MC-ICPMS for Earth, Planetary and Environmental science	$610,000
Arculus, Cohen, Gallagher, Vasconcelos, Elders, Foden, Coffin, Nebel, McGregor, Clennell, Sloss, Heap, Webster, Kemp, George	ARC LIEF (LE160100067)	Australian membership of the International Ocean Discovery Program	$2,000,000
Danisik, Evans, McInnes, Kirkland, Li, Fiorentini, Wingate	ARC LIEF (LE190100079)	The Western Australia ThermoChronology Hub	$365,380
Grice, Rickard, Benedix, Jiang, Reddy, Kilburn, Clode, Peyrot, Wacey, Lavery, Masque, Trengove, Xia, Deditius, Maker	ARC LIEF (LE190100053)	A novel ToF-SIMS facility for organic and inorganic analyses in WA	$1,267,674
Jessell, Gorczyk, Cruden, Rey, Lindsay, Betts, Salles, Aitken, Kee, Lang, Denyszyn, Gessner, Schmid, Occhipinti, Cameron, McCuaig, McCracken, Subramanya	ARC LIEF (LE190100146)	Evolution of Proterozoic multistage rift basins – key to mineral systems	$311,202

Investigators	2020 Funding Source	Project Title	Amount
Miller, Kennett, Yuan, Allen, Greay, Gessner, Murdie	ARC Linkage Project (LP180101118)	Enhanced 3-D seismic structure for Southwest Australia	$140,788
Ailleres, Jessell, Armit, Droniou, Lindsay, Cui, Betts, Cruden, de Kemp, Caumon, Wellmann, Kemp, Gessner, Spampinato, Harrison, Kessler	ARC Linkage Project	Enabling 3D stochastic geological modelling	$237,000
Regenauer-Lieb, Afonso, Clark, Thiel, Czarnota, Poulet, Jones, Walsh	ARC Linkage Project (LP170100233)	A newly developed science approach to the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP)	$220,000
Ailleres, Jessell, de Kemp, Caumon, Florian Wellmann, Armit, Droniou, Lindsay, Cui, Betts, Cruden, Kemp, Gessner, Spampinato, Harrison, Kessler	ARC Linkage Project (LP170100985)	Mitigating 3D geological risk in resources management	$240,000
Conrad, Selway, Steinberger, Tarasov, Kellogg, Nisancioglu	Norwegian Research Council, FRINATEK	Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution (MAGPIE)	$283,700
Afonso	Geoscience Australia	Developing thermochemical models of Australia's lithosphere	$83,000
Thebaud, Aitken, Jessell, Occhipinti, Dentith, Hagemann, Kemp, Fiorentini, Smithies, Lu, Gessner	MRIWA M530, Industry	Yilgarn 2020	$663,500
LaFlamme, Thebaud, Fiorentini, Sugiono	Northern Star Resources	Multiple sulfur isotope systematics of the Kanowna Belle Gold deposit	$73,774
Barnes, Fiorentini	IGO Independence Group	Genesis of the Nova Nickel Deposit	$160,000
Loucks, Fiorentini	BHP Billiton	Improving zircon morphology and chemistry as a tool of assessing and ranking the relative prospectivity for Cu porphyry deposits in "*greenfield*" terrains	$176,000
Olierook, Kirkland, Evans, McDonald, Rankenburg, McInnes, Kumara, Kennedy	Fortescue Metals Group	Stratigraphy of the Karara Basin, Australia	$70,000
Olierook, Kirkland, Evans, McDonald, Rankenburg, McInnes, Kumara, Rowins	Atlas Iron	Prospectivity and explorational potential of paleoplacers in the Pilbara Craton, Australia	$31,000
George, Fiorentini, Parra Avila	Auldana	Tectonic evolution and amalgamation of continental, arc and arc-related terranes of Northern Thailand	€ 24,000
Olierook, Kirkland, Evans, McDonald, Rankenburg, McInnes, Kumara, Kennedy	Anglo American	Genesis and stratigraphy south of Diamantina Project, Australia	$62,000
Olierook, Kumara, Voute	Breaker Resources	Mineralogical and textural analyses of selected samples from the Bombora gold deposit, Lake Roe, Western Australia: implications for mineral paragenesis	$2,000

Investigators	2020 Funding Source	Project Title	Amount
Olierook, Kumara, Voute	Latitude 66 Cobalt	Mineralogical and textural analyses of selected samples from the Kuusamo Schist Belt, Finland: Implication for mineral paragenesis	$3,000
Olierook, Kirkland, McInnes, Guergouz, Conner, Evans, Kumara.	Regis Resources	4D architecture of the Duketon Greenstone Belt, Eastern Goldfields, WA	$14,000
Pisarevsky	Ministry of Science and Higher Education of the Russian Federation Megagrant	Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, Irkutsk	~$1,200,000
O'Reilly	NCRIS AuScope	AuScope Project Plan 3.53 - Earth composition and evolution	$200,382
O'Reilly	NCRIS AuScope (MQ contribution)	AuScope Project Plan 3.53 - Earth composition and evolution	$60,000
Campbell, Van Kranendonk, Guido	Royal Society of New Zealand, Marsden Fund	Some liked it hot: Searching for early life in terrestrial hot springs	$333,000
Liu, Li, Mitchell	ANZIC IODP Legacy Analytical Funding (AILAF)	Testing Late Cretaceous true polar wander on the Western Australian Margin	$19,300
Daczko, Gardner	ANZIC IODP Legacy Analytical Funding (AILAF)	Significance of syn-deformational melt migration for oxide enrichment in oceanic crust	$10,000
Pages, Barnes, Laukamp, Van Kranendonk, Michalski, Schulte	CSIRO	From the Red Sea to the Red Planet	$120,000
Wilde, Nemchin, Whitehouse, Harley, Kusiak, Dunkley	Australian Antarctic Science Grant	Determining the extent and nature of the oldest crust in Antarctica	$36,000
O'Reilly	Commercial - ACCESS MQ	GLITTER	$13,795
Lanati	MQPGRF	Petrology, geochemistry and origin of the shoshonites	$5,000
Lanati	Macquarie University	Student Representative Council Post-Graduate Grant	$1,500
Lanati	Geological Society of Australia	Post-Graduate Research award	$5,000
Lanati	Deutscher Akademischer Austauschdienst	DAAD, German Academic Exchange Service) Cotutelle Scholarship	€ 80,000

Contact details

- **CCFS information is accessible at:**
  http://www.ccfs.mq.edu.au/

- **Contact CCFS via email at:**
  ccfs.admin@mq.edu.au

CCFS
ARC Centre of Excellence for
Core to Crust Fluid Systems
Administering Institution
Department of Earth & Environmental Sciences
Macquarie University NSW 2109
AUSTRALIA

Professor Suzanne Y. O'Reilly
Director
Phone: 61 2 9850 8362
Email: sue.oreilly@mq.edu.au

Sally-Ann Hodgekiss
Reporting and Communications Manager
Phone: 61 2 9850 6124
Email: sally-ann.hodgekiss@mq.edu.au

Australian Government
Australian Research Council

Glossary

AMIRA	Australian Mineral Industry Research Association
AMMRF	Australian Microscopy and Microanalysis Research Facility
(RSES) ANU	(Research School of Earth Sciences) Australian National University
ANSTO	Australian Nuclear Science and Technology Organisation
APA	Australian Postgraduate Award
ARC	Australian Research Council
CAS	Chinese Academy of Sciences
CAGS	Chinese Academy of Geological Sciences
CCFS	Core to Crust Fluid Systems
CET	Centre for Exploration Targeting
CMCA	Centre for Microscopy, Characterisation and Analysis (UWA)
CNRS	French National Research Foundation
CoE	Centre of Excellence
COO	Chief Operating Officer
CSIRO	Commonwealth Scientific Industrial Research Organisation
CU	Curtin University
CWAS	China-Western Australia Seismic Survey
DP	Discovery Project
EBSD	Electron Backscatter Diffraction
ECR	Early Career Researcher
EES	Earth and Environmental Sciences (MQ Department, formerly EPS)
FIM	Facility for Integrated Microanalysis
FSE	Faculty of Science and Engineering (MQ)
FTIR	Fourier Transfer Infrared Spectroscopy
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
(C)IPRS	(Curtin) International Postgraduate Research Scholarship
KIT	Karlsruhe Institute of Technology, Germany
LAM-ICPMS	Laser Ablation Microprobe - ICPMS
LIEF	Linkage Infrastructure, Equipment and Facilities
ING PAN	Institute of Geological Sciences, Polish Academy of Sciences
MC-ICPMS	Multi-Collector - ICPMS
MG3	Geophysics and Geodynamics Group
MQGA	Macquarie University GeoAnalytical (formerly GAU Geochemical Analysis Unit) EES, Macquarie University
MRIWA	Minerals Research Institute of Western Australia
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
MOU	Memoranda of Understanding
NASA	National Aeronautics and Space Administration
NCRIS	National Collaborative Research Infrastructure Scheme
PGE	Platinum Group Element
RAAP	NSW Research Attraction and Acceleration Program
RTPS	Research Training Program Stipend (formerly APA)
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
SIEF	Science & Industry Endowment Fund
SIRF	UWA Scholarship for International Research Fees
TIGeR	The Institute for Geoscience Research
UM	University of Melbourne
UNSW	University of New South Wales
UWA	University of Western Australia

Australian Government
Australian Research Council

MACQUARIE University

Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ARC Centre of Excellence for Core to Crust Fluid Systems

2020 Annual Report

ISSN:2205-9717

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