CCFS

2021 Annual Report

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

- **CCFS information is accessible on WWW at:**

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

- **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.

Cover: A newly installed seismic site forming part of the Pilbara seismic array, 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). See p. 46

Continuing achievements of CCFS are given under "Flagship Programs", p. 18, 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) since January 2021 (CCFS formally commenced mid-2011). Activities include research, technology development, stakeholder engagement, international links and research training. It also provides future research directions.

The overarching goal of CCFS is to understand Earth's internal dynamics, evolution and fluid cycles from core to crust. CCFS leverages 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 participation of key researchers.

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 led 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, thus advancing geoscience capabilities.

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

CCFS has so far graduated 139 PhD students and 50 early-career researchers have participated in CCFS with formal allocated positions. In addition, over 30 international PhD students and more early-career researchers have had extended periods of research in CCFS on externally-funded scholarships and grants, resulting in significant research outputs with CCFS bylines (see *CCFS Publications*). CCFS postgraduates are producing world-class research with authorship of 20 publications (14 first-authored) in high-impact journals in 2021 and 14 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 from geoscience.

We are particularly proud that CCFS-aligned early-career researchers have populated a broad cross-section of professions nationally and internationally including industry, government and commercial environmental agencies, stock exchange advising, state and national geological surveys, commercial geochemical laboratories (e.g., Rio Tinto has now employed 9 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 has, since 2011, produced 1732 publications in both high-impact journals and books, and in journals targeted for specific audiences. Many more are in the publication pipeline.

The Clarivate/Thomson Reuters ongoing recognition of 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 naming a CCFS Chief Investigator as one of the "*World's Most Influential Minds*" across several years have been documented in preceding Reports. 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 (e.g., *CCFS Publication #1681* in *Nature Geoscience, 2022*). All of these seminal contributions and many others are detailed in this and previous Reports and embed geochemical, tectonic, geological and/or advanced imaging, computational and modelling components, emphasising integration across diverse datasets and methodologies.

Technology Development and New Directions

Technology Development sections of the CCFS Reports document 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 the volatile and element distributions and concentrations of volatiles and other elements at increasing resolution and smaller spatial scales.

CCFS is a very active participant in the new and burgeoning NCRIS AuScope Australian Geochemistry Network (AGN: https://www.auscope.org.au/agn). AGN has implemented 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 properties, time) in multidimensional space for unprecedented imaging of Earth characteristics.

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

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, and continue to inform, the relevance of the fundamental research directions, and enabled continuation of relevant CCFS activities. These are fully documented in previous Reports.

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 have leveraged the Centre funding, expertise and researcher resources and commonly include cotutelle PhD programs, providing the basis for a new generation of productive global research alliances.

Recognition of the significance of international collaborations is evidenced by my recent 2020 China International Science and Technology Cooperation Award (delayed due to COVID-19). Presented by H.E. Ambassador Xiao Qian, the award is China's

Sue O'Reilly receiving the 2020 China International Science and Technology Cooperation Award by H.E. Ambassador Xiao Qian (photo: Australian Academy of Science).

highest scientific honour for foreign individuals and institutions. Although this award was given to me personally, it is truly shared with the many wonderful Chinese, GEMOC and CCFS scientific colleagues and postgraduate students with whom I have worked over many years. As I said in my acceptance speech, "*Science across national borders is the way to a better world for all, and for a more sustainable future for our planet and society.*"

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.

Legacy archiving of CCFS Annual Reports and web pages

CCFS Annual Reports and web pages are a treasure trove of geoscience information as well as documenting the annual achievements of participants, the research highlights and advances relevant to national (and international) benefits for our society. These have been archived in the National Library (https://trove.nla.gov.au/). All the Annual Reports have a registered ISBN number and are lodged at the Library. They are available online in perpetuity at https://nla.gov.au/nla.obj-366647091. The CCFS web pages are archived at https://webarchive.nla.gov.au/awa/20210303014751/http://ccfs.mq.edu.au/

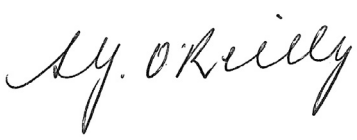
In the future?

2020 and 2021 were the most difficult years for Australian universities in many decades (ever?) and many hard choices were made 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 proved to not be immune from these effects, and in 2021, CCFS world-leading geophysicists (three) and a geochemist were made redundant, a decision determined on the basis of low undergraduate student numbers without considering performance. It is noteworthy that all quickly gained excellent new (and higher) positions in that very tough employment environment, a testament to their excellence and their esteem in the geoscience milieu. It is also noteworthy that this dramatic curtailment of geoscience capability at Macquarie was reported in high-impact media and journal outlets: in *The Conversation* nationally (https://theconversation.com/australia-badly-needs-earth-science-skills-but-universities-are-cutting-the-supply-163248) and internationally in *Nature* (https://www.nature.com/articles/s43017-021-00216-1) and EOS (https://eos.org/opinions/australias-unfolding-geoscience-malady), testifying to the high profile and reputation of the CCFS researchers at Macquarie.

Interestingly, the high-technology instrument laboratories at Macquarie (MQGA – see the *Technology Development* Section) have been guaranteed ongoing support and full staffing and will continue delivering high-quality user-friendly access to a wide range of geochemical analytical imaging and analysis with the strong support from AuScope through NCRIS. Continuation of the CCFS space for researchers, staff, postgraduate and visitors has also been guaranteed.

As I noted in the 2020 Report, dozens of CCFS alumni across the world have sent unforgettable supportive emails about their experiences in CCFS 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 and the impact of its work in geoscience.

So CCFS now continues as a virtual centre, and as GEMOC/CCFS at Macquarie.



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

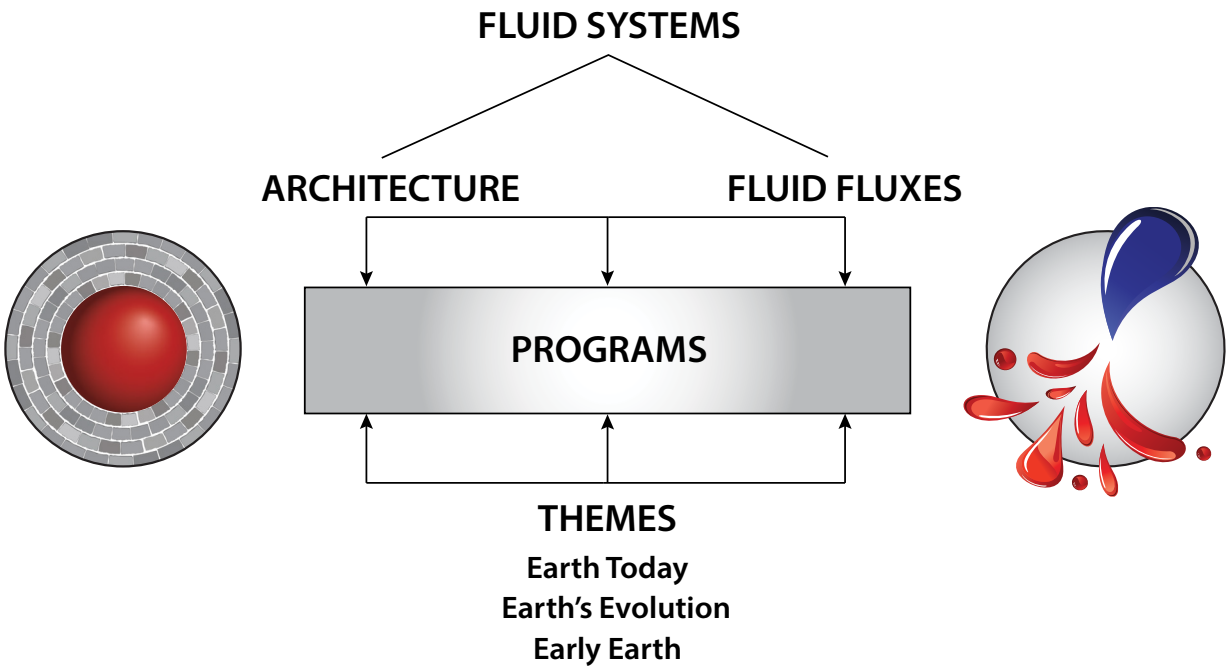
Research programs within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research is carried out in parallel,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

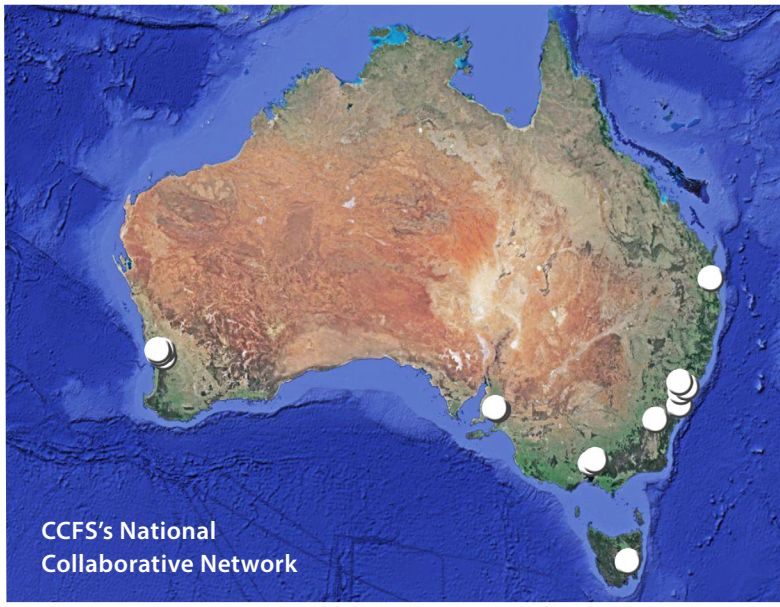
Earth Today - Dynamics, decoding geophysical imaging, and Earth resources. Geophysical imagery gives us a snapshot of the current status of the deep Earth but also carries the imprints of past processes. Realistic interpretation of these data provide us with new insights into Earth's internal dynamics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

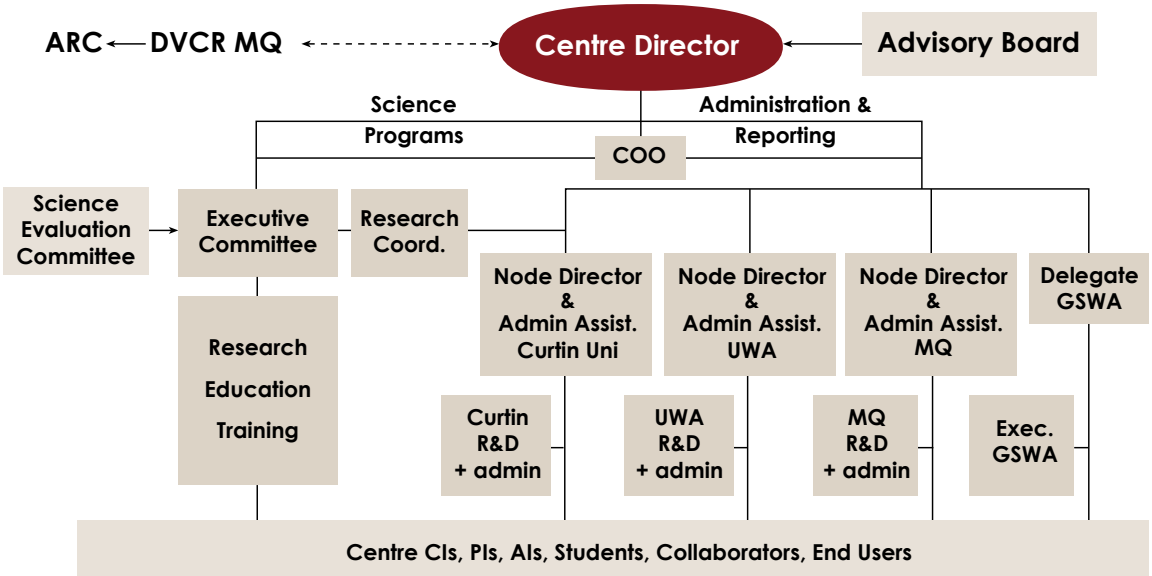
Huaiyu Yuan looking for possible surface ruptures of a M5.3 earthquake occured at 21:05 local time on Nov 13 2021.

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 contribute 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. 46*). 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 Environmental Sciences
Macquarie University

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

Associate Professor Craig O'Neill
Department of Earth and Environmental 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 Environmental 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

Emeritus 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 - 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

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.

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.

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*".

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.

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).

CCFS Participants at the 2017 Whole-of Centre Meeting, Cairns (photo Will Powell)

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

Anthony Lanati hiking the mountains around Prad am Stilfser Joch, Italy (photo Marthe Klöcking)

Elena Belousova panning for zircons on Lord Howe Island

WHERE IN THE WORLD IS CCFS?

The Pilbara region (photo Huaiyu Yuan)

Communications 2021

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 2021 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 2021 are given in Appendix 3.

The 106 CCFS publications that were published in 2021 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 2021

CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at 8 peak geophysical, metallogenic, geodynamic and geochemical conferences and workshops as convenors, invited speakers, or presenters, with 51 presentations including:

- Australian Earth Sciences Convention: 'Core to Cosmos' 19-12 February 2021
- EGU General Assembly 2021: Gather Online 19-30 April 2021
- Goldschmidt Virtual 2021, online, 4-9 July 2021
- 3rd European Mineralogical Conference, Krakow, Poland, 29 August-2 September, 2021
- AuScope Research Conference 2021, 12-13 October 2021
- eResearch Australasia 2021 Conference 11-15 October 2021
- Deep 2021, Virtual Meeting and International Everywhere, 1-2 November 2021
- AGU Fall Meeting New Orleans, LA and Online Everywhere, 13-17 December 2021

CONFERENCE ROLES

AUSTRALIA EARTH SCIENCES CONVENTION CONFERENCE: CORE TO COSMOS, 9-12 FEBRUARY 2021	Structural evolution of a 1.6 Ga orogeny related to the final assembly of the supercontinent Nuna: coupling of episodic and progressive deformation S. Volante, W.J. Collins, A. Pourteau, Z.-X. Li, J. Li and A. Nordsvan Keynote
GOLDSCHMIDT VIRTUAL 2021, ONLINE, 4-9 JULY 2021	A glimpse into the secular change of mantle-derived magmatism at the transition between Neoarchean and Paleoproterozoic M. Fiorentini, S. Caruso, A. Giuliani Keynote
3RD EUROPEAN MINERALOGICAL CONFERENCE, KRAKOW, POLAND, 29 AUGUST-2 SEPTEMBER, 2021	Comparing Eoarchean records of crustal growth in the North Atlantic Craton between the Saglek Block of Labrador, Canada and the Itsaq Gneiss, SW Greenland D.J. Dunkley, M.A. Kusiak, M.J. Whitehouse, S.A. Wilde and M. Mieszcak Invited Observation and inference in the interpretation of zircon ages obtained from a purported >3.9 Ga gneiss in the Saglek Block, Labrador M.J. Whitehouse, D.J. Dunkley, M.A. Kusiak, S.A. Wilde and T.T. Keluskar Invited Evaluating radiogenic lead nanoscale inclusions and clusters in zircon S.A. Wilde, M.A. Kusiak, D.J. Dunkley, M.J. Whitehouse and R. Wirth Invited

CONFERENCE/WORKSHOP ROLES *cont...*

DEEP 2021, VIRTUAL MEETING AND INTERNATIONAL EVERYWHERE, 1-2 NOVEMBER 2021	Probing the physical state of the Earth's interior with thermochemical tomography J.C. Afonso, W.L. Griffin, S.Y. O'Reilly, W. Ben-mansour, F. Salajeghegh, I. Fomon, S. Foley, G. Begg, K. Selway. A Macdonald and A. Nyblade Keynote Mantle Lithosphere architecture through the sulfide and olivine lenses O. Alard, Y. Greau, M. Veter and S. Foley Keynote The architecture and evolution of continental lithosphere: Outcomes from multi-disciplinary mapping G.C. Begg, W.L. Griffin and S.Y. O'Reilly Plenary The evolution and power of 4D lithospheric mapping S.Y. O'Reilly and W.L. Griffin Plenary Geodynamic and Geophysical consequences of stealth(y) mantle metasomatism: Craton evoluion and fluid pathways S.Y. O'Reilly, W.L. Griffin, N.J. Pearson and collaborators Keynote
AGU FALL MEETING, NEW ORLEANS, LA & ONLINE EVERYWHERE, 13-17 DECEMBER 2021	*Lead convenor: Huaiyu Yuan* Session: T31A: Continental Collisions: Structure and Evolution I Oral, Dec 15 2021 Session: T32A: Continental Collisions: Structure and Evolution II Oral, Dec 15 2021 Session: T35A: Continental Collisions: Structure and Evolution III Poster, Dec 15 2021 *Co-convenor: Juan Carlos Afonso* Session: DI44B: Integrative Perspectives on Present-Day Mantle Structure I Oral Session: DI44B: Integrative Perspectives on Present-Day Mantle Structure II Poster Session: DI44B: Integrative Perspectives on Present-Day Mantle Structure I Oral

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

Elena Belousova attended the Campbell Miles Drill Core Storage Facility to view several IOCG deposits, during the Technical Workshop at Mt Isa organised by GSQ in December 2021.

ESTEEM

AWARDS

Participant	Activity
Sue O'Reilly	2020 International Science and Technology Cooperation Award of the People's Republic of China. This prestigious award was presented on the 24 March 2022 at the Chinese Embassy, Canberra by H.E. Ambassador Xiao Qian.

Nathan Daczko and FOSE3000	2021 – Faculty of Science and Engineering Awards, Excellence in Inter-Department Collaboration
Nathan Daczko, Tom England and Casey Kavanagh	2021 – Faculty of Science and Engineering Awards, Excellence in Inter-Department Collaboration

For Postgraduate awards see the "*Postgraduate*" section *p. 27.*

2021 APPOINTMENTS AND POSITIONS

Sue O'Reilly	Member of Council, Australian Academy of Science Member of Executive Committee, Australian Academy of Sciences (from 2018) Project Leader - IGCP 622: *"Orogenic architecture and crustal growth from accretion to collision"* Chair, Equity and Diversity Reference Group, Australian Academy of Science Co-Convenor DEEP-2021 conference China November 2021 Appointed member of the Early- and Mid-Career Researcher (EMCR) Committee of Council (Australian Academy of Science). Advisory Board member "*Minerals*" international journal (from 2020)
Simon Wilde	Director- International Precambrian Research Center of China, Chi-nese Academy of Geological Sciences

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	O'Reilly, Wilde (Assoc. Ed.)
American Journal of Science	Wilde (Assoc. Ed.)
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	Griffin
Mineralium Deposita	Fiorentini (Assoc. Ed.)
Nature Scientific Reports	Daczko, Li
Precambrian Research	Pisarevsky
Russian Geology and Geophysics	Pisarevsky
Science China - Solid Earth	Yuan
Solid Earth Sciences	Griffin
Tectonophysics	Li (Co-editor in chief)

OUTREACH

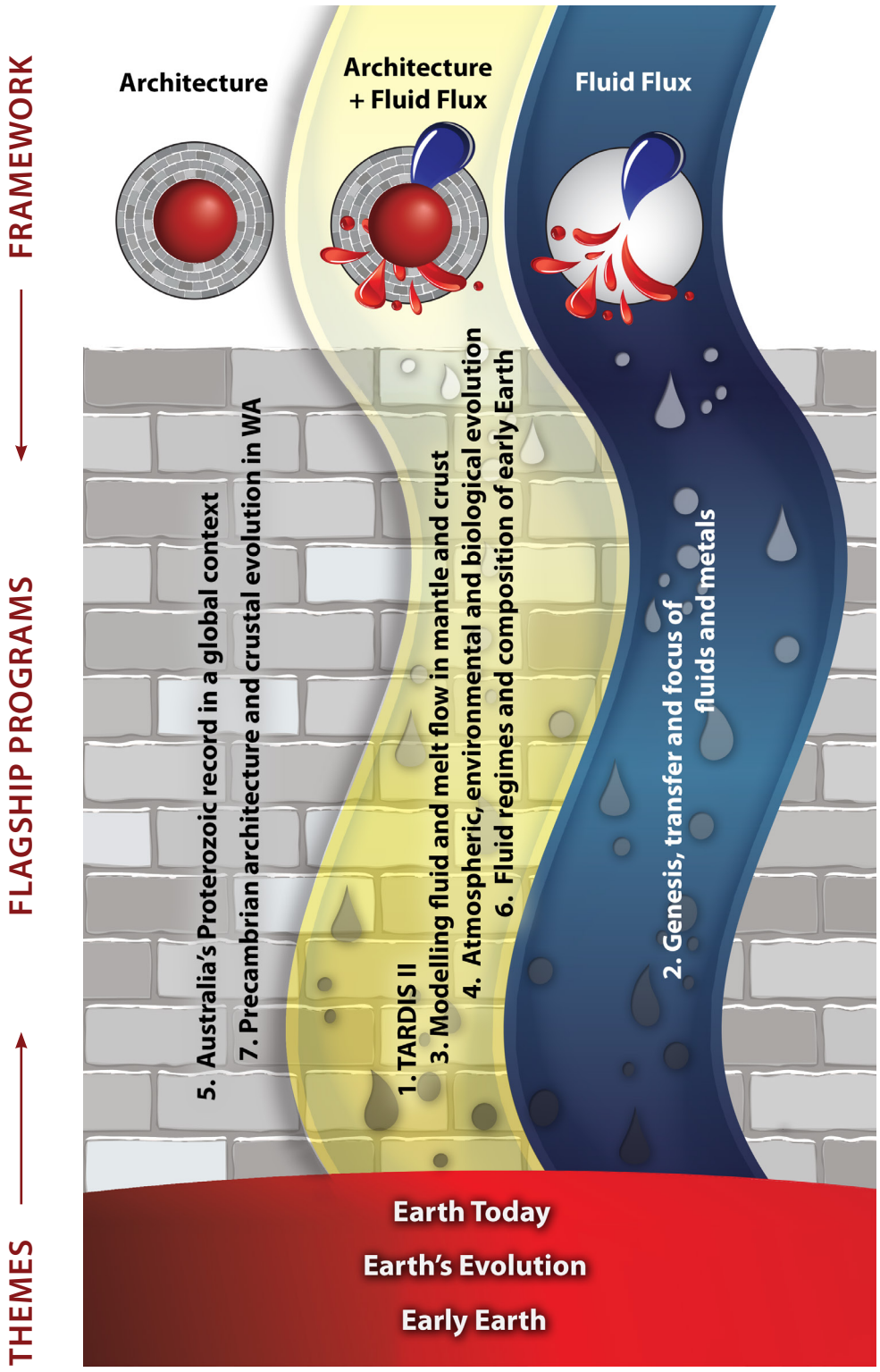
Forum	Participant/s	Date
EMinar - "*Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's inerior*"	Juan Carlos Afonso	9 June 2021
The Royal Society of WA, Inaugural John Glover Symposium (The Southwest Biodiversity Hotspot): Inaugural John Glover Lecture - "*The break-up of Gondwana: formation and erosion of the Darling Scarp* "	Simon Wilde	3-4 September 2021

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 for face to face interaction in 2021. Despite these difficulties, collaboration continued remotely via video conferencing and webinars. 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.*

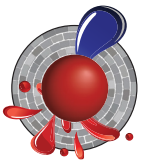
Flagship Programs

Following the conceptual framework outlined on *page 5,* 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.

2021 REPORT

Most of the work on the kimberlites and related rocks and the North China Craton was focused on finalising these projects to the stage envisaged and forecast by the end of 2021 after a successful year of completing and publishing a significant amount of the work undertaken. This included writing up the remaining results and concepts for publication in high-ranked journals. A milestone for CCFS Vision was achieved in 2021 with the acceptance of a benchmark paper for *Nature Geoscience*, *"Thermochemical structure and evolution of cratonic lithosphere in Central and South Africa"*, with 7 CCFS co-authors (Juan Carlos Afonso as first author). This paper demonstrates the power of the LitMod technology developed at CCFS and provides remarkable new insights into the evolution of the African lithospheric mantle and its response to tectonic forces over time.

Ultra-reduced magmatic assemblages, Mt Carmel, Israel: Work continues on this topic as the project has expanded to include 3D Xray micro-tomography imaging in collaboration with Dr Jeremy Shaw (UWA) to understand volumetric and spatial relationships of the relevant phases in aggregates of corundum crystals, whose growth history was analysed earlier by Oliveira et al. (*CCFS publication #1533, Fig. 1*). Another new development was a collaboration with Dr Chi Ma (CalTech, USA), a specialist in micromineralogy who is using a combination of microchemistry and microstructural analysis (EBSD) to characterise tiny grains of minerals in the corundum aggregates. He has discovered a range of new minerals, of which 4 have been submitted to the International Mineralogical Association for approval.

Tethyan Belt: Work continued 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. A new strand of work in Tibet started in 2021 focussing on understanding the origin of previously collected samples in the Kangjinla region and implications for the tectonic history. This is a collaboration with CCFS PhD student Hongkun Dai (graduated 2021), former CCFS PhD student Qing Xiong and other colleagues from CCFS, Macquarie and China University of Geosciences, Wuhan (China). The first manuscript is in advanced stages of preparation for Nature Communications.

An invited major review paper, "*Hf-Nd isotopes in the mantle: a global review and new geodynamic perspectives*" by CCFS researchers Romain Tilhac, Bill Griffin, Sue O'Reilly and Graham Begg has been submitted to Chemical Geology. This is a major contribution with a strong focus on the geodynamic processes that control the broad correlations, and some striking deviations from correlation, between Nd and Hf isotopes in the mantle globally.

A new phase of the TARDIS Project will continue in 2022, funded by ARC DP grant DP210102196, titled "*The link between cratonic roots, redox state, and mantle geodynamic.*" Chief investigator

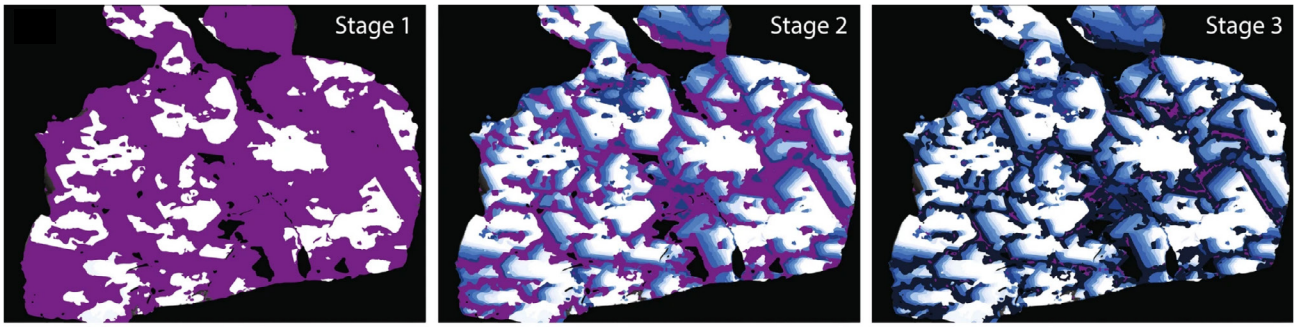


Figure 1: The distribution of corundum crystallised during the different stages of growth, in a crystal aggregate cut roughly subparallel to the C axes of the corundum. Aggregate is 2 mm long. From: Oliveira, B., Griffin, W.L., Gain, S.E.M., Saunders, M., Shaw, J., Toledo, V., Afonso, J.C. and O'Reilly, S.Y. 2021. Ti^{3+} in corundum: Tracing crystal growth in a highly reduced magma. Scientific Reports, 11, 2439.

Craig O'Neill withdrew from the project, and Dr Olivier Alard, a specialist in mantle redox has been added as a Chief Investigator. 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.

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

A collaboration between colleagues from the University of Sydney and CCFS researchers resulted in the award of ARC DP220100709 funding for 2022 for the project "*Mapping mineral systems of deep Australia*" aimed at enabling mineral resource discoveries by calibrating geophysical surveys against 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 and other essential resources. More 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.

Published outputs for 2021

CCFS Publications: #1519a, 1528, 1530, 1532, 1533, 1539, 1540, 1541, 1543, 1544, 1545, 1548 1561, 1565, 1569, 1568, 1578, 1613, 1614, 1658, 1659, 1660, 1663, 1665, 1668, 1669, 1670, 1674, 1677, 1680, 1683, 1694, 1696, 1703

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.

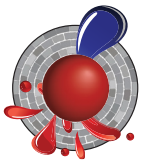
2021 REPORT

Work in 2021 was 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 was sampling and analysis for the key industry-funded projects that started in 2020. Strategic partnerships with overseas and national institutions were significantly strengthened, with engagement of Master students in other countries who carried out sampling at specific locations. An example is the involvement of Masters students from the University of Bologna (Italy), who worked in the framework of ARC LP190100785 and will be graduating in mid 2022. A new strategic two-year project on the role of carbon in the transport of metals in collaboration with the University of Leicester and Macquarie University was funded by BHP at the end of 2021. This project builds on the results from CCFS Flagship Program 2 over the past decade and embodies the legacy of significant research excellence that was generated.

Published outputs for 2021

CCFS Publications: #1540, 1555, 1576, 1667

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.

2021 REPORT

Work continued 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*" continued 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), processes during the subduction of carbonate-rich materials (Chunfei Chen *pictured right*), melting of sulphur-bearing pyroxenites as possible sources of Cu-porphyries and shoshonites (Anthony Lanati, Isra Ezad), the occurrence of salts in subducting slabs (Chunfei Chen, Michael Förster), 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. New HDR students who have arrived in January 2022 after having commenced overseas due to COVID-19-related travel restrictions are Matt Phillips (solubility of trace elements in fluids), Patrick Manselle (role of amphibole in convergent margin magmatism) and Lesego Ramokgaba (unusual metasomatic effects in the the Kaapvaal cratonic lithosphere). The latter two are collaborations with the Universities of Illinois and Cape Town, where the students were hosted to commence their projects.

Stephen Foley and Chunfei Chen loading an experiment into the Walker cell of the multi-anvil apparatus (Photo: Morris McLennan)

Published outputs for 2021

CCFS Publications: #1375, 1533, 1549, 1555, 1571, 1578, 1613, 1621, 1622, 1656, 1657, 1662, 1664, 1675, 1676, 1695

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.

2021 REPORT

Work in 2021 has been carried out within the framework of a number of ongoing PhD projects and post-doctoral research programs mainly funded by the ARC. Post-doc Dr Stefano Caruso completed his study at UNSW of the source and composition of fluids associated with hydrothermal alteration of the 3.48 Ga Dresser Formation (Pilbara Craton), while both Brendan Nomchong and Georgia Soares successfully submitted and defended their PhD theses on the development of more complex life forms as preserved in the 2.4 Ga Turee Creek microbialite reef complex of Western Australia. Georgia obtained a post-doctoral position at Penn State University in the US, as did graduated UNSW PhD student Dr Erica Barlow on a prestigious NASA Astrobiology post-doctoral fellowship. Bonnie Teece (UNSW, co-supervised by Dr Simon George) submitted her PhD thesis "*Organic geochemical signatures of complex life forms from the GoE of Australia*" at the very end of the year and will graduate in 2022.

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, although fieldwork for that project was hampered by Covid. However, fieldwork was undertaken during a window of opportunity in May, when Prof Van Kranendonk and honours student Alec Byrne collected samples of possible gypsum crystals in the Pilbara Craton (3.35 Ga) and the Hamersley Province (2.56 Ga), during periods of low atmospheric oxygen when sulfate crystals should not be present. During this trip, Masters of philosophy student Clare Fletcher accompanied Prof Van Kranendonk to assess the ancient stromatolite sites of the Pilbara for her thesis that focusses on how to conserve these internationally significant sites and to participate in the filming of a Canada-Australia-French co-production documentary by Wildbear productions titled "*Carbon: the Unauthorised biography*" due in theatres worldwide in March 2022 (*see photo below*). On this trip, we also had the enormous privilege of meeting Njamal elders Mr Jamie Haynes and his brother Eginbah to discuss ways

Filming in the Pilbara on the banks of the Shaw River for the documentary "Carbon: An unauthorised biography" by Wildbear Productions due for international release in March 2022.

to partner in conservation of the ancient Pilbara fossils and share deep time scientific and cultural stories of this amazing landscape.

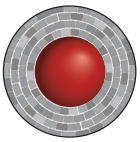
Due to Covid, 2021 was a year with limited international travel but lots of time for writing, resulting in several significant publications. The third issue on hot spring research was published in the Journal of Astrobiology (v. 21, No. 1), which was edited by Prof Van Kranendonk and includes three papers from his group (papers by Djokic et al. *#1382*, Murphy et al. *#1726*, and Van Kranendonk et al. #1486). In addition, three papers by Allen Nutman et al. on the Eoarchean of West Greenland provide greater detail on the environments of some of the earliest crust on Earth and the biogenicity of stromatolites found at Isua (*CCFS publications #1727, 1728, 1732*). There was also a major chapter published in the Elsevier book "*Mars Geological Enigmas*" (*#1731*), which summarises the settings of early life found in the Pilbara and their analogues on Mars, and a paper by Rouillard et al. (*#1729*) re-examined the setting of the (in)famous putative Apex chert microfossils in 3.46 Ga rocks of the Pilbara, previously the oldest accepted evidence of life on Earth but now the subject of much uncertainty.

Published outputs for 2021

CCFS Publications: #1382, 1486, 1534, 1592, 1725, 1726, 1727, 1728, 1729, 1730, 1731, 1732

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.

2021 REPORT

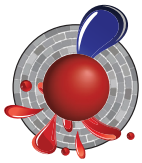
This project was completed in 2020.

Published outputs for 2021

CCFS Publications: #1526, 1599, 1608, 1699, 1700, 1704

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 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.

2021 REPORT

As in 2020, work in 2021 was severely disrupted by COVID-19. This impacted in many ways, including the cancellation of fieldwork in both Greenland and Labrador. The Australian Antarctic Division research project on legacy samples stored with Geoscience Australia commenced in April following a visit to Canberra to collect the samples. Work continued with Monika Kusiak in Poland on Antarctic material collected earlier from GA and resulted in 2 publications.

Work commenced on samples collected in 2019 from Isua and Nuuk in Greenland. However, new research was mainly focussed on ancient rocks in the Ukrainian Shield with Curtin post-doctoral research fellow Dr Leonid Shumlyanskyy. This resulted in 5 publications in 2021.

Lead nanospheres were discovered in Hadean and Eoarchean zircon at Jack Hills, in association with former CCFS Marie Curie fellow Monika Kusiak from Poland and Dr Richard Wirth from Potsdam, Germany. Delays have meant that the results have yet to be published.

A study of gneisses in the southwest Tarim Craton has identified Mesoarchean rocks as old as 3.2 Ga and further work is in progress with former CCFS post-doctoral fellow, Associate Professor Rongfeng Ge from Nanjing University.

The Lu-Hf investigation of ancient zircon crystals from Aker

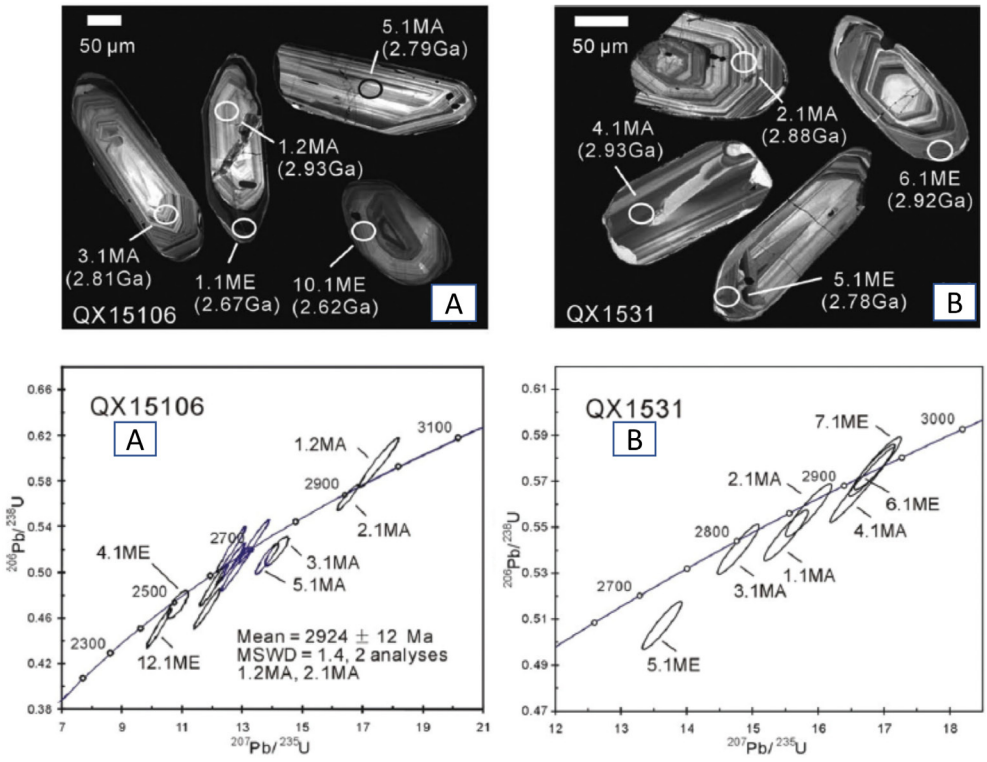


Figure 1: Mesoarchean rocks yielding zircons ages of (A) ~2.9 Ga for trondhjemite and (B) ~2.9 Ga for tonalite from the Qixia area of eastern Shandong in the eastern North China Craton (modified from CCFS Publication 1707, Wan et al., 2021).

Peaks in Kemp Land, Antarctica, has now been published in Gondwana Research. Also in Antarctica, new data from the Scott and Raggatt Mountains in the Napier Complex, collected by Piotr Krol (PhD student of Monika Kusiak), identified TTG gneisses with ages of 2.7 Ga and 2.5 Ga, the latter overlapping with the widespread high-grade metamorphic event. It is postulated that the rocks may have formed in separate domains that did not come together until the 2.5 Ga tectonothermal event. The paper is now accepted for publication in Precambrian Research and will come out early in 2022.

Work commenced with Santanu Bhowmik of the IIT at Kharagpur on a suite of metasedimentary samples from the southern margin of the Central Indian Tectonic Zone to test the age of rocks in the Sausar Basin, and on samples from greenstone belts in the Western Dharwar Craton.

Long-time collaboration with the Chinese Academy of Geological Sciences, especially the Beijing SHRIMP Center, continued in the North China Craton with Profs Dunyi Liu and Yusheng Wan and their colleagues, leading to 2 publications in the year (Fig. 1). It also included a geological investigation of the 2022 Winter Olympic sites that will be published in early 2022 in time for the opening of the games.

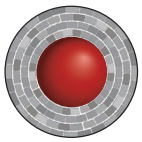
Lunar work in 2021 included modelling conditions in the lunar magma ocean and the effect of large impact cratering during its consolation (2 papers published). The outcome of the latter study suggested that if a low viscosity layer was present between the crust and mantle during early Lunar history, it would result in impact basins of variable size and nature that would be difficult to identify. Thus, any basins formed early in the history of the Moon might go undetected, obscuring a potentially higher impact flux that has been postulated by several workers. The stand-out research was on the lunar samples collected in December 2020 by the Chinese Chang'e-5 lunar mission. Alex Nemchin and members of the Beijing SHRIMP Center and others investigated the age and composition of lunar basalts from the Oceanus Procellarem region. These are young basalts with an age of 1963±57 Ma. Geochemical modelling indicates a lack of heat-producing elements in the deep mantle where these basalts were generated, meaning that it is unclear what process was involved in their generation. However, the new date provides an important step in correlating magmatic activity with the cratering record of the Moon; previously unconstrained between 3 and 1 billion years ago.

Published outputs for 2021

CCFS Publications: #1705, 1706, 1707, 1708, 1709, 1710, 1711, 1712, 1713, 1714, 1715, 1716, 1717, 1718, 1719, 1720, 1721

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.

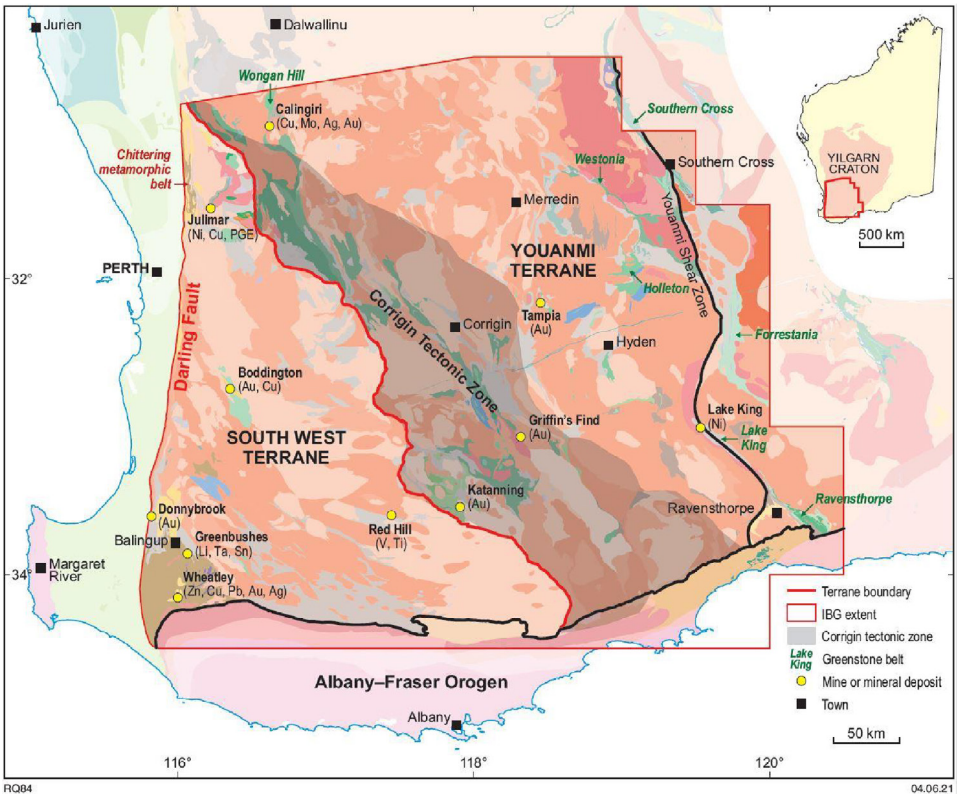
2021 REPORT

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) reprioritized its 2020–21 work program and embarked on the Accelerated Geoscience Program (AGP). The focus shifted from field-work intensive acquisition of new data to delivering new state-wide interpretive datasets as well as products for in key regions of the State to accelerate understanding of the region's geology and mineral prospectivity. State-wide data products released in 2021 as a result of the AGP include major crustal boundaries (2D and 3D), critical minerals and Nd, Hf and O isotope maps. Regional products include the Southwest and Far-Eastern Yilgarn Craton, for which a large number of new digital layer and related data have been released.

One of the most significant outputs has been a new interpreted bedrock geology map out the south-western part of the Yilgarn Craton, including a modification of terrane boundaries (Fig. 1). All AGP data products are described in an extended abstract volume (Accelerated Geoscience Program extended abstracts, GSWA Record 2021/4) that can be obtained through GSWA's eBookshop (https://dmpbookshop.eruditetechnologies.com.au/product/accelerated-geoscience-program-extended-abstracts-2021.do). Further activities related to the Yilgarn Craton were the publication of a journal article on seismic hazard and reactivation (*CCFS publication #1661)* and a presentation of a digital poster by Gessner et al. on the Yilgarn's cryptic basement structures at the 2021 Australian Earth Science Convention.

Published outputs for 2021

CCFS Publications: #1661, 1672, 1673, 1682

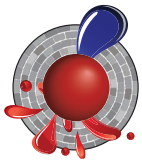


Simplified pre-Mesozoic interpreted bedrock geology of the southwest Yilgarn Craton. The thick red line shows the location of the redefined terrane boundary between the Youanmi and South West Terranes, the yellow dots show the location of mines and mineral deposits.

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.



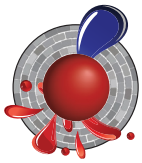
AIMS

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"

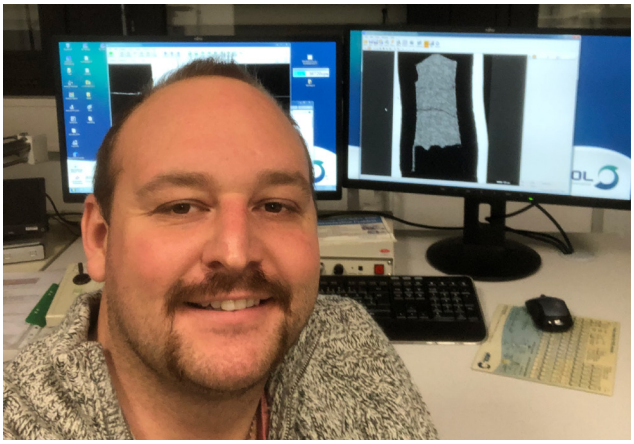
CCFS postgraduates

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 2012-2020. 20 papers with CCFS postgraduates as authors were published in high-profile international journals in 2021 including *Nature Communications, GSA Bulletin, Astrobiology, Lithos, Geopysical Research letters, Journal of Metamorphic Geology, Journal of Petrology* and *Journal of Geophysical Research*. 14 presentations were also given at international conferences (see *Appendix 4*).

2021 HIGHLIGHTS

Anthony Lanati was the Geological Society of Australia Victoria Division PhD Award. *Pictured below.*



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)

Jason Bennett (PhD): On the geochemistry of cassiterite (UWA 2021)

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)

Vili Boykova Grigorova (PhD): Development of an apparatus for the study of liquids and melts up to megabar pressures (MQ 2021)

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)

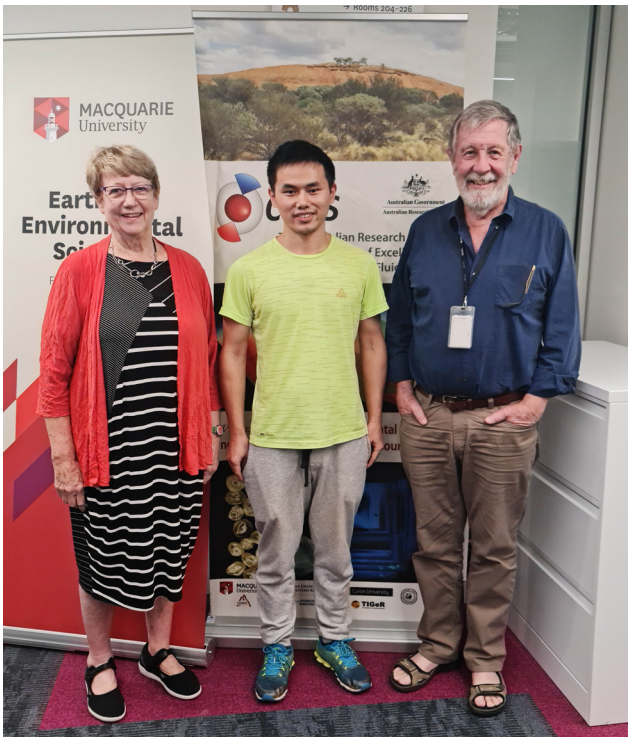
Bruno Colas (PhD): Structural constraints on the crystallisation of Amorphous Calcium Carbonate (MQ 2017)

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)

Hongkun Dai (PhD): Nature and evolution of the northwest North China Craton (MQ 2021) *Pictured below with Sue O'Reilly and Bill Griffin.*



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)

Benedikt Demmert (PhD): Modelling the effect of minority components in biominerals via biomimetic mineralisation (MQ 2021)

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)

Hindol Ghatak (PhD): Deformation-assisted melt migration and melt-rock interaction during the intracontinental Alice Springs Orogeny, central Australia (MQ 2021)

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)

Stephanie Greene (PhD): Evolution of the lithospheric mantle sampled by the Jericho kimberlite, northern Slave craton, Canada (MQ 2021)

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)

Gonzalo Henriquez (PhD): Improving zircon morphology and chemistry as a tool for assessing and ranking the prospectivity for Cu porphyry deposits in greenfield terranes (UWA 2021)

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)

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 (MQ 2021)

Constanza Jara Barra (PhD): Gold pathways: in the El Indio Belt, Chile-Argentina (UWA 2021)

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)

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 2021)

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)

Jiangyu Li (PhD): Thermal history of Proterozoic NE Australia: Insights into Nuna assembly and breakup (CU 2021)

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)

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)

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)

Jonathan Munnikhuis (PhD): Microchemical and microstructural evolution of fluid and melt transfer in deep crustal shear zones (MQ 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)

Thusitha Nimalsiri (PhD): Gravity and magnetic response of the Marulan Supersuite, focusing around the Yerranderie Area (MQ 2019)

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

Brendan Nomchong (PhD): Depositional and diagenetic environment of a c. 2.4 Ga microbialite reef complex from the Turee Creek Group, Western Australia (UNSW 2021)

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)

Sinan Özaydin (PhD): Measuring the mantle hydrogen content of cratons by implementing the magnetotelluric method (MQ 2021)

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)

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

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)

Greg Poole (PhD): Permian magmatism in an early Andean metallogenic belt, Cordillera Frontal, Argentina (UWA 2021)

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)

Farshad Salajegheh (PhD): 3D multivariable probabilistic inversion for thermochemical structure of Earth (MQ 2020)

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)

Georgia Soares (PhD): The rise of complexity: Macroscopic Branching Organic Siliceous Structures from the c. 2.4 Ga Turee Creek Group, Western Australia (UNSW 2021)

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)

Dennis Sugiono (PhD): Sulfur isotope application on the Kanowna Belle Deposit (UWA 2021)

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)

Marina Veter (PhD): Calibration of geochemical *"scouts"* for mantle processes (MQ 2021)

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 (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)

Anqi Zhang (PhD): Joint inversion of multiple geophysical data sets to constrain the evolution of the lithosphere beneath the Junggar and Tianshan, NW China (MQ 2021)

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

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

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)

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)

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

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

Anthony Lanati (PhD): Petrology, geochemistry and orgin of the shoshonites; *RTP, DAAD Cotutelle* (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, submitted 2021)

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

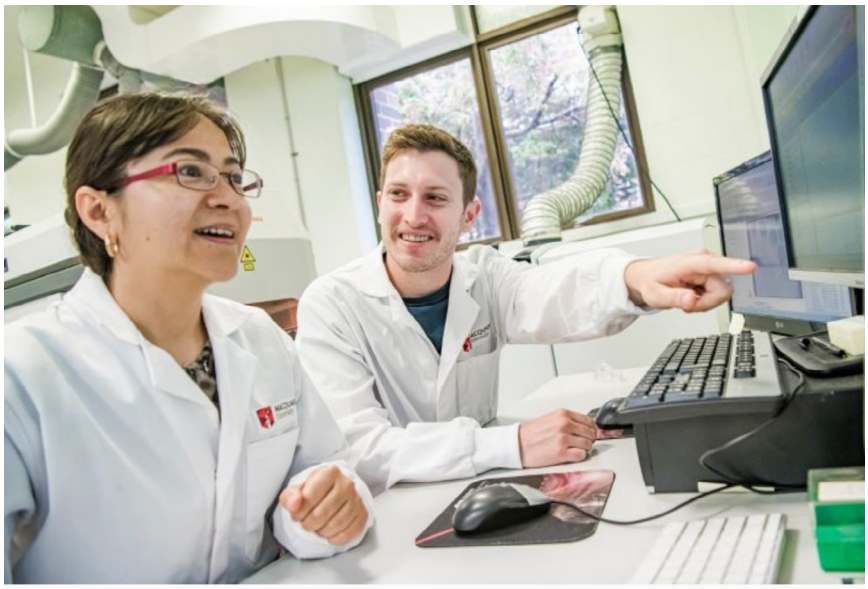
Chutian Shu (PhD): The role of hydrous pyroxenite in producing primary and intermediate arc magmas; *CTIMRTPS* (MQ, commenced 2019)

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)

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 geochemical signatures of complex life forms from the GoE of Australia; *RTP* (UNSW, submitted 2021)

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)



Ananuer Halimulati and Liam Ramage at the wheel of the ICPMS (photo Morris McLennan)

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 (MQGA) 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)
- a JEOL benchtop Scanning electron microscope
- a Nanomin FEI Field Emission SEM
- a Micro XRF M4 Tornado from Bruecker
- three Agilent quadrupole ICPMS (industry collaboration; one 7500cs; two 7700cx)
- a triple quad (Q3) ICPMS 8900
- a Nu Plasma multi-collector ICPMS
- 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 Iridia Excimer laser ablation system
- a Photon Machines Analyte198 Femtosecond laser ablation system
- a Thermo Fisher Neptune Plus MC-ICPMS
- a PANalytical Axios 1kW XRF with rocker-furnace sample preparation equipment
- a Vario El Cube CHNS elemental analyser
- an 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
- a MP-AES (Microwave Plasma Mass Spectrometer)
- a 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 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 renovated 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 and in frequent use. There is also a Griggs deformation apparatus, a one-atmosphere quench apparatus and a diamond-anvil cell apparatus.

Current projects are continuing the investigation of the melting curves and melt compositions produced from peridotites with mixed volatile components, and now emphasizing investigation of the partial melts of pyroxenites containing hydrous phases such as amphiboles and micas. The melting of these and sedimentary rocks, including limestones, is being investigated in combination with reaction experiments that juxtapose hydrous pyroxenites and 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.

Michael Förster and Slava Shcheka (Lab manager) running a high-pressure experiment on the rapid-quench piston-cylinder apparatus (photo Morris McLennan)

PROGRESS IN 2021:

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. The Selfrag is currently being refurbished and will be fully operational in mid 2022.

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 p. 35*)

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. Last year the PANalytical was refurbished to maintain high accuracy and precision. This refurbishment was a success and the XRF is working at full capacity. Recent round-robin tests (GeoPT) show that the PANalytica Axios is performing very well (top 10%).

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) and is being submitted to Geostandard and Geoanalytical Research. 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).

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. 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. pyroxenes) 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 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. The raman system is being upgraded (MQSIS funding) with a supplementary laser (780 nm) to suit the research needs of our colleagues from physic as we developed new application in material science.

2020-21 research and applications of Raman Spectrometry included:

- 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
- Earth and Planetary Science, characterisation of serpentinite (Dr Oliver Alard and Jo-Hannah Aestre)
- 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 (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 (*pictured p. 36*), 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

Montgarri Castillo-Oliver using the Zeiss EVO SEM.

diamond) and crystallographic information on how specific elements are incorporated in the mineral crystal lattices (e.g. Mn in aragonite). A new, larger detector (170x170 mm) has been acquired to provide better image quality/resolution and lower detection limit and is now being fitted to the instruments. The instrumentation has acquired a large (and still growing) group of users and has been instrumental for new projects in biomineralisation (Laura Otter/Prof Dorrit Jacob), diamond growth (Prof Dorrit Jacob) and zircon characterisation (Dr Christoph Lenz/Dr Elena Belousova) and is heavily subscribed by the experimental petrologists (e.g. Prof S. Foley, Dr I. Ezad) and *Terranechron®* users and projects.

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 was appointed to oversee 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). These instruments, 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. However, given their respective ages (≥17 years) repair and downtime have become a problem. Therefore, some of the workload has been transferred to the Nanomin and Zeiss SEM. We are actively working on a replacement strategy with our partners.

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.

The Excite and G2 excimer laser will be extensively refurbished in 2022: the older Excite platform is being replaced by a new Iridia laser which will have a number of interesting innovations allowing more flexibility to address new analytical challenges in material science and biomaterials. This instrument was purchased with a MQSIS grant (O. Alard) and a 10% co-funding from AuScope infrastructure funds. However, this acquisition will have not been possible without the strong technical and financial support of Teledyne with whom we signed a memorandum of understanding for further development works.

The Photon Machines Excite/G2 laser system and Agilent 7700 ICPMS are used for *in situ* trace element analyses and U-Pb geochronology. A flexibly 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.

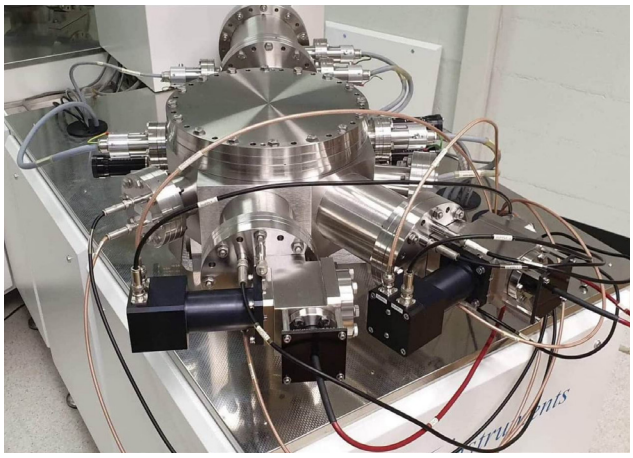
Yi-Jen Lai and collaborators have launched an initiative aiming to develop LA-ICPMS trace-element imaging. These techniques have been applied to biological samples (e.g. skin) and archaeological samples (e.g. cattle teeth). The enhanced collaboration with Teledyne – PhotonMachine has enabled the recent installation of an Aerosol Rapid Introduction System (ARIS) 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-bearing 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 valuable geochronological data for low-temperature events (e.g. mid–low-T, metamorphic, hydrothermal events) and rock types (mafic, ultramafic, metasomatic) that lack zircons.

MQGA had remarkable results (Top 2) in the international proficiency testing programme devoted to U-Pb dating (G-Chron).

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; Jo-Hannah Aestre (HDR) and Olivier Alard).

The 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 now published (Gorojovsky and Alard, 2020, JAAS (*CCFS publication #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. Through multiple national and international collaborations, Dr O. Alard is developing dating and fingerprinting of melt/fluid percolation reaction during metamorphic, deformation and ore forming processes. The team led by Olivier Alard is also working on other developments for the precise (interference-free) measurement of chalcophile and siderophile elements for precise S-Se and Te analyses by LA-ICPMS in submarine glasses.



Daly detectors on the Nu Plasma II MC-ICPMS.

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).

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.

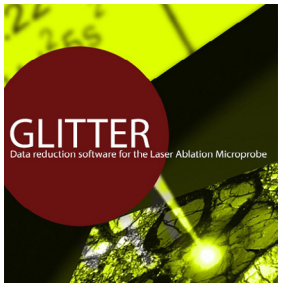
MC-ICPMS: A Nu Plasma II MC-ICPMS was installed in June 2015 and followed the decommissioning of the Nu Plasma 005 after 16 years of service. Although the Nu Plasma II represents a significant advance in its electronics and engineering, much of the fundamental design is adapted from the Nu Plasma I. 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 in 2021 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.43)*.

An UPS and new Daly detectors (*pictured p. 37*) 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. International collaborations focussing on *in situ* Re-Os, with both Germany (Prof A. Holzeid, Prof B. Zoheir, supported by a DFG grant) and Japan (Dr N Akizawa) are underway. As the COVID restrictions ease, Dr Norikatsu Akisawa, will visit the MQGA in 2022 (Jun-Dec), to establish further cooperation program and work on the evolution of the Pacific mantle. Prof B. Zoheir will arive soon after.

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 GEMOC as well as customer service and technical backup. During 2021 a further 6 licences of GLITTER were sold, bringing the total number in use to more than 330 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 2021 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 2022. 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) has implemented a national geoscience database, AusGeochem (https://www.auscope.org.au/ausgeochem), capturing legacy and real-time geochemical datasets aligned with FAIR (Findable, Accessible, Interoperable and Reusable) principles. The database alows users to easily visualise, analyse and extract georeferenced data produced by Australian geochemistry laboratories

The platform was officially launched at the AuScope Research Conference, 12-13 October 2021 (https://www.youtube.com/watch?v=OfVtpogGUF4).

Guillaume Florin and Yoann Gréau continued to develop data templates for data masks specific to *in situ* U-Pb and Lu-Hf in zircon analysed by LA-(MC)-ICP-MS. 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 AGN has an ongoing webinar series, Webinar 3 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

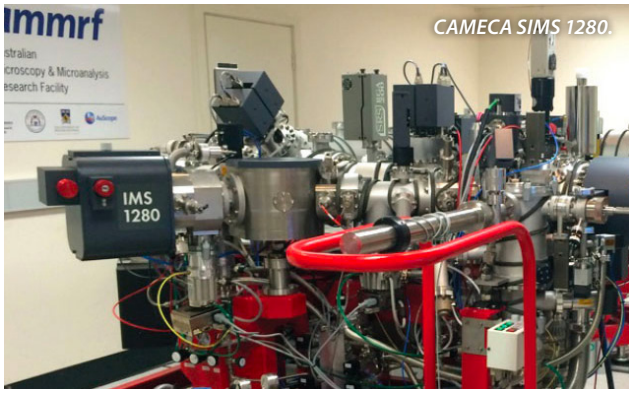
The University of Western Australia's Centre for Microscopy, Characterisation and Analysis (CMCA) is a $50M core facility providing analytical solutions across a diverse array of scientific research. The world-class facilities and associated technical and academic expertise are the focus of micro-analytical 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.



CAMECA SIMS 1280.

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.

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 2021:

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 visit 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. At the end of 2021, the JdLC hosts $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.

In 2021 the JdLC comissioned a state-of-the-art IONTOF M6 ToF-SIMS - https://jdlc.curtin.edu.au/facilities/tof-sims-facility/

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

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.

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).

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.

Inside the Shielded Room

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:

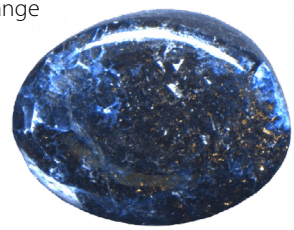
- direct funding of research programs
- industry subscriptions (CET)
- '*in kind*' funding including field support (Australia and overseas), access to proprietary databases, sample collections, digital datasets and support for GIS platforms
- logistical support for fieldwork for postgraduate projects
- 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 2021

- The CCFS' formal collaboration with Shefa Yamim (A.T.M.) Ltd. (Akko, Israel) ended in 2021 with the resignation of Vered Toledo as COO, but the project continued with the material already provided by the company. 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. During 2021 we were joined by Chi Ma (Caltech), an expert in micromineralogy,

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/***

who has since found a whole range of new minerals in the Carmel Sapphire; four are awaiting approval by the International Mineralogical Association, who have adopted the Carmel Sapphire (*pictured*), the host of these new minerals, as their signature gemstone for their 2022 program of activities.



- The popular annual event, GSWA Open Day 2021, was held on Friday, 12th November at the Hyall Regency Hotel, Perth. 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 2021. 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.
- *TerraneChron*® studies (*see p. 43* and http://www.gemoc.mq.edu.au/TerraneChron.html) have enjoyed continued uptake by a significant segment of the global mineral exploration industry. This methodology, currently unique to CCFS/GEMOC, requires the integration of data from three instruments (electron microprobe, LAM-ICPMS and LAM-MC-ICPMS) and delivers fast, cost-effective information on the tectonic history of regional terranes (http://www.gemoc.mq.edu.au/TerraneChron.html). The unique, extensive database (over 32,000 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry.
- In 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 2021.

  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.
- 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.
- In 2021, 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.
- The multi-sponsored MRIWA project (M 530 Yilgarn 2020) has continued in 2021. 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 on the Nova-Bollinger Nickel Deposit, in the Albany-Fraser Belt of Western Australia.
- Industry face-to-face interaction to discuss our research and technology development was hampered during 2021 by the continuing COVID pandemic. Despite these difficulties, collaboration continued remotely via video conferencing and webinars.
- 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 2021 (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.

Evolution of Proterozoic multistage rift basins – key to mineral systems	***Linkage Project (LP190100146)*** ***Industry Collaborators: CSIRO, BHP GROUP LIMITED, IGO LIMITED, Geological Survey of Western Australia, Anglo American, Minerals Research Institute of Western Australia*** ***CIs: Jessell, Gorczyk, Cruden, Rey, Lindsay, Betts, Salles, Aitken, Kee, Lang, Denyszyn, Gessner, Schmid, Occhipinti, Cameron, McCuaig, McCracken, Subramanya*** ***Summary:*** This project will deliver a new quantitative and integrated exploratory framework for the mineral industry in Australia's frontier sedimentary basins by integrating the latest advances in laboratory experimental tectonics with thermo-mechanical numerical, surface process and geophysical modelling. The project will use northern Australian basins as a natural laboratory to address the fundamental processes involved in the development of sedimentary ore systems. The project will investigate how they can be detected by modern exploration techniques using a multidisciplinary approach with a team of experts with backgrounds in mineral and petroleum systems.
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.
Enabling three dimensional stochastic geological modelling	***Linkage Project (LP170100985)*** ***Industry Collaborators: AUSCOPE, British Geological Survey, Department of Planning and Environment, Geological Survey of Canada, Geological Survey of South Australia, GSWA, Geoscience Australia, Northern Territory Geological Survey, Research for Integrative Numerical Geology, Georessources - Université de Lorraine, RWTH Aachen University of Technology, Germany*** ***CIs: Ailleres, Jessell, de Kemp, Caumon, Wellmann, Armit, Droniou, Lindsay, Cui, Betts, Cruden, Kemp, Gessner, Spampinato, Harrison, Kessler*** ***Summary:*** The project aims to develop technologies to mitigate 3D geological risk in resources management. The project is expected to create new knowledge and methods in the field of 3D geological modelling through the innovative application of mathematical methods, structural geology concepts and cutting-edge probabilistic programming. The expected outcomes are an enhanced capability to model the subsurface, characterise model uncertainty and test multiple geological scenarios. This enhanced capability is extremely important for the future of Australia's subsurface management; including urban geology and our continuously growing sustainable resources industry (including water).
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.

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*** ***CIs: 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

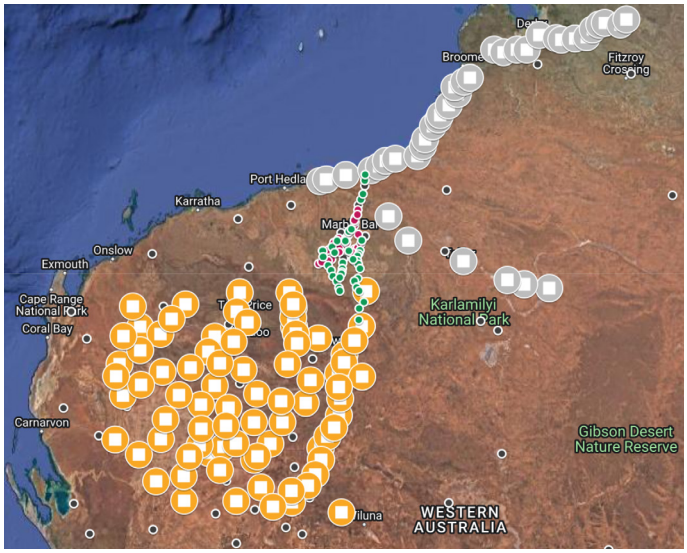
Cotutelle MOU aim to establish deep, continuing relationships with international research universities through joint research candidate supervision. CCFS has agreements with the following international institutions:

- 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 - 2021 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).

  Following the sucessful two phases of seismic deployments in the Canning Basin Western Australia, the collaboration with the IGG-CAS moved to the Pilbara region in 2021. This two-year field deployment (*pictured below*) targets the unique granite domes and greenstone keels in the Archean Pilbara Craton. The new seismic models are expected to shed light onto how early Earth operated in the Vertical Tectonic regime.



Seismic deployments in collaboration with the IGG-CAS. Green dots: 2022 Pilbara project, red dots: 2021 Pilbara project, gold dots: 2014-2018 Capricorn project, silver dots: 2018-2020 Canning project.

CCFS INTERNATIONAL COLLABORATIVE NETWORK

- 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 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.
- 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 includes 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 includes participants from more than 143 countries with diverse socio-economic and political contexts.

  IGCP 662 was a co-sponsor for the very successful Session 7: *"Lithospheric architecture and deep material probing"* at the DEEP 2021 virtual meeting International Symposium on Deep Earth Exploration and Practices held from 26 to 31 October. *(see abstracts p. 61)*

  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 2021. 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 - http://geodynamics.curtin.edu.au/igcp-648-virtual-seminar-series/.

  For more information visit http://geodynamics.curtin.edu.au/igcp-648/
- Simon Wilde has continued as director of the International Precambrian Research Center of China, Chinese Academy of Geological Sciences.
- 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

National benefit

- Scientific innovation relevant to National Priority Areas
  - ***Research Priority 1:*** An Environmentally Sustainable Australia
    - ***Goal 1:*** Water - A Critical Resource
    - ***Goal 2:*** Transforming Existing Industries
    - ***Goal 6:*** Developing Deep Earth Resources
  - ***Research Priority 3:*** Frontier Technologies for Building and Transforming Australian Industries
    - ***Goal 1:*** Breakthrough Sciences
    - ***Goal 2:*** Frontier Technologies
- Enhanced international links
- Excellence in training of our future generation of geoscientists
- Enhanced industry links nationally and internationally
- Improved exploration tools and strategies for Australian mineral exploration companies both on- and off-shore
- Technological innovation (scientific advances, intellectual property, commercialisation, value-added consulting services)
- Implementation of significant parts of the UNCOVER initiative set out in: "*Searching the deep earth: a vision for exploration geoscience in Australia*" published by the Australian Academy of Science (2012; https://www.science.org.au/supporting-science/science-sector-analysis/reports-and-publications/searching-deep-earth-vision). CCFS addresses initiatives (ii) - (iii): investigating Australia's lithospheric architecture, 4D geodynamic and metallogenic evolution, and distal footprints of ore deposits.

Appendix 1: 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. 41*.

Experimental and empirical insight into melting of the early Earth's mantle	B. Kamber, G. Yaxley, **N. Daczko**, P. Hayman, S. Piazolo: *Supported by ARC DP (commencing 2022)* ***Summary:*** The early Earth's mantle produced melt at much higher temperature than today, creating rocks with unique chemistries and mineralogies. But pressing knowledge gaps about hot mantle melting remain. The aim of this project is to generate new experimental and empirical knowledge to help closing these gaps by: (i) conducting high pressure experiments to refine phase-composition relationships and element partitioning; (ii) quantifying mineral fabrics in cratonic peridotites to understand the movement of early continents; and (iii) constructing the first petrological deep time model for greenstone belt volcanic rocks. The expected outcomes are better models for the early Earth's melting and tectonic regimes and insight into the emergence of land.
Identifying mineral systems by mapping deep Australia	P. Rey, V. Chatzaras, **S.Y. O'Reilly**, **O. Alard**, **H. Yuan**, **K. Selway**, S. Demouchy, M. Haynes: *Supported by ARC DP (commening 2022)* ***Summary:*** This Project aims to enable 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.
The link between cratonic roots, redox state, and mantle geodynamics	**C. O'Neill**, **S. Hansen**, **S. O'Reilly**, **W. Griffin**, G. Begg: *Supported by ARC DP (commenced 2021)* ***Summary:*** 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.
Unlocking Earth's inner secrets in deep time using palaeointensities	**Z.-X. Li**, A. Biggin: *Supported 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: *Supported 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: *Supported 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.
Magma dynamics and ore deposits	A. Cruden, **M. Fiorentini**, S. Barnes, A. Bunger, C. Jackson: *Supported 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: *Supported 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: *Supported 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 (commenced 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.
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**: *Supported by ARC LIEF (commenced 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: *Supported 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**: *Supported 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.

Determining the extent and nature of the oldest crust in Antarctica	**S. Wilde**, **A. Nemchin**, M. Whitehouse, S. Harley, **M. Kusiak**, D. Dunkley: *Supported 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.
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)
- Emeritus Professor William Griffin (MQ)
- Associate Professor Matthew Kilburn (CMCA, UWA)
- Professor Zheng-Xiang Li (CU)
- Associate Professor Alexander Nemchin (CU)
- Associate Professor Craig O'Neill (MQ)
- Professor Martin Van Kranendonk (UNSW)
- Associate Professor Yingjie Yang (MQ)

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- Associate Professor Nathan Daczko (MQ)
- Dr Richard Glen (Adjunct Professor)
- Dr Masahiko Honda (ANU)
- Professor Dorrit Jacob (ANU)
- Associate Professor Mary-Alix Kaczmarek (University Paul Sabatier Toulouse III)
- Associate Professor Christopher Kirkland (CU)
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- Dr Louis-Noel Moresi (UM)
- Professor Steven Reddy (CU)
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- 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)
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- Dr Isra Ezad (MQ)
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- Dr Guillaume Florin (MQ)
- Dr Michael Förster (MQ)
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- Dr Yoann Gréau (MQ)
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Dr Oded Navon
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Ms Ananuer Halimulati (MQ)
Mr Anthony Lanati (MQ)
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Mr Matthew Rowe (UWA)
Mr Joshua Shea (MQ)
Mr Chutian Shu (MQ)
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Ms Bronwyn Teece (UNSW)
Ms Anne Vernes (UWA)

Appendix 3: 2021 Publications

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

1375. **Foley, S.F.** 2021. Redox melting in the mantle. *R. Moretii and D Neuville (eds). Magma Redox Geochemistry. AGU Geophysical Monograph Series, Washington, USA, Part 1, Ch 5.*

1382. **Djokic, T.**, **Van Kranendonk, M.J.**, Campbell, K.A., Havig, J., Walter, M.R., and Guidoa, D. M. 2021. A reconstructed subaerial hot spring field in the ~3.5 billion-year-old Dresser Formation, North Pole Dome, Pilbara Craton, Western Australia. *Astrobiology, 21, 1-38.*

1486. **Van Kranendonk, M.J.**, **Baumgartner, R.**, **Djokic, T.**, Ota, T., **Steller, L.**, Garbe, U. and Nakamura, E. 2021. Elements for the origin of life on land: a Deep-time perspective from the Pilbara Craton of Western Australia. *Astrobiology, 21, 39-59.*

1491. Wu, C., **Lu, Y.**, and Chen, H. 2021. Crustal structure control on porphyry copper systems in accretionary orogen: Insights from Nd isotopic mapping in Central Asian Orogenic Belt. *Mineralium Deposita, https://doi.org/10.1007/s00126-021-01074-z.*

1519. **Etheridge, M.A.**, **Daczko, N.R.**, Chapman, T. and **Stuart, C.A.** 2021. Mechanisms of Melt Extraction during Lower Crustal Partial Melting. *Journal of Metamorphic Geology, 39, 57-75.*

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1725. **Caruso, S.**, **Van Kranendonk, M.J.**, **Baumgartner, R.J.**, **Fiorentini, M.L.** and Forster, M.A. 2021. The role of magmatic fluids in the ~3.48 Ga Dresser Caldera, Pilbara Craton: New insights from the geochemical investigation of hydrothermal alteration. *Precambrian Research, 362, 106299.*

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1727. Nutman, A.P., Bennet, V.C., Friend, C.R.L., Polat, A., Hoffmann, E. and **Van Kranendonk, M.J.** 2021. Fifty years of the Eoarchean and the case for evolving uniformitarianism. *Precambrian Research , 367, 106442.*

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1730. Sriaporn, C., Campbell, K.A., **Van Kranendonk, M.J.**and Handley, K.M. 2021. Genomic adaptations enabling Acidithiobacillus distribution across wide-ranging hot spring temperatures and pHs. *Microbiome, 9, 135.*

1731. **Van Kranendonk, M.J.**, **Djokic, T.**, **Baumgartner, R.**, Bontognali, T., Sugitani, K., Kiyokawa, S. and Walter, M.R. 2021. Life analogue sites for Mars from early Earth: Diverse habitats from the Pilbara Craton and Mount Bruce Supergroup, Western Australia. *In: R.J. Soare, S.J. Conway, D.Z. Oehler, and J.-P. Williams (eds), Mars Geological Enigmas: From the Late Noachian Epoch to the Present Day, pp. 357-403, Elsevier Inc. USA, 554p..*

1732. Nutman, A.P., Bennett, V.C. Friend, C.R.L. and **Van Kranendonk, M.J.** 2021. In support of rare relict ~3700 Ma stromatolites from Isua (Greenland). *Earth and Planetary Science Letters, 562, 116850.*

Appendix 4: 2021 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: CORE TO COSMOS', 9-12 FEBRUARY 2021	The AuScope Geochemistry Network and AusGeochem H. Dalton, A. Prent, S. Boone, **G. Florin**, **Y. Greau**, B. McInnes, A. Gleadow, **S.Y. O'Reilly**, B. Kohn, E. Matchan, **O. Alard**, T. Rawling, F. Kohlmann, M. Theile and W. Noble Mantle refertilization from 3.2 billion years ago points to an early start of plate tectonics **H. Gamal EL Dien**, L.-S. Doucet, J.B. Murphy and **Z.-X. Li** Chasing lower crustal tectonic domains in the Yilgarn Craton. **K. Gessner**, R.H. Smithies and Y. Lu Composition and evolution of the southern African lithosphere from combined xenocryst and magnetotelluric data **S. Özaydin** and **K. Selway** Lithospheric-scale magnetotellurics over the Eastern Goldfields Superterrane, Yilgarn Craton **K. Selway**, M. Dentith and **K. Gessner** Assembly of proto-Australia prior to the formation of the Nuna supercontinent in the Paleoproterozoic **U. Kirscher**, **R. Mitchell**, **Y. Liu**, **A. Nordsvan**, L. Wu, **S. Pisarevsky** and **Z.X. Li** Structural evolution of a 1.6 Ga orogeny related to the final assembly of the supercontinent Nuna: coupling of episodic and progressive deformation **S. Volante**, W.J. Collins, **A. Pourteau**, **Z.-X. Li**, J. Li and **A. Nordsvan** Keynote
EGU GENERAL ASSEMBLY 2021: GATHER ONLINE 19-30 APRIL 2021	Thermochemical structure of the lithosphere and upper mantle beneath Superior craton: Results from multi-observable probabilistic inversion R. Dave, F.A. Darbyshire, **J.C. Afonso** and K. Ali Porosity evolution within the active Alpine Fault zone, New Zealand. Implications for fault zone rheology M. Kirilova, V. Toy, K.Sauer, F. Renard, **K. Gessner**, R. Wirth, R. and X. Xiao Receiver Function mapping of mantle transition zone discontinuities beneath Western Alps using scaled 3-D velocity corrections D. Liu, L. Zhao, A. Paul, **H. Yuan**, S. Solarino, C. Aubert, T. Dumont, E. Eva, S. Guillot, M.G. Malusà, S. Pondrelli, S. Salimbeni and S. Schwartz The AuScope Geochemistry Network and the AusGeochem geochemistry data platform B. McInnes, A. Gleadow, **S. O'Reilly**, S. Boone, B. Kohn, E. Matchan and T. Rawling Managing Geochemical Data from Field to Lab to Publication to Archive A. Prent, H. Dalton, S. Boone, **G. Florin**, **Y. Greau**, B. McInnes, A. Gleadow, **S.Y. O'Reilly**, B. Kohn, E. Matchan, **O. Alard**, T. Rawling, F. Kohlmann, M. Theile and W. Noble Basaltic mantle reservoirs from seismic inversion of reflection data B. Tauzin, L. Waszek, J. Yan, M. Ballmer, N. Schmerr, **J.C. Afonso** and T. Bodin A combined Reduced Order-Bayesian scheme to drastically accelerate stochastic inversions S. Zlotnik, O. Ortega, P. Díez, and **J.C. Afonso**

GOLDSCHMIDT VIRTUAL 2021, ONLINE, 4-9 JULY 2021	Calcium isotope compositions and fractionation in the mantle and oceanic crust **C. Chen**, **S.F. Foley**, Z. Wang and Y. Liu Distribution of fluorine between phlogopite, K-richterite, apatite and lamproitic melt in high-pressure experiments **I.S. Ezad** and **S.F. Foley** A glimpse into the secular change of mantle-derived magmatism at the transition between Neoarchean and Paleoproterozoic **M. Fiorentini**, **S. Caruso** and **A. Giuliani** Keynote Is Fe-Ni alloy in Ordinary Chondrites formed by precursors partial melting? **G. Florin**, **O. Alard**, B. Luais and T. Rushmer Compositions of partial melts of hydrous pyroxenites in the cratonic mantle lithosphere and their implications for alkaline magma sources **S.F. Foley** and **I.S. Ezad** Oxidization of the mantle caused by recycling of sedimentary carbonates may contribute to the formation of iron-rich mantle melts D. He, Y. Liu, **C. Chen**, **S.F. Foley** and M. Ducea Petrology and geochemistry of the eastern Australian leucitites **A.W. Lanati**, **J.J. Shea**, **S.F. Foley**, S. Klemme and J. Berndt A new duo for mineral exploration: apatite and zircon in granitoids from Mt Isa, Australia M. Moxey and **E. Belousova** Photo-induced Force Microscopy (PiFM): A new technique at the (bio)mineralogist's fingertips L.M. Otter, **M.W. Förster**, **E. Belousova**, P. O'Reilly, D. Nowak, S. Clark, **S.F. Foley** and **D.E. Jacob** In situ Rb-Sr dating of glauconite in partially altered Cambrian sedimentary sequences M. Rafiei, S. Löhr, **O. Alard**, J. Farkas, A. Baldermann and G. Brock The mantle source of the eastern Australian leucitites: evidence from whole rock and olivine compositions (and why the olivine compositions do matter **J.J. Shea**, **A.W. Lanati**, **I.S. Ezad**, **S. Özaydin** and **S.F. Foley** Petrological confirmation of lithosphere thermally eroded by asthenospheric flow beneath the NE margin of the Tibetan plateau C. Shu, X. Long, **S.F. Foley** and Y. Kaizhang LA-ICP-MS Signal Enhancement by Hydrogen Gas Addition to Carrier Gasfor the Analysis of Ultra-trace Elements in Olivine and Orthopyroxene **M. Veter**, **O. Alard** and **S.F. Foley**
3RD EUROPEAN MINERALOGICAL CONFERENCE, KRAKOW, POLAND, 29 AUGUST-2 SEPTEMBER 2021	Comparing Eoarchean records of crustal growth in the North Atlantic Craton between the Saglek Block of Labrador, Canada and the Itsaq Gneiss, SW Greenland D.J. Dunkley, **M.A. Kusiak**, M.J. Whitehouse, **S.A. Wilde** and M. Mieszcak Invited Observation and inference in the interpretation of zircon ages obtained from a purported >3.9 Ga gneiss in the Saglek Block, Labrador M.J. Whitehouse, D.J. Dunkley, **M.A. Kusiak**, **S.A. Wilde** and T.T. Keluskar Invited Evaluating radiogenic lead nanoscale inclusions and clusters in zircon **S.A. Wilde**, **M.A. Kusiak**, D.J. Dunkley, M.J. Whitehouse and R. Wirth Invited

AUSCOPE RESEARCH CONFERENCE 2021, 12-13 OCTOBER 2021	AusGeochem Launch: the AuScope Geochemistry Network's laboratory data platform goes live B. McInnes, A. Gleadow, **S. O'Reilly**, B. Kohn, D. Phillips, **O. Alard**, **S.-A. Hodgekiss**, A. Prent, S. Boone, E. Matchan, H. Dalton, **Y. Greau**, **G. Florin**, B. Ware, T. Rawling, T. Down, J. Condon, F. Kohlmann, M. Theile and W. Noble AGN-LabFinder, a web application to help you find the right laboratory **G. Florin**, A. Prent, P.Golodoniuc, V. Fazio, Y. Li and the AGN Team
ERESEARCH AUSTRALASIA 2021 CONFERENCE 11-15 OCTOBER 2021	Launching AusGeochem: the AuScope Geochemistry Network's laboratory data platform B. Ware, A. Prent, S. Boone, H. Dalton, **G. Florin**, **Y. Greau**, F. Kohlmann, M. Theile, W. Noble, E. Matchan, B. Kohn, A. Gleadow and B. McInnes
DEEP 2021, VIRTUAL MEETING AND INTERNATIONAL EVERYWHERE, 1-2 NOVEMBER 2021	Probing the physical state of the Earth's interior with thermochemical tomography **J.C. Afonso**, **W.L. Griffin**, **S.Y. O'Reilly**, W. Ben-mansour, **F. Salajeghegh**, I. Fomon, **S. Foley**, G. Begg, **K. Selway**. A Macdonald and A. Nyblade Keynote Mantle Lithosphere architecture through the sulfide and olivine lenses **O. Alard**, **Y. Greau**, **M. Veter** and **S. Foley** Keynote The architecture and evolution of continental lithosphere: Outcomes from multi-disciplinary mapping **G.C. Begg**, **W.L. Griffin** and **S.Y. O'Reilly** Plenary Deep lithosphere of the North China Craton archives the fate of the Paleo-Asian Ocean **H.-K. Dai**, J.-P. Zheng, Q. Xiong, **S.Y. O'Reilly** and **W.L. Griffin** Continental breakup-driven mantle growth: insights from the circum-Ordos mantle underneath the northern North China Craton **H.-K. Dai**, Q. Xiong, Y. Xu, J.-P. Zheng, **W.L. Griffin**, J. Liu and **S.Y. O'Reilly** Tracking upper mantle heterogeneities using seismic anisotropy: the case of pyroxenite-rich domains **H. Henry**, **S.Y. O'Reilly**, **W.L. Griffin** and G. Begg The evolution and power of 4D lithospheric mapping **S.Y. O'Reilly** and **W.L. Griffin** Plenary Geodynamic and Geophysical consequences of stealth(y) mantle metasomatism: Craton evoluion and fluid pathways **S.Y. O'Reilly**, **W.L. Griffin**, N.J. Pearson and collaborators Keynote When the mantle hides its (magmatic) sources: disequilibium, volatiles and other tricks affecting lithosphere composition **R. Tilhac** and **B. Oliveira** Mantle dunitic melt plumbing system under oceanic slow-ultraslow spreading centres: Tibetan ophiolitic evidence Q. Xiong, J.-P. Zheng, L. Wang, L.-R. Tian, X. Zhou, Z.-Y. Li, **S.Y. O'Reilly** and **W.L. Griffin** Cenezoic lithosphere architecture and metallogenesis in Southeastern Tibet B. Xu. Z.-Q. Hou, **W.L. Griffin** and **S.Y. O'Reilly**
AGU FALL MEETING NEW ORLEANS, LA AND ONLINE EVERYWHERE, 13-17 DECEMBER 2021	Seismic imaging of layered crust in the Pilbara Craton: A challenge for Paleoarchean crustal overturn **K. Gessner**, A.J. Calvert, M.P. Doublier, L. Brisbout, **H. Yuan** and R.E. Murdie Inference of the 3D lithosphere and upper mantle structure beneath Greenland and Eastern Canada using a joint inversion of regional datasets P. Ajourlou, **F. Salajegheh**, G.A. Milne, **J.C. Afonso**, A. Schaeffer, P. Audet, C. Civiero and S. Lebedev

AGU FALL MEETING NEW ORLEANS, LA AND ONLINE EVERYWHERE, 13-17 DECEMBER 2021
cont...

Continental orogens and role in lithosphere evolution–Examples from the South China Block
T. Li, M. Jiang, L. Zhao, W. Yao, L. Chen, Y. Chu, B. Sun, Y. Ai, B. Wan and **H. Yuan**

Development of William's Ridge (Kerguelen Plateau) and Broken Ridge: Tectonics, hotspot magmatism, microcontinents, and Australia's extended continental shelf
M.F. Coffin, J.M. Whittaker, **N.R. Daczko**, J. Halpin, G. Bernardel, K. Picard, R. Gardner, D. Gurer, S. Brune, S.A. Gibson, K. Hoernle, A. Koppers, M. Storey, G. Uenzelmann-Neben, L. Magri, D.J. Neuharth, S.H. Christiansen and L. Easton

Preliminary earthquake catalogue for an ongoing temporary seismic network in SW Australia derived using machine-learning phase picker and an automated workflow
R.C. Pickle, M.S. Miller, R. Murdie, T. Allen, **H. Yuan**, **K. Gessner** and B.L.N. Kennett

Greenland's lithospheric structure based on integrated modelling with multiple geophysical datasets
A. Wansing, J. Ebbing, M. Moorkamp, B.H. Heincke and **J.C. Afonso**

Zircons as tracers for ignimbrite flare-ups in the Central Andes: Sources and processes of magma generation
G. Worner, **E.A. Belousova**, S. Turner, **J. Keeman**, A.K. Schmitt, A. Gerdes and S.L. de Silva

Appendix 5: Research funding

GRANTS AND OTHER INCOME FOR 2021

Investigators	Funding Source	Project Title	Amount
Kamber, Yaxley, Daczko, Hayman, Piazolo	ARC Discovery Project (DP220100709)	Experimental and empirical insight into melting of the early Earth's mantle	$417,427
Rey, Chatzaras, O'Reilly, Alard, Yuan, Selway, Demouchy, Haynes	ARC Discovery Project (DP220100136)	Identifying mineral systems by mapping deep Australia	$492,445
O'Neill, Hansen, O'Reilly, Griffin, Begg	ARC Discovery Project (DP210102196)	The link between cratonic roots, redox state, and mantle geodynamics	$386,072
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	$234,364
Kemp, Wilde, Van Kranendonk, Elliot	ARC Discovery Project (DP200103298)	Testing continental growth models with calcium and strontium isotopes	$412,246
Yang, Afonso, Rawling, Ritzwoller, Niu	ARC Discovery Project (DP190102940)	Unveiling the fine structure of the Australian continent using ocean waves	$389,709
Cruden, Fiorentini, Barnes, Bunger, Jackson	ARC Discovery Project (DP190102422)	Magma dynamics and ore deposits	$315,809
Van Kranendonk, Fiorentini, Campbell, Deamer	ARC Discovery Project (DP180103204)	A terrestrial hot spring setting for the origin of life?	$620,621
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	$3,157,394
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
Danisik, Evans, McInnes, Kirkland, Li, Fiorentini, Wingate	ARC LIEF (LE190100079)	The Western Australia ThermoChronology Hub	$365,380
Jessell, Gorczyk, Cruden, Rey, Lindsay, Betts, Salles, Aitken, Kee, Lang, Denyszyn, Gessner, Schmid, Occhipinti, Cameron, McCuaig, McCracken, Subramanya	ARC Linkage Project (LP190100146)	Evolution of Proterozoic multistage rift basins – key to mineral systems	$1,102,662
Miller, Kennett, Yuan, Allen, Greay, Gessner, Murdie	ARC Linkage Project (LP180101118)	Enhanced 3-D seismic structure for Southwest Australia	$468,364

Investigators	Funding Source	Project Title	Amount
Ailleres, Jessell, Armit, Droniou, Lindsay, Cui, Betts, Cruden, de Kemp, Caumon, Wellmann, Kemp, Gessner, Spampinato, Harrison, Kessler	ARC Linkage Project (LP170100985)	Enabling 3D stochastic geological modelling	$752,912
Regenauer-Lieb, Afonso, Clark, Thiel, Czarnota, Poulet, Jones, Walsh	ARC Linkage Project (LP170100233)	Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP)	$699,066
Fiorentini, Bennett, Gorczyk	BHP Billiton	Craton margin exploration targeting: 4D perspective	$329,000
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
George, Fiorentini, Parra Avila	Auldana	Tectonic evolution and amalgamation of continental, arc and arc-related terranes of Northern Thailand	€ 24,000
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	$321,181
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
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	$59,000
Lanati	Deutscher Akademischer Austauschdienst Study	Completion grant	~€ 10,000
Lanati	Geological Society of Australia	Victoria Division Post-Graduate Research award	$5,000
Lanati	Deutscher Akademischer Austauschdienst	DAAD, German Academic Exchange Service) Cotutelle Scholarship	€ 80,000

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Australian Government
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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
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 (Department)
FIM	Facility for Integrated Microanalysis
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
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
RTPS	Research Training Program Stipend (formerly APA)
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
TIGeR	The Institute for Geoscience Research
UM	University of Melbourne
UNSW	University of New South Wales
UWA	University of Western Australia

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MACQUARIE University

Curtin University

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