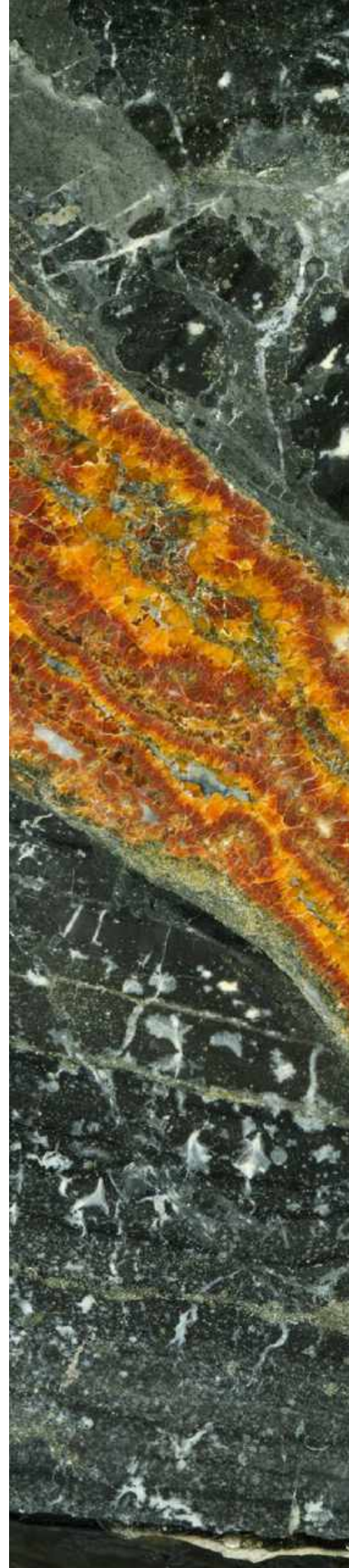




# Contents

|                                                                           |     |
|---------------------------------------------------------------------------|-----|
| Director's report                                                         | 2   |
| Profile and research structure                                            | 8   |
| Staff and management                                                      | 10  |
| <b>Program 1:</b> Ore deposits and mineral exploration                    | 16  |
| <b>Program 2:</b> Geometallurgy, geoenvironment and mining                | 24  |
| <b>Program 3:</b> Sedimentation, tectonics and Earth evolution            | 30  |
| <b>Program 4:</b> Magmatic and volcanic processes                         | 36  |
| <b>Program 5:</b> Analytical research                                     | 56  |
| <b>Program 6:</b> Geophysics and computational geosciences                | 62  |
| <b>TMVC:</b> The ARC Research Hub for Transforming the Mining Value Chain | 70  |
| Training and education                                                    | 86  |
| Outreach                                                                  | 100 |
| Industry links                                                            | 106 |
| Technology transfer                                                       | 108 |
| Performance indicators                                                    | 110 |
| Finances                                                                  | 112 |
| 2019 publications                                                         | 116 |
| Appendices                                                                | 136 |

*FRONT COVER: Senior Lecturer in Earth Sciences Dr Rebecca Carey at the foot of Mount Ngauruhoe in New Zealand pictured while teaching students on a joint UTAS and University of Hawaii 'Volcanic Processes and Products' short course in March 2019. BACK COVER: Master of Economic Geology 'Ores in Magmatic Arcs' field excursion participants in front of a faulted syncline in the Lower Cretaceous sedimentary rocks of the Oyon Formation and overlying Gollar group to the south of the Antamina Cu-Zn skarn, Central Peruvian Andes fold and thrust belt, October 2019. RIGHT: Colloform banded sphalerite – enargite – pyrite vein in pyrophyllite – alunite – dickite-altered feldspathic pyritic carbonaceous volcanoclastic mudstone, Pueblo Viejo high sulfidation epithermal Au-Ag deposit, Dominican Republic.*



# 2019 Director's report

CODES enjoyed another highly productive and successful year in 2019, with new staff and students joining the team, research funding secured for several new projects, and a number of individuals and research teams receiving awards in recognition of their outstanding contributions.

Several of our industry-funded research projects had very productive years of data acquisition and interpretation, with sponsors' research

meetings held in Hobart, Santiago and online. A total of ten PhD students graduated in 2019, with another six new PhD students joining our program. 2019 was only the second time that we have presented four short courses as part of the Master of Economic Geology program, with 'Ores in Magmatic Arcs' run in Indonesia in March and repeated in South America in October.

## Research highlights

Dr Rebecca Carey, Professor David Cooke, Associate Professor Sebastien Meffre and Associate Professor Shaun Barker, together with Professor Ray Cas (Monash University), Dr Kate Bull (Geological Survey of NSW), Professor Julie Rowland (University of Auckland) and Professor Michael Heap (University of Strasbourg), were successful in winning an Australian Research

Council Linkage grant in November 2019 for the project 'Exploration targeting from next-generation volcanic facies reconstruction'. This project is scheduled to commence in 2020 and run until 2022, and will be conducted by postdoctoral research fellow Dr Martin Jutzeler and several graduate students. The grant application was supported by Evolution Mining, the Geological Survey of NSW, Department of State Growth Tasmania and OceanaGold.

CODES/TMVC initiated AMIRA project P1206 'Identifying unique Resistate Indicator Mineral (RIM) chemistry as a guide in prospectivity for sediment-hosted copper mineralisation' in late 2019. This project is led by Associate Professor Shaun Barker in collaboration with Professor Murray Hitzman and Dr Sean Johnson (iCRAG), Dr David Selley

(Base Instinct Consulting and CODES) and Dr Scott Halley (Mineral Mapping). AMIRA International's project P1206, which is focussed on deposits found in the Central African Copper Belt, aims to provide a rapid assessment of how resistate indicator minerals (RIMs) can be used to aid exploration for sediment-hosted copper deposits.

The volcanology team were highly successful in grant applications in 2019. Dr Martin Jutzeler and Dr Rebecca Carey secured a \$20,000 grant from ANZIC, the Australian and New Zealand International Ocean Discovery Program Consortium, to investigate the volcanic architecture and eruption behaviour at Site U1437 Izu-Bonin-Mariana rear-arc, IODP 350.

This 'legacy grant' covers research into existing cores and is for geochemical analyses. Rebecca also won two Australian Antarctic Science Program research grants in November 2019 for projects on 'The re-awakening of a mantle plume – the nature and petrogenesis of Neogene volcanism on the Central Kerguelen Plateau' and 'Seamounts in the Tasman Sea and Southwest Pacific: Deep seated Balleny plume vs. Pacific Superswell'. Martin secured ship-time to conduct three voyages with the Australian research flagship RV *Investigator*. These voyages address the catastrophic 2018 collapse of Anak Krakatau volcano in Indonesia (with co-PI Rebecca Carey), and large-scale shelf collapse offshore Tasmania and eastern Australia. Rebecca was also successful with Sydney colleagues in securing an ARC Discovery grant titled 'Eruption and disruption: How Earth's deep interior and surface communicate'; she will act as CI on this project.

The Lachlan Orogen Linkage project entered its final stages of activity in 2019, with a final sponsors' meeting scheduled for March 2020.

The project aimed to develop predictive and explanatory models to help mineral exploration in southeast Australia, as

well as to provide deeper knowledge of the geology and tectonic evolution of the Lachlan Orogen. The research team, led by Associate Professor Sebastien Meffre, has generated significant new mineral chemistry data sets, and geochronological analyses have led to the discovery of new Cambrian island arc rocks beneath the Ordovician rocks of the Macquarie Arc. Other research highlights include new fertility maps for porphyry deposits in New South Wales and a tectonic model in the G-Plates software allowing reconstruction of ore deposit fertility maps data back in time to their configuration 445 million years ago.

AMIRA project P1202 expanded in 2019 with additional sponsors and students joining the program. The research team held three highly successful sponsors' research meetings in June (Hobart), October (Santiago) and November (Hobart), along with a one-day field excursion for sponsors in Central Chile in October, and several technology transfer workshops in South America and Australia.

In the Australian Research Council Excellence in Research for Australia (ERA) National Report for 2018–19, the

University of Tasmania achieved 5 out of 5 in the geology and geophysics categories, and the highest level rankings across all three fields of the engagement and impact assessment process (impact, approach to impact and engagement). Overall, in the Earth Sciences (04) field of research code, the University of Tasmania was ranked highest out of all Australian universities when considering impact, engagement, quality of research output and number of categories assessed. This result was due to the combined efforts of CODES, Earth Sciences and other Disciplines and Centres at the university that conduct research in the Earth and marine sciences.

## Awards and accolades

2019 saw several of our staff and students honoured by their peers. In recognition of his 'distinguished service to education, and to scientific research, in the field of economic geology, and to professional societies', Emeritus Professor Ross Large, former director and founder of CODES, was awarded the Officer of the Order of Australia (AO) in the Australia Day Honours list in January 2019. This is the second highest honour given by the Council for the Order of Australia.

## STATISTICS AT A GLANCE 2019

|                                    |                |
|------------------------------------|----------------|
| Academic research staff            | 59             |
| Postgraduate Students              | 128            |
| Major research projects            | 59             |
| Countries involved                 | 28             |
| Publications in refereed journals  | 68             |
| Research reports to industry       | 208            |
| <b>WORKSHOPS AND SHORT COURSES</b> |                |
| Number                             | 24             |
| Countries                          | 7              |
| Attendees                          | 643            |
| <b>FUNDING</b>                     |                |
| Industry                           | \$1.02 million |
| UTAS                               | \$1.87 million |
| TMVC                               | \$1.35 million |
| <b>WORLDWIDE COLLABORATIONS</b>    |                |
| Industry                           | 45             |
| Institutes and universities        | 136            |



Participants of the 'Ores in Magmatic Arcs – South America' Master of Economic Geology short course in front of gypsum evaporite formations in Valle de la Luna, Cordillera del Sal, Northern Chile, October 2019. Professor David Cooke is on the far left.

We are thrilled that Ross' career, characterised by sustained excellence, brilliant insights and unstinting hard work and dedication, has been duly recognised with this prestigious honour.

PhD students Christopher Leslie, Shawn Hood and Ayesha Ahmed, and research fellows Dr Matthew Cracknell and Dr Angela Escolme won the Student Team Prize (\$50,000) in the Uearthed/OZ Minerals Explorer Challenge, which tasked entrants to identify new exploration targets in the Prominent Hill region of South Australia. Dr Rebecca Carey won the 2019 Tasmanian Young Tall Poppy Scientist of the Year Award for her research on volcanology in modern and ancient terrains and her outstanding ongoing efforts to communicate her science to the wider community.

In June, Professor Jocelyn McPhie was presented with the Twelvetreets Medal for 2019 by the Tasmanian Division of the Geological Society of Australia. She is the first woman to receive this award.

Professor Khin Zaw was awarded an Honorary Fellowship to the Geological Society of London, in recognition of his achievements in science and as an ambassador for geological science and its promotion to the wider public. Former CODES PhD student and now Head of Discovery Strategy at Anglo American, Dr David Braxton, received the Brian J. Skinner Award for the most outstanding paper published in *Economic Geology* during 2018, for an article based on his PhD thesis entitled 'Geology of the Boyongan and Bayugo porphyry Cu-Au deposits: An emerging porphyry district in northeast Mindanao, Philippines'. CODES PhD student Adam Abersteiner was awarded the Peter W. Smith CSL Postgraduate Award for his manuscript entitled 'Djerfisherite in kimberlites and their xenoliths: implications for kimberlite melt evolution'. And Dr Michael Roach's 25 years of continual service to the University of Tasmania was acknowledged at an awards ceremony in November.



Professor Ross Large AO with Her Excellency Professor the Honourable Kate Warner AC, the Governor of Tasmania, after the presentation of his Officer of the Order of Australia medal at Government House in Hobart during May.



Dr Rebecca Carey receiving the 2019 Tasmanian Young Tall Poppy Scientist of the Year Award from Deputy VC (Research) Professor Anthony Koutoulis on 15 October. The Tall Poppy Campaign is run by the independent Australian Institute of Policy and Science, with awards presented in each state and territory.

## Masters program

The Master of Economic Geology program is the foundation upon which CODES was built, and in November 2019 CODES celebrated 30 years of this program during the 'Geometallurgy' short course. The program started in 1989 when Ross Large and his team won an Australian Research Council Key Centre grant for the establishment of this world-class industry training program. The Masters program has evolved over the years, but has traditionally involved CODES offering six two-week intensive short courses to participants over a two-year cycle. Due to high demand, in 2019 we offered four short courses in a single year for only the second time, with the field-based 'Ores in Magmatic Arcs' run in Indonesia (March) and in South America (October). The Indonesian short course had 29 participants, the largest ever number for a field-based course in the Masters program. Our 'Ore Deposit Geochemistry, Hydrology and Geochronology' short course in Hobart was also well-attended (48 participants), and the November 'Geometallurgy' course attracted a record number of 25 participants.

The October 'Ores in Magmatic Arcs' short course encountered some unique challenges due to civil unrest in Ecuador, which required last-minute rescheduling of the entire first week of the short course to Peru with one week's notice. It was extremely helpful for our team to be well-placed at the SEG conference while this was

happening, as it was easy to organise new site visits because the relevant company representatives were all attending the conference. Additional disruptions were then encountered in the second week as civil unrest spread to Chile. Thanks to nimble work by Karen Huizing, Victor Torres, Carlos Diaz, Dr Mike Baker, Shelley Urquhart and Miles Smith, these difficulties were overcome, and the course proceeded successfully, concluding with a two-day porphyry workshop in Santiago. All participants and staff are thanked for their efforts in making this course a success.

## Conferences and short courses

Dr Michael Roach's 3D-visualisation displays were the star attraction in the exhibition hall at the Society of Economic Geologists conference in Santiago in October 2019. Michael was ably assisted by Karen Huizing, with the booth a constant hub of activity throughout the three days of the conference. CODES staff and students were very well represented at the meeting, and oral presentations were given by Professor David Cooke, Dr Angela Escolme and PhD student Javier Merrill. David Cooke also gave a one-day pre-conference porphyry short course at short notice after another presenter was forced to cancel their course at the last minute.

CODES had a strong contingent at the SGA conference in Glasgow in August, with Dr Jonathan Cloutier part



Dr Dave Braxton (left) pictured with the Director of CODES Professor David Cooke at the SEG Conference Dinner and Awards Ceremony in Santiago, Chile, October 2019. Dr Braxton was presented with the prestigious Brian J. Skinner Award for the most outstanding paper to be published in *Economic Geology* during 2018. Professor Cooke was Dr Braxton's supervisor for his thesis, completed at CODES in 2007, on which his winning paper was based.



Dr Michael Roach (left) from the Discipline of Earth Sciences received recognition for his 25 years of service to UTAS at a ceremony in November 2019; he is pictured here with the Vice-Chancellor Professor Rufus Black.



(L-R): CODES-TMVC PhD students Shawn Hood and Ayesha Ahmed, TMVC Postdoctoral Research Fellows Dr Angela Escolme and Dr Matthew Cracknell, and CODES PhD student Christopher Leslie won the student prize in the 2019 Uearthed/OZ Minerals Explorer Challenge. The CODES name was used to witty effect and became 'deCODES' as the team name.

of the organising committee and co-presenting a pre-conference workshop on 'Mineralising Processes in Basins'. Professor David Cooke co-presented a short course on 'Fertility to Vectors: Porphyry Exploration' and gave a technical presentation as part of the main conference, as did Dr Angela Escolme. Helen Scott ably managed the CODES booth throughout the conference, handling inquiries from potential students and research collaborators. PhD student Sibebe Nascimento won a best student talk award for her presentation on the King River tailings delta.

PACRIM 2019 was held in Auckland in April, where papers were presented by PhD students Shawn Hood and Christopher Leslie, Research Fellow Dr Matthew Cracknell, Associate Professor Shaun Barker, and a keynote address was given by Professor David Cooke. Shawn Hood and Matthew Cracknell ran a short course on the application of machine learning and data analytics in the geosciences.

CODES/TMVC hosted 62 participants for the annual meeting of the Thermochronology and Noble Gas Geochronology and Geochemistry Organisation (TANG<sup>3</sup>O) in early November. TANG<sup>3</sup>O is a voluntary association of researchers in the fields of thermochronology, noble gas geochemistry and geochronology, and its purpose is to optimise access to facilities and results, enhancing technical developments and technique implementation, and creating a forum for dissemination of technical advances and research results relevant to the Australian geochronological, geochemical and geological communities. This year's meeting was a great success. The capabilities of CODES Analytical Laboratories were showcased through a pre-conference workshop on the laser ablation data reduction (LADR) software, recently developed by Professor Leonid Danyushevsky (CODES) and Dr Ashley Norris (Norris Scientific). The session demonstrated the LADR's workflow and capacity to process U/Pb LA-ICP-MS data.

### Staff changes

CODES was pleased to welcome several former staff and students back in 2019. Dr Julie Hunt returned



Professor David Cooke teaching the 'Ores in Magmatic Arcs – Indonesia' Master of Economic Geology short course, March 2019.

in May, taking up the role as lead researcher on the CRC ORE project 'Geological controls on grade by size fractionation'. Former CODES graduate Dr Margaret Hawke returned to commence a postdoctoral research fellowship, working with Professor Ross Large on 'Pyrite vectors for the Cobar Basin'. Dr Indrani Mukherjee commenced a postdoctoral position in late September supported by an Ian Potter Foundation grant and various industry partners, and is working on 'Characterising pyrite chemistry of black shales hosting stratiform Zn-Pb-Ag and application to mineral exploration'. Terrie Sawyer re-joined the CODES Analytical Laboratories team in the second half of 2019, with the responsibilities of operation of our clean room, sample preparation and solution ICP-MS analysis. Also joining CODES in February 2019 was Dr Jonathan Cloutier, who commenced a postdoctoral study of the geochemical halos to Proterozoic sediment-hosted ore deposits. 2020 will see some changes to our staff profile, with Dr Angela Escolme accepting a new role as a Lecturer in Geology and Geometallurgy; she will move from her current postdoctoral fellowship

to this new role in January 2020. Dr Clare Miller will also join our group as a lecturer in Environmental Geochemistry in February 2020. Several staff departed CODES in 2019 – we thank Jay Thompson, Dr Wei Hong, Dr Sasha Stepanov, Dr Anita Parbhakar-Fox, Dr Nathan Fox, Dr Irina Zhukova and Dr Jane Higgins for all their hard work and great contributions to our group and wish them well in the next phase of their careers.



Participants in the Ores in Magmatic Arcs Workshop held at Universitas Gadjah Mada, Yogyakarta, Indonesia, in early March 2019 prior to the 'Ores in Magmatic Arcs' MEconGeol short course.

### Publications

December 2019 saw the publication of another *Economic Geology* special publication involving CODES staff and students. The Geometallurgy special issue was co-edited by Dr Julie Hunt and Associate Professor Ron Berry, and included publications by former TMVC PhD students Dr Angela Escolme and Dr Cassidy Harraden. Another *Economic Geology* special publication dealing with the applications of mineral chemistry to porphyry exploration was being prepared in 2019, with an anticipated publication date of mid-2020.

### CODES Annual Review

CODES held its 2019 Annual Review meeting in late November. Our industry, government and academic stakeholders witnessed 19 oral presentations from CODES and TMVC staff and students who showcased major research outcomes for the year and discussed new research initiatives for 2020 and beyond. A highlight of the day was the 15 poster displays by our students and staff, which stimulated considerable interaction with the meeting participants.

### The year ahead: what does 2020 hold?

At the time of writing, it is clear that 2020 will be a year like no other for us all. The COVID-19 crisis has transformed where and how we work, and what we are able to do. Research staff and students have mostly been working from home since March 2020 and our teaching



The Masters program at CODES celebrated 30 years of operation during 2019; here (L–R) Dr Robert Scott (current Masters Program Coordinator), Professor Ross Large (founder of CODES) and Dr Tony Webster (a former Masters Program Coordinator) cut three cakes at a function held at CODES to pay tribute to all those who have organised and contributed to the courses over the decades.

staff have been investing considerable efforts into migrating our undergraduate and postgraduate teaching online. CODES Analytical Laboratories have remained fully operational thanks to swift action in establishing appropriate social distancing and operational protocols. Thanks to the hard work of our dedicated laboratory staff, CODES research staff and students have been able to continue to prepare their samples and generate analytical data, minimising disruptions to our laboratory-based research activities. Our industry partners have been sending additional sample material to CODES from around the world, helping our new students to initiate their research projects during this time of lockdown. Field activities have mostly been curtailed since the onset of the crisis, and international students are unable to travel to Australia, impacting on our PhD recruitment.

Online meetings have become part of our daily routines. The University of Tasmania has initiated a curriculum renewal program and is currently reviewing all aspects of its operations in response to the budgetary impacts of COVID-19. Every day brings new challenges, but our staff and students continually strive to conduct world-class research and training and are rising to the challenges presented by the global pandemic, and I thank them all for their unstinting commitment, hard work and adaptability – it is our people who have allowed CODES to sustain excellence over three decades.

# Profile and research structure

## An overview

CODES commenced operations in 1989, evolving over two and a half decades from an Australian Research Council-funded Key Centre to a Special Research Centre and then a Centre of Excellence. As we enter our fourth decade of operations, CODES is now known as the Centre for Ore Deposit and Earth Sciences. Based at the University of Tasmania, CODES has grown substantially over the years and is regarded widely by industry and academia as a global leader in ore deposit research and postgraduate

training. With 59 highly qualified research staff and 128 postgraduate students, CODES is one of the largest university-based teams of ore deposit researchers in the world.

Highly productive worldwide collaborations have been developed with over 45 industry companies, plus a host of joint research initiatives with 136 institutions and universities – 23 in Australia and 113 overseas. It currently has 59 major research projects spanning 28 countries, and all seven continents. It is also the leading academic group to publish in

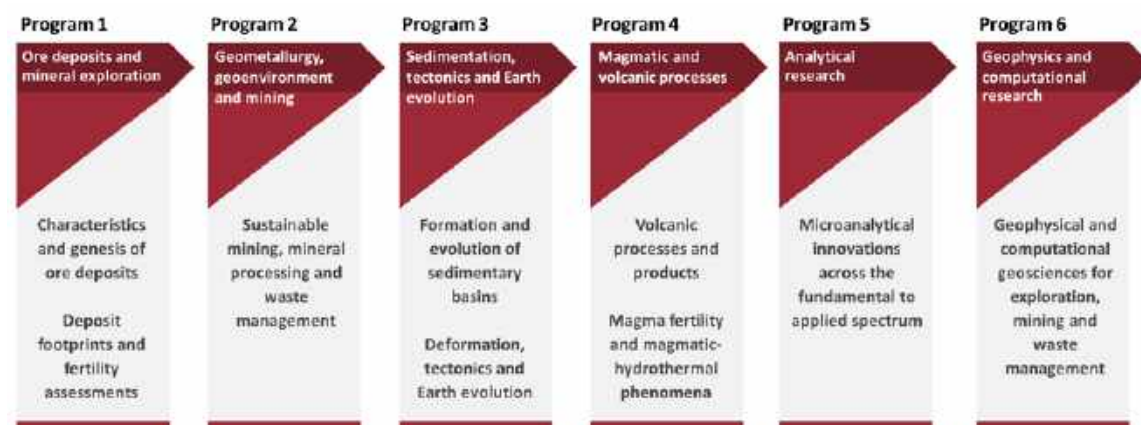
*Economic Geology*. In the past year, it maintained its reputation for delivering excellence in technology transfer by producing 208 reports to industry and conducting 24 short courses, workshops, conferences and field trips in seven countries across the world as well as here in Australia.

## Industry-focussed research and training

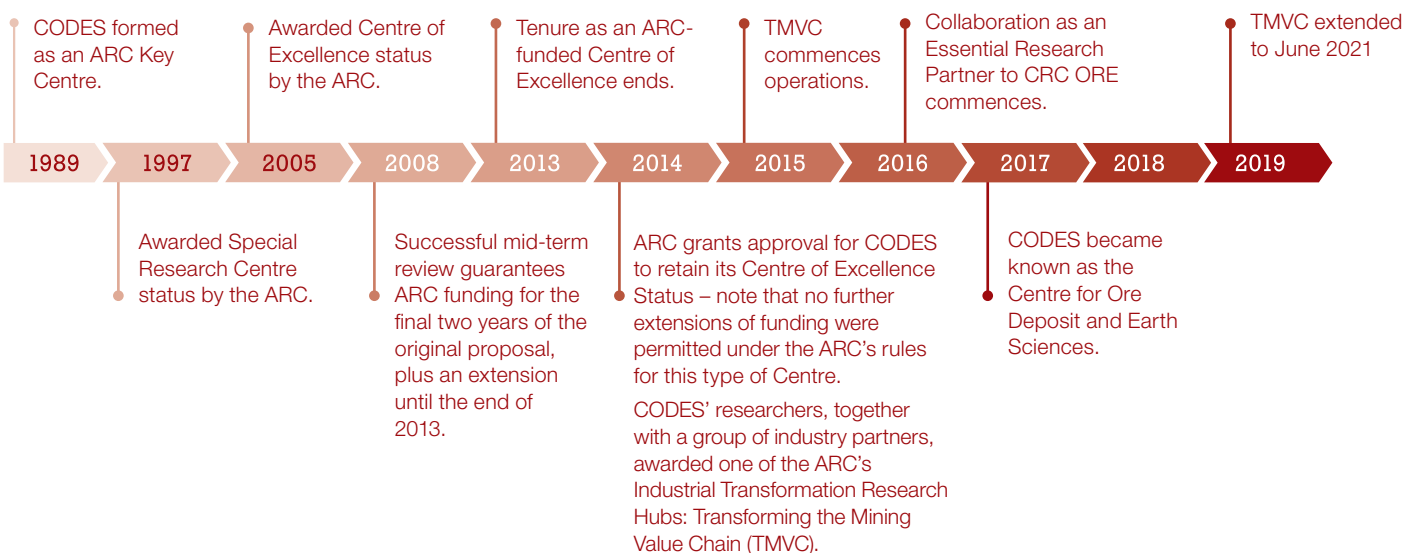
CODES' research is conducted within and across six research programs. Our research spans a range of fundamental and applied activities, with our

## CODES PROGRAM STRUCTURE

The CODES program structure covers the full spectrum of research from fundamental to applied:



## TIMELINE



CODES-TMVC staff and PhD students pictured here were among the participants of the AMIRA P1202 Sponsors' Review Meeting 3 ('Far-field and near-mine footprints – finding and defining the next generation of Tier 1 ore deposits'), which took place in Santiago, Chile, during October 2019.

industry-focussed research aiming to develop new exploration techniques for mineral discoveries, and new practices for sustainable mining, mineral processing and waste management. Our research across this spectrum of activities allows CODES to provide the minerals industry with a constant supply of world-class geoscience graduates and creates the platform for our training and upskilling of minerals industry professionals through our Master of Economic Geology program.

## Training and education

Training and education at CODES provides an ongoing supply of world-class geoscience graduates, and delivers a range of professional development short courses and workshops tailored to meet the needs of the minerals industry in terms of upskilling its workforce. The schedule for upskilling courses varies in line with demand. Postgraduate courses are offered at the following levels:

## Honours

A one-year degree that will significantly increase employment options, or can be used as a stepping-stone to a PhD. Courses are available in Economic Geology, Geophysics and Geochemistry.

## Master of Economic Geology

Industry geologists can participate in a series of intensive, two-week courses aimed at the working geologist in order to upgrade their skills; the MEconGeol is available in coursework only (8 units) and coursework (6 units) plus research thesis options. The degree is part

of the national Minerals Geoscience Masters (MGM) program. We are working towards expanding short course offerings in the MEconGeol program in 2020.

## PhD and MSc

These higher degree by research programs enable students to complete their theses in an environment that provides access to state-of-the-art technology, exceptional links with industry, and supervisors who are international leaders in their respective fields.

## Research facilities

CODES Analytical Laboratories contain state-of-the-art analytical facilities for a wide range of geological analyses, encompassing the routine multi-element analysis of sulfide and oxide minerals, including the full range of platinum group elements; U/Pb dating of zircon and monazite; and multi-element analysis of silicates. These facilities include five laser ablation ICP-MS laboratories specialising in ore deposit applications, an XRF laboratory, solution ICP-MS and clean room, fluid/melt inclusion laboratory, a lapidary department and sample preparation facilities. In addition, portable analytical techniques are provided, including shortwave infrared (SWIR) and portable XRF.

CODES has reciprocal access arrangements with the UTAS Central Science Laboratory, which has an extensive suite of complementary equipment, particularly in the areas of electron microscopy and mineral liberation analysis (MLA), X-ray microanalysis, laser Raman and FTIR spectroscopy, and ICP-MS.

CODES' has established its position at the leading edge in mineral chemistry research for exploration through the development of unique analytical techniques, data processing and screening methods, and calibration standards, combined with employing staff who have extensive expertise in analytical protocols and the interpretation of results.

## Transforming the Mining Value Chain An ARC Industrial Transformation Research Hub

The Australian Research Council Industrial Transformation Research Hub for Transforming the Mining Value Chain (TMVC) is based at CODES. The Hub encompasses a wide array of activities from exploration, discovery, ore deposit characterisation, mineral processing and environmental management. The main objective of the TMVC is to improve efficiencies within the mining value chain, focussing on areas that will have a marked impact on the value of mineral resources. In addition to CODES, the industry partners involved in the Research Hub include BHP, Corescan, Newcrest Mining and a consortium of global companies co-ordinated by AMIRA International. Other organisations affiliated with the initiative include Laurin Technic, UTAS Engineering and RWTH Aachen University in Germany.

TMVC activities are covered later in this annual report.

# Staff and management 2019

## Centre Director

Professor David Cooke has been the Centre Director since mid-2017; he is responsible for the scientific leadership and operational management of the Centre, and is assisted in this role by Professor Leonid Danyushevsky, Deputy Director of the Centre. Assisting them in these roles are the Advisory Board and the Executive Committee.

## ARC TMVC Research Hub Director

Professor David Cooke is Director of the ARC Research Hub for Transforming the Mining Value Chain. He is supported in these duties by Deputy Director Professor Leonid Danyushevsky.

## Advisory Board

The Advisory Board meets at least once a year to review the progress of the Centre and to advise on future directions. The Board is composed of representatives from major Industry Partners, University of Tasmania senior management and key national geoscience organisations. It is chaired by Dr Paul Heithersay from the Department for Energy and Mining,

South Australia, who has extensive experience in the minerals industry and the public service. Paul Agnew from Rio Tinto is Deputy Chair.

## Executive Committee

The Executive Committee consists of the Centre Director, Deputy Director, Head of the Discipline of Earth Sciences, and a representative from the areas of applied research, fundamental research, education and administration. It meets approximately six times a year, working closely with the Director to develop the Centre's goals, strategies and research directions.

## Annual Review

The Annual Review is an annual one-day forum of presentations relating to the Centre's research. The membership is wider than that of the Advisory Board and includes representatives from partner companies, research collaborators and other geoscience stakeholders. The Annual Review is designed to provide stakeholders and interested parties with an opportunity to see the breadth of the research conducted at CODES and to influence future research directions.



*CODES staff and stakeholders concentrating hard during the 2019 Annual Review held in November. The Annual Review enables CODES to disseminate its latest research findings and future plans to partner companies and geoscience organisations.*

## Staff movements 2019

### Appointments

#### Academic staff

Dr Jonathan Cloutier, who hails from Canada, joined CODES at the beginning of February as a Postdoctoral Research Fellow in Geochemical halos to Proterozoic sediment-hosted ore deposits; he is working in Programs 3 and 4. He was previously working as a lecturer at the University of St Andrews in Scotland.

Dr Julie Hunt returned to CODES in May to lead the 'Geological controls on grade by size fractionation' project, a CODES-CRC ORE collaboration within Program 2. Julie had previously been leading the Geometallurgy Initiative at the Mineral Deposit Research Unit at the University of British Columbia in Canada.

Dr Margaret Hawke, who completed her PhD at CODES, returned to CODES at the start of September to work with Professor Ross Large on 'Pyrite vectors for the Cobar Basin', a six-month project.

#### Professional/technical staff

Terrie Sawyer, who had previously worked at CODES, rejoined the CODES Analytical Laboratories team in October. She is working on LA-ICP-MS analytical methods for in-situ trace element analysis of minerals.

### Departures

#### Academic staff

Dr Nathan Fox left his role as postdoctoral researcher for the CODES-CRC ORE 'Geological controls on grade by size fractionation' project in February 2019. He moved to the W.H. Bryan Mining and Geology Research Centre, part of the

Sustainable Minerals Institute at the University of Queensland, where he will continue research in the fields of ore deposit geology and geometallurgy.

Dr Wei Hong, a postdoctoral researcher, moved to South Australia in October to take up a role as a postdoctoral research fellow at the MinEx CRC at the University of Adelaide.

Dr Anita Parbhakar-Fox, who was a postdoctoral researcher within the ARC TMVC Research Hub, left CODES in late January to take up a role as a senior research fellow in geometallurgy/environmental geochemistry at the W.H. Bryan Mining and Geology Research Centre at the University of Queensland.

Dr Sasha Stepanov, who worked in the CODES Analytical Laboratories, left CODES in February to take up a role as a professor at the China University of Geosciences at Wuhan in China.

#### Professional/technical staff

Dr Jane Higgins moved from her role as PA to the Director of CODES in June to take up other administrative roles within UTAS.

Mr Jay Thompson resigned from his position as a laboratory analyst at CODES in August and took up a role with NASA at the Johnson Space Center at Houston, USA.

Dr Irina Zhukova left her roles as a research assistant and laboratory analyst at CODES in February to take up a role as an associate professor at the China University of Geosciences at Wuhan in China.



*RIGHT (TOP) (L-R): Dr Indrani Mukherjee chats with Chris Large and Dr David Selley at a gathering to celebrate the 30th anniversary of the CODES Masters Program. (2ND ROW LEFT) Associate Professor Sebastien Meffre, Head of the Discipline of Earth Sciences. (2ND ROW RIGHT) Dr Michael Roach and Dr Karin Orth at a CODES social function. (3RD ROW) CODES staff and students listening to an address at the Masters celebration. (BOTTOM LEFT) Ken Morrison, the first ever CODES MEconGeol graduate, at the 2019 CODES Annual Review. (BOTTOM RIGHT) Consultant Professor Noel White presenting in Yogyakarta, Indonesia.*

SENIOR MANAGEMENT

| NAME                                                                  |                                             | %* | TMVC† |
|-----------------------------------------------------------------------|---------------------------------------------|----|-------|
| Director, Professor David Cooke, BSc Hons (Latrobe), PhD (Monash)     | Porphyry Cu-Au, fluid-rock geochemistry     | 50 | ✓     |
| Deputy Director, Professor Leonid Danyushevsky, PhD (Vernadsky Inst.) | Petrology, geochemistry, LA-ICP-MS analysis | 50 | ✓     |

ACADEMIC/RESEARCH STAFF AT UTAS

| NAME                                                                         |                                                                                          | %*  | TMVC† |
|------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-----|-------|
| Dr Sharon Allen, BSc (Massey), MSc (Auckland), PhD (Monash)                  | Volcanic facies analysis                                                                 | Hon |       |
| Dr Mike Baker, BSc Hons (Sydney), PhD (UTAS)                                 | Igneous petrology, mineral chemistry                                                     | 100 | ✓     |
| Associate Professor Shaun Barker, BSc Hons (Otago), PhD (ANU)                | Isotope geochemistry, mineral chemistry, structural controls on hydrothermal fluids      | 50  |       |
| Associate Professor Ron Berry, BSc, PhD (Flinders)                           | Structure of mineralised provinces, CHIME dating, geometallurgy                          | Hon | ✓     |
| Dr Stuart Bull, BSc Hons, PhD (Monash)                                       | Clastic and carbonate sedimentology and volcanology                                      | Hon |       |
| Dr Rebecca Carey, BSc Hons (UTAS), PhD (U Hawaii)                            | Volcanology                                                                              | 50  |       |
| Dr Jonathan Cloutier, BSc, MSc, PhD (Queen's U, Canada)                      | Economic geology, geochemistry, hyperspectral reflectance                                | 100 |       |
| Dr Matthew Cracknell, BSc Hons, PhD (UTAS)                                   | Geophysics, machine learning and data mining                                             | 100 | ✓     |
| Professor Tony Crawford, BSc Hons, PhD (Melbourne)                           | Petrology, geochemistry and tectonics of volcanic arcs                                   | Hon |       |
| Dr Paul Davidson, BSc Hons, PhD (UTAS)                                       | Melt and fluid inclusions                                                                | Hon |       |
| Dr Angela Escolme, MEarthSci Hons (Manchester), PhD (UTAS)                   | Geomettallurgy, geochemistry, mineralogy                                                 | 100 | ✓     |
| Dr Trevor Falloon, BSc Hons (Canterbury), BTeaching, PhD (UTAS)              | Marine geoscience, petrology                                                             | Hon |       |
| Professor J Bruce Gemmell, BSc (UBC), MA, PhD (Dartmouth)                    | VHMS deposits and epithermal Au-Ag                                                       | Hon | ✓     |
| Professor David Green, BSc Hons, MSc, DSc, DLitt Hon (UTAS), PhD (Cambridge) | Experimental petrology                                                                   | Hon |       |
| Dr Jacqui Halpin, BSc Hons (Melbourne), PhD (Sydney)                         | Metamorphic petrology, geochronology                                                     | Hon |       |
| Dr Margaret Hawke, BSc Hons (UMelb), MEconGeol, PhD (UTAS)                   | Exploration geology, economic geology, VHMS deposits, geochronology, pyrite geochemistry | 50  |       |
| Dr Julie Hunt, MSc (UBC), PhD (JCU)                                          | Geomettallurgy, economic geology                                                         | 100 |       |
| Dr Martin Jutzeler, MSc (U Lausanne), PhD (UTAS)                             | Volcanology and clastic sedimentology                                                    | 50  |       |
| Dr Maya Kamenetsky, PhD (UTAS)                                               | MLA-SEM, geomettallurgy, petrology                                                       | 100 | ✓     |
| Professor Vadim Kamenetsky, BSc Hons (Moscow), PhD (Vernadsky Inst.)         | Petrology and geochemistry of melt inclusions                                            | 50  |       |
| Professor Ross Large, BSc Hons (UTAS), PhD (UNE)                             | Volcanic-hosted and sediment-hosted base metal and gold ores                             | Hon | ✓     |
| Dr Peter McGoldrick, BSc Hons, PhD (Melbourne)                               | Ore deposits and their halos                                                             | Hon |       |
| Professor Jocelyn McPhie, BA Hons (Macquarie), PhD (UNE)                     | Volcanic facies architecture and volcanic textures                                       | Hon |       |
| Associate Professor Sebastien Meffre, BSc Hons, PhD (Sydney)                 | Petrology and tectonics of the SW Pacific                                                | 50  | ✓     |
| Dr Indrani Mukherjee, BSc Hons, MSc (Delhi), PhD (UTAS)                      | Deep time geology and pyrite chemistry                                                   | 100 |       |
| Dr Evan Orovan, BSc Hons (Carleton), PhD (UTAS)                              | Porphyry environment, mineral chemistry and hydrothermal geochemistry                    | 100 | ✓     |
| Dr Michael Roach, BSc Hons (Newcastle), PhD (UTAS)                           | Geophysical responses of ore deposits                                                    | 20  |       |
| Dr Robert Scott, BSc Hons, PhD (Monash)                                      | Structural geology, gold deposits/MTEC Senior Lecturer and Masters Program Coordinator   | 70  |       |
| Dr David Selley, BSc Hons (Adelaide), PhD (UTAS)                             | Structural geology, basin analysis, ore deposit modelling                                | Hon |       |
| Dr Jeff Steadman, BSc (Central Missouri), MSc (Iowa)                         | Ore and sedimentary pyrite geochemistry; seawater composition through geologic time      | 100 |       |
| Mr Francisco Testa, MSc (UNS, Argentina)                                     | Magmatic-hydrothermal breccias, porphyry and epithermal deposits, geochemistry           | 100 |       |
| Dr James Tolley, MSc (Imperial), PhD (ANU)                                   | LA-ICP-MS and geochemistry of REE in carbonatites                                        | 100 |       |

|                                                                                                                |                                                        |     |   |
|----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|-----|---|
| Dr Tony Webster, BSc Hons (Latrobe), BA (UNE), BAVE, BEd Hons (UTAS), GDipMinEng (UNSW), MSc (JCU), PhD (UTAS) | Mining structural geology, complexly deformed deposits | Hon |   |
| Dr Lejun Zhang, BSc, PhD (HFUT)                                                                                | Porphyry Cu-Au and HS epithermal                       | 100 | ✓ |

ACADEMIC/RESEARCH STAFF BASED AT COLLABORATIVE INSTITUTIONS/INDUSTRY

| NAME                                                  |                                                          |     | TMVC |
|-------------------------------------------------------|----------------------------------------------------------|-----|------|
| Dr John Bishop                                        | Consultant                                               | Hon |      |
| Mr Ralph Bottrill                                     | Mineral Resources Tasmania                               | Hon |      |
| Dr Tony Brown                                         | Consultant                                               | Hon |      |
| Dr Kathy Ehrig                                        | BHP                                                      | Hon | ✓    |
| Professor Andrea Gerson                               | Blue Minerals Consultancy                                | Hon |      |
| Neil Goodey                                           | Corescan                                                 |     | ✓    |
| Dr Scott Halley                                       | Mineral Mapping                                          | Hon |      |
| Professor Mark Hannington                             | University of Ottawa                                     | Hon |      |
| Dr Anthony Harris                                     | Newcrest Mining                                          | Hon | ✓    |
| Professor Peter Hollings                              | Lakehead University                                      | Hon |      |
| Mr Terry Hoschke                                      | Consultant                                               | Hon |      |
| Dr David Huston                                       | Geoscience Australia                                     | Hon |      |
| Dr Tim Ireland                                        | First Quantum Minerals                                   | Hon |      |
| Professor Bernd Lottermoser                           | RWTH Aachen University                                   | Hon | ✓    |
| Mr Adi Maryono                                        | J Resources                                              | Hon |      |
| Dr Andrew McNeill                                     | Mineral Resources Tasmania                               | Hon |      |
| Dr Anita Parbhakar-Fox, MSc Hons (London), PhD (UTAS) | Sustainable Minerals Institute, University of Queensland | Hon | ✓    |
| Adele Seymon                                          | AMIRA Global                                             |     | ✓    |
| Michael Shelley                                       | Laurin Technic                                           |     | ✓    |
| Professor Roger Smart                                 | Blue Minerals Consultancy                                | Hon |      |
| Dr Steve Walters                                      | MINOREvation                                             | Hon |      |
| Professor Noel White                                  | Consultant                                               | Hon |      |
| Professor Jamie Wilkinson                             | Natural History Museum/Imperial College London           | Hon |      |

TECHNICAL/ADMINISTRATIVE STAFF

| NAME                                                       |                                                  | %*  | TMVC† |
|------------------------------------------------------------|--------------------------------------------------|-----|-------|
| Dr Ivan Belousov, BSc, MSc (Moscow), PhD (Vernadsky Inst.) | Research Associate – ARC TMVC Research Hub       | 100 | ✓     |
| Mrs Michele Chapple-Smith, Grad Dip App Sc (UTAS)          | Lapidary Technician                              | 80  |       |
| Mr Stephen Cooke                                           | Research Assistant                               | 35  |       |
| Mr Alex Cuison, BSCE (SLU, Philippines)                    | Lapidary Manager                                 | 100 |       |
| Mr Troy Finearty                                           | Maintenance, Field Equipment, and Safety Officer | 50  |       |
| Ms Karen Huizing                                           | Administrative Assistant                         | 100 |       |
| Ms Elena Lounejeva, MSc (UNAM)                             | Laboratory Analyst                               | 100 |       |
| Mrs Michelle Makoundi, B Acc (U Marien Ngouabi)            | Laboratory Assistant                             | 50  |       |
| Ms Caroline Mordaunt, BA Hons (King's London)              | Administrative Assistant                         | 60  |       |
| Dr Paul Olin, BA (SOU), MSc, PhD (WSU)                     | Deputy Leader – CODES Analytical Laboratories    | 100 |       |
| Mrs Claire Rutherford, BBus (Acc) (RMIT)                   | Administrative Assistant – ARC TMVC Research Hub | 60  | ✓     |
| Ms Terrie Sawyer, BSc Hons (UH)                            | Laboratory Analyst                               | 100 |       |
| Ms Helen Scott, BSc Hons (UTAS), BEd (QUT)                 | Hub Manager – ARC TMVC Research Hub              | 100 | ✓     |
| Ms Isabella von Lichten, BSc Hons (UTAS)                   | Curator                                          | 25  |       |

\*Research percentage † TMVC affiliated

### ADVISORY BOARD

|                          |                                                   |
|--------------------------|---------------------------------------------------|
| Chair: Paul Heithersay   | Department for Energy and Mining, South Australia |
| Deputy Chair: Paul Agnew | Rio Tinto Exploration                             |
| Laurent Ailleres         | Monash University                                 |
| Ben Andrew               | Mt Isa Mines (Glencore)                           |
| Robin Armit              | Monash University                                 |
| Shaun Barker             | CODES, UTAS                                       |
| John Barr                | Anglo American                                    |
| Rufus Black              | Vice Chancellor, UTAS                             |
| Dave Braxton             | Anglo American (dial-in)                          |
| Alex Brown               | Mt Isa Mines (Glencore)                           |
| David Cooke              | CODES, UTAS                                       |
| Leonid Danyushevsky      | CODES, UTAS                                       |
| Andrew Davies            | Teck (dial-in)                                    |
| Anthony Harris           | Newcrest Mining                                   |
| Brett Harris             | College of Sciences and Engineering, UTAS         |
| Mary Harris              | Newcrest Mining                                   |
| Ned Howard               | Evolution Mining                                  |
| Mark Hunt                | School of Natural Sciences, UTAS                  |
| Anthony Koutoulis        | Research, UTAS                                    |
| Neil Macalalad           | Anglo American                                    |
| Andrew McNeill           | Mineral Resources Tasmania                        |
| Sebastien Meffre         | Earth Sciences, UTAS                              |
| John Miller              | BHP                                               |
| Brett Paull              | College of Sciences and Engineering, UTAS         |
| Peter Rea                | Mt Isa Mines (Glencore)                           |
| Chris Reed               | Teck                                              |
| Kevin Robinson           | Mineral Resources Tasmania                        |
| Adele Seymon             | AMIRA International                               |
| Trevor Shaw              | Mt Isa Mines (Glencore)                           |
| Adam Simmons             | Anglo American                                    |
| Miles Smith              | School of Natural Sciences, UTAS                  |
| Noel White               | CODES, UTAS                                       |
| Brian Yates              | College of Sciences and Engineering, UTAS         |

### EXECUTIVE COMMITTEE

|                     |                                           |
|---------------------|-------------------------------------------|
| Chair: David Cooke  | Director, CODES and ARC TMVC Research Hub |
| Shaun Barker        | Applied Research                          |
| Rebecca Carey       | Fundamental Research                      |
| Leonid Danyushevsky | Deputy Director, CODES                    |

### ANNUAL REVIEW

also includes the Executive Committee and all CODES research staff and students

|                         |                                           |
|-------------------------|-------------------------------------------|
| Chair: David Cooke      | Director, CODES, UTAS                     |
| Paul Agnew              | Rio Tinto Exploration                     |
| Laurent Ailleres        | Monash University                         |
| John Barr               | Anglo American                            |
| Ralph Bottrill          | Mineral Resources Tasmania                |
| Andrew Cole             | Physics, UTAS                             |
| Mark Duffett            | Mineral Resources Tasmania                |
| Simon Ellingsen         | Natural Sciences, UTAS                    |
| Kim Frankcombe          | ExploreGeo                                |
| David Green             | Mineral Resources Tasmania                |
| Geoff Green             | Visitor                                   |
| Xianzheng Guo (student) | China University of Geosciences - Wuhan   |
| Mary Harris             | Newcrest Mining                           |
| Tony Hope               | Copper Gold Cambodia                      |
| Ned Howard              | Evolution Mining                          |
| Lorraine Ingham         | College of Sciences and Engineering, UTAS |
| Peter Manchester        | Visitor                                   |
| Andrew McNeill          | Mineral Resources Tasmania                |
| John Miller             | BHP                                       |
| Cui Minlli              | China Geological Survey                   |
| Brenda Mooney (student) | Chemistry/ACROSS, UTAS                    |
| Ken Morrison            | Visitor                                   |
| Josh Phillips           | Freeport McMoRan Exploration              |
| Hongying Qu             | Chinese Academy of Geological Sciences    |
| Chris Reed              | Teck                                      |
| Adele Seymon            | AMIRA International                       |
| Clint Siggins           | Mineral Resources Tasmania                |
| Miles Smith             | Natural Sciences, UTAS                    |
| Tony Webster            | GeoDiscovery Group                        |
| Greg Wilkie             | CRC ORE                                   |
| Noel White              | Consultant                                |
| Tao Zhang (student)     | China University of Geosciences - Beijing |
| Shaorui Zhao (student)  | China University of Geosciences - Wuhan   |

|                  |                                    |
|------------------|------------------------------------|
| Sebastien Meffre | Head, Discipline of Earth Sciences |
| Helen Scott      | Administration                     |
| Robert Scott     | Education                          |

OPPOSITE: Students and industry participants on the Master of Economic Geology 'Ores in Magmatic Arcs' field short course examining drill core at Tinka Resources' Ayawilca Sn-Zn deposit, Central Peru, October 2019.



# Program One

## Ore deposits and mineral exploration



### Objective

This program aims to use newly developed geological, geochemical, mineral chemical and geophysical features of ore forming systems and terrains in order to devise better means of discovering mineral resources at surface and under cover.

## Introduction

**Program 1: Ore Deposits and Mineral Exploration** provides industry-focussed process-based models for the formation of base and precious metal ore deposits. It also seeks to develop innovative new tools for determining the most prospective regions for minerals exploration (fertility), and for targeting of buried ore deposits (vectoring). Program 1 consists of seven key sub-projects (as well as other smaller projects), which reflect the range of expertise and level of diversity in the field of hard-rock geology at CODES.

## Highlights

Program 1 within CODES has continued to retain a critical mass of projects, spread across a diverse range of geological fields, deposit types and locations. 2019 has seen Program 1 continue with the carry-over of several major projects from previous years, as well as the commencement of new graduate student research projects to take the place of those recently completed. The current list of projects and research continue to have an impact around the world, as the following highlights illustrate:

### SW Pacific

Yi Sun has continued his PhD study on the Lepanto quartz-pyrite-gold (QPG) veins in the Mankayan district, Philippines. In 2019 Yi commenced analytical work on these newly discovered epithermal vein systems, located underneath and beside the Lepanto high sulfidation orebody. This

*OPPOSITE PAGE: (TOP) Dr Lejun Zhang and TMVC PhD student Takeshy Coaquira exploring the Range Front near Superior, Arizona, August 2019. This trip was related to Takeshy's PhD research which lies within TMVC – Module 4 of AMIRA Project P1202 and Program 1. (BOTTOM) Underground at the Francine intermediate sulfidation epithermal vein, San Sebastian mine, Durango, Mexico: a group of Hecla exploration and mine geologists – along with CODES PhD student Rob Davidson – investigating the vein. Rob is carrying out his PhD into epithermal research within Program 1 with support from Hecla Mining.*

work has helped to unravel the complex overlapping stages of copper and gold mineralisation that led to significant grade enhancement at Lepanto. (See the TMVC section of this report for further details about Yi Sun's research.)

### SE Asia

A new 'Power of pyrite' sub-project has commenced in 2019, aimed at the study of bio-essential and redox-sensitive trace element concentrations in sedimentary pyrites in three black shale sequences in the Yanliao area in the northern North China Craton. This sub-project will build upon work undertaken by the 'Power of pyrite' research team over the past decade.

A research project focussing on the tectonic and mineral resources of Myanmar terranes has been under development by Professor Khin Zaw and the SE Asia research team at CODES. It is hoped that this proposed new project can be linked to the ARC Linkage bid 'Geochemical, isotopic, hyperspectral and geochronological constraints on the metallogenic evolution of VHMS deposits of Australia and SE Asia: Enhancing the exploration potential and discovery', which already involves some of the SE Asia research team members.

### North America

Brian McNulty has completed his PhD research on the Myra Falls VHMS district on Vancouver Island, Canada. Also in 2019, Brian submitted a paper to *Economic Geology* on 'Assessing hydrothermal alteration intensity in VHMS systems using pXRF analysis of drill core: An example from Myra Falls, Canada'. This paper should be available in 2020.

Rob Davidson has also continued his PhD research on the sediment-hosted San Sebastian intermediate sulfidation epithermal vein system in Durango, Mexico, and has now documented three key hydrothermal alteration events at the deposit.

### South America

Carlos Diaz is continuing his Master of Economic Geology project on the Cascabel porphyry deposit cluster in Ecuador. In 2019, Carlos completed his field mapping, drill core logging and sampling at several prospects, and is working towards building new models

for the magmatic and metallogenic evolution of the Cascabel district.

Victor Torres' Master of Economic Geology project on the Soledad tourmaline breccia complex in the Cordillera Negra of central Peru has also continued throughout 2019.

In 2019, Victor logged new drillholes in the district and completed geochronological analyses of several key units, along with detailed petrographic and mineral chemistry analyses.

### Australia

David Douch has completed his PhD project on the geology and genesis of the Invincible gold deposit in the St Ives Goldfield, Western Australia. His project has resulted in the development of a new multi-stage structural and mineralisation model for the deposit in addition to a new approach to geochemical mass balance calculations in altered rocks.

The 'Power of pyrite' project has also continued to investigate sedimentary pyrite chemical trace element and isotopic halos in high-priority black shale formations of northern Australia, such as the Stuart Shelf, with the goal of determining their potential to host stratiform Zn-Pb-Ag and stratiform Cu deposits.

For the Tasmanian tin granites project, 2019 saw the publication of an *American Mineralogist* article that documented the characteristics, origins and significance of unidirectional solidification textures from the Heemskirk granite. A draft manuscript on the boron and oxygen isotope systematics of tourmaline and quartz from magmatic-hydrothermal textures in Sn granites was also readied for publication, likely in 2020.

# The program team

**LEADER** MIKE BAKER

**DEPUTY LEADER** LEJUN ZHANG

## TEAM MEMBERS:

Shaun Barker, Ron Berry, Stuart Bull, David Cooke, Matthew Cracknell, Leonid Danyushevsky, Angela Escolme, Nathan Fox, Bruce Gemmell, Margaret Hawke, Wei Hong, Ross Large, Charles Makoundi, Adi Maryono, Sebastien Meffre, Indrani Mukherjee, Evan Orovan, Robert Scott, David Selley, Jeff Steadman, Jay Thompson, Khin Zaw

## PHD STUDENTS:

Ayesha Ahmed, Peter Berger, Jing Chen, Takeshy Coaquira, Rob Davidson, David Douth, Alex Farrar, Amos Garay, Jacob Heathcote, Joseph Knight, Erin Lawlis, Christopher Leslie, Brian McNulty, Joshua Phillips, Xin Ni Seow, Emily Smyk, Yi Sun, Francisco Testa, Jennifer Thompson, Tristan Wells

## MASTERS STUDENTS:

Chloe Cavill, Carlos Diaz, Batbayar Enkhbold, Arga Firmansyah, Brendan Hardwick, Corey Jago, Juan Diego Rojas Lopez, George Maroa, Victor Torres, Zebedee Zivkovic

## HONOURS STUDENTS:

Cameron Foster, Robert James, Hugh Rivett, Matthew Vincent

## COLLABORATORS:

### AKITA UNIVERSITY JAPAN

Akira Imai

### AUSTRALIAN MUSEUM

Lin Sutherland

### BRITISH GEOLOGICAL SURVEY, UK

Mike Crow

### CHAKANA COPPER CORP

David Kelley, Doug Kirwin

### CHIANG MAI UNIVERSITY, THAILAND

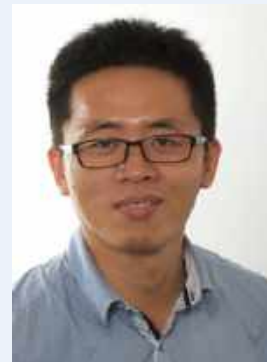
Phisit Limtrakun

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Xue Gao, Bin Lin

### CHINA UNIVERSITY OF GEOSCIENCES, WUHAN, CHINA

Jian Ma



### CHULALONGKORN UNIVERSITY, THAILAND

Abhisit Salam, Peerapong Sritangsirikul, Chakkaphan Sutthirat

### COLORADO STATE UNIVERSITY, USA

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### DEPARTMENT OF MINERAL RESOURCES, THAILAND

Punya Charusiri

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Eduard Eshuys

### DIRECTORATE OF GEOLOGICAL SURVEY AND EXPLORATION, MYANMAR

Ye Myint Swe

### EAST YANGON UNIVERSITY, MYANMAR

Cho Cho Aye

### GEOLOGICAL SURVEY OF CANADA

Mike Gadd

### GEOLOGICAL SURVEY OF SOUTH AUSTRALIA

Adrian Fabris, Anthony Reid

### GEOSCIENCE AUSTRALIA

David Huston

### GUANGZHOU INSTITUTE OF GEOCHEMISTRY, CHINESE ACADEMY OF SCIENCES, CHINA

Chao Wu

### HANOI UNIVERSITY OF MINING AND GEOLOGY, VIETNAM

Hai Thanh Tran

### HECLA MINING

Kurt Allen, Stephen Redak

### INSTITUTE OF GEOMECHANICS, CHINESE ACADEMY OF SCIENCES, BEIJING, CHINA

Shuanhong Zhang

### IRISH CENTRE FOR RESEARCH IN APPLIED GEOSCIENCES (iCRAG), IRELAND

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### MACQUARIE UNIVERSITY

Nathan Daczko

### MAHASARAKHAM UNIVERSITY, THAILAND

Clive Burrett

### MANDALAY UNIVERSITY, MYANMAR

Tin Aung Myint

### MANITOBA GEOLOGICAL SURVEY, CANADA

Marc Rinne

### MINERAL RESOURCES TASMANIA

Clive Calver, Grace Cumming, John Everard

### MONASH UNIVERSITY

Ray Cas

### NANYANG TECHNOLOGY UNIVERSITY, SINGAPORE

Lin Thu Aung

### NEWCREST MINING

Karyn Gardner, Anthony Harris

### NYRSTAR

Rick Sawyer, Armond Stansell

### ROYAL HOLLOWAY UNIVERSITY OF LONDON, UK

Tony Barber, Ian Watkinson

### SANDFIRE RESOURCES

Bruce Hooper, Jerry Zieg

### SOLGOLD

Steve Garwin, Santiago Vaca

### TRINITY COLLEGE, DUBLIN, IRELAND

Seán H McClenaghan

### UNIVERSITAS PADJADJARAN, INDONESIA

Mega Rosana

### UNIVERSITI BRUNEI DARRUSALAM, BRUNEI

Kit Chun Lai

### UNIVERSITI KEBANGSAAN, MALAYSIA

Mohd Basril Iswadi Bin Basori

### UNIVERSITY OF GENEVA, SWITZERLAND

Robert Moritz

### UNIVERSITY OF HONG KONG

Mei Fu Zhang

### UNIVERSITY OF MANITOBA, CANADA

Mostafa Fayek

### UNIVERSITY OF MELBOURNE

Roland Maas

### UNIVERSITY OF NEW BRUNSWICK, CANADA

David Lentz

### UNIVERSITY OF NEW MEXICO, USA

Karl Karlstrom

### UNIVERSITY OF QUEENSLAND

Jonathan Aitchison

### UNIVERSITY OF SYDNEY

Dietmar Müller, Sabin Zahirovic

### UNIVERSITY OF TORONTO

Dan Gregory

### YANGON UNIVERSITY, MYANMAR

Nyein Nyein Sint



*CODES Masters student Carlos Diaz is researching the Cascabel porphyry deposit cluster in Ecuador, supported by SolGold within the 'Porphyry research' project. Here he is pictured during a University of Arizona course field trip to the Miami-Globe district in December 2019.*

## Projects

Geology and genesis of the Invincible gold deposit, St Ives

Geology of the West Block area of the late Devonian Myra Falls VHMS district, BC, Canada

The power of pyrite: Application in ore deposit and deep time geology

Tectonic and mineral resources of Myanmar terranes

Epithermal research

Porphyry research

Tasmanian tin granites

## Project summaries

### GEOLOGY AND GENESIS OF THE INVINCIBLE GOLD DEPOSIT, ST IVES

**Leaders:** Robert Scott, Shaun Barker

**Student:** David Douth

**Collaborator:** Ray Cas

David Douth completed his PhD on the geology and genesis of the >1 Moz Au Invincible deposit in the St Ives Goldfield, Kambalda, WA, in mid-2019. Unlike most deposits in the >12 Moz Au St Ives Goldfield, Invincible is hosted by sedimentary rocks at the top of the Black Flag Group (2680–2665 Ma), rather than by mafic rocks of the older mafic Kambalda Sequence (2720–2680 Ma). David’s study has improved our understanding of stratigraphic and structural controls on gold mineralisation at Invincible, and included detailed investigations of ore paragenesis and geochemical dispersion around the deposit.

Significant outcomes of David’s work include:

- a new stratigraphic subdivision and facies model for the upper Black Flag Group (BFG) and overlying lower Merougil Formation;
- a new multi-stage structural and mineralisation model for Invincible;
- development of a new approach to geochemical mass balance in altered rocks; and
- the application of that approach to understanding hydrothermal alteration patterns around the Invincible deposit.

### GEOLOGY OF THE WEST BLOCK AREA OF THE LATE DEVONIAN MYRA FALLS VHMS DISTRICT, BC, CANADA

**Leaders:** Nathan Fox, Bruce Gemmell

**Student:** Brian McNulty

**Collaborators:** Rick Sawyer, Armond Stansell

Brian McNulty completed his PhD research on the lithological setting and geochronology of the West Block area at the Myra Falls VHMS district on Vancouver Island, Canada, during 2019. Brian’s research has advanced the overall understanding of the H-W member stratigraphy, the nature of hydrothermal alteration, and the temporal relationship of felsic host rocks at Myra Falls. These advancements have implications for the geology and genesis of the Myra Falls district VHMS deposits, as well as for mineral exploration within the Myra Falls district and throughout Vancouver Island.

In 2019 Brian submitted a paper to *Economic Geology*, co-authored with Dr Nathan Fox and Professor Bruce Gemmell, entitled ‘Assessing hydrothermal alteration intensity in VHMS systems using pXRF analysis of drill core: An example from Myra Falls, Canada’. Current portable X-ray fluorescence (pXRF) technology can rapidly and inexpensively yield concentrations of geologically significant elements, typically with instrument detection limits below several 10’s of ppm. Based on conventional XRF whole-rock geochemical data, both the Ishikawa Alteration Index and the Chlorite-Carbonate-Pyrite Index increase with

proximity to sulfide mineralisation at Myra Falls. However, available pXRF technology is typically unable to detect all of the elements required to calculate these alteration indices. As a result, there is a need to utilise the elements that are readily detectable using pXRF and apply these to hydrothermal alteration assessment. Brian proposed that Rb/Sr ratios provide a robust proxy for the Ishikawa Alteration Index and demonstrate that conventional whole-rock XRF analytical results for Rb and Sr can be reproduced using pXRF analysis from drill core surfaces. At Myra Falls, the Rb/Sr ratios range from <0.1 for least altered rocks, 0.1 to 0.5 for weakly altered rocks, 0.5 to 1.0 for moderately altered rocks, 1.0 to 2.0 for strongly altered rocks and >2.0 for intensely altered rocks. Down-hole profiles of alteration intensity generated from systematic pXRF analysis of drill core surfaces can be used to inform drilling and targeting decisions. The application of the Rb/Sr ratio as a proxy for alteration intensity extends beyond this case study and can be applied to other hydrothermal systems that produce phyllosilicate minerals as alteration products of feldspar. This paper has been accepted and will be published in 2020.

### THE POWER OF PYRITE: APPLICATION IN ORE DEPOSIT AND DEEP TIME GEOLOGY

**Leaders:** Ross Large, Indrani Mukherjee

**Team members:** Stuart Bull, Leonid Danyushevsky, Margaret Hawke, Jeff Steadman

**Collaborators:** Mike Gadd, Dan Gregory, Shuanhong Zhang

The ‘Power of pyrite’ project is split into two sub-projects owing to its fundamental and applied aspects:

- Using pyrite chemistry in marine black shales to track changes in ocean chemistry and associated evolutionary responses.
- Multi-client industry research on ‘Characterizing pyrite chemistry of black shales hosting stratiform Zn-Pb-Ag and stratiform Cu deposits: Application to mineral exploration’ (referred to as PY005).

The first of these sub-projects is funded by the Ian Potter Foundation and a collaboration with Professor Shuanhong Zhang at the Institute of Geomechanics, Chinese Academy of Sciences. The objectives are to provide key insights into the evolution of the first complex cell and subsequent macroscopic life. We aim to undertake a detailed comparison between Chinese and Australian black shales (particularly Middle Proterozoic) to advance our understanding of the geochemical conditions of the two sedimentary basins (McArthur Basin in North Australia and Yanliao Basin in North China). We propose to analyse a suite of bio-essential and redox-sensitive trace element concentrations in sedimentary pyrites, using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) in the three black shale sequences in the Yanliao area in the northern North China Craton. They are located in the Xiamaling, Hongshuizhuang and Chuanlinggou Formations, respectively. The peak age of black shales within the Xiamaling Formation is around 1380 Ma, similar to the Upper Velkerri Formation in northern Australia. The peak age of the black shales within the Hongshuizhuang Formation is around 1450 Ma. The peak age of the black shales within the Chuanlinggou Formation is around 1650 Ma, similar to the Barney Creek Formation in Australia.

The second of these sub-projects, which commenced in mid-2019, is currently funded by eight mining companies and two state geological surveys (Teck, Sandfire Resources, First Quantum, Anglo American, Glencore, Rio Tinto, Red Metal, DGO Ltd., the Geological Survey of South Australia and the Geological Survey of Queensland).

The main aims of this sub-project are to:

- focus sampling in ore deposit districts to determine pyrite chemical trace element and isotopic halos (footprints) around major ore deposit types of stratiform Zn-Pb-Ag and stratiform Cu;
- study sedimentary pyrite in other high-priority black shale formations, principally in Australia, to determine their potential to host stratiform Zn-Pb-Ag and stratiform Cu deposits; and



*The Xiamaling Formation, in the Yanliao area in the northern North China Craton, is part of the study area for the ‘Power of pyrite’ project that is using pyrite chemistry in marine black shales to track changes in ocean chemistry and associated evolutionary responses. This project is being led by Dr Indrani Mukherjee and Professor Ross Large.*

- assess the pyrite database, using both conventional and machine learning statistical techniques, in terms of basin fertility and stratigraphic potential for sediment-hosted Zn-Pb-Ag and sediment-hosted Cu.

In 2020 a Masters student (Ben Johnson) will be joining the project and we will also be employing Dr Asher Riaz as a database officer.

### TECTONIC AND MINERAL RESOURCES OF MYANMAR TERRANES

**Leader:** Khin Zaw

**Team members:** Ross Large, Charles Makoundi, Sebastien Meffre

**Collaborators:** Jonathan Aitchison, Tony Barber, Mohd Basril Iswadi Bin Basori, Clive Burrett, Punya Charusiri, Cho Cho Aye, Mike Crow, Akira Imai, Kit Chun Lai, Phisit Limtrakun, Nyein Nyein Sint, Abhisit Salam, Peerapong Sritangirikul, Lin Sutherland, Chakkaphan Sutthirat, Ye Myint Swe, Ian Watkinson

Myanmar is vastly rich in gold, silver, base metals, tin–tungsten, gems and hydrocarbons. Recent political changes and reforms, with reconciliations with various ethnic groups, will permit access to large areas in the country enabling further metallogenic research and exploration in new crustal blocks and terranes.

The new project will be focussed on metallogenesis and its tectonic development using geochronology, and deposit styles such as porphyry-epithermal, Sn-W, orogenic Au and VHMS deposits of the Myanmar Region. It will look mainly at the zircon geochronology, whole rock geochemistry, pyrite chemistry and mineralisation of the Western Myanmar and Sibumasu Terranes. It is hoped that this proposed project can be linked with the ARC Linkage bid ‘Geochemical, isotopic, hyperspectral and geochronological constraints on the metallogenic evolution of VHMS deposits of Australia and SE Asia: Enhancing the exploration potential and discovery’ led by Jonathan Cloutier.



Crustiform banded vein underground at the Francine intermediate sulfidation epithermal vein, San Sebastian mine, Durango, Mexico. This photo was taken during fieldwork undertaken by CODES PhD student Rob Davidson.

EPITHERMAL RESEARCH

**Leaders:** Bruce Gemmell, David Cooke

**Student:** Rob Davidson

**Collaborators:** Kurt Allen, Stephen Redak

Rob Davidson continued his PhD research on the sediment-hosted San Sebastian intermediate sulfidation epithermal vein system in Durango, Mexico, in 2019 with support from Hecla Mining. His research aims are to: determine the relationship between the vein systems and occurrences within the San Sebastian district; characterise the Mesozoic sedimentary host rock lithologies; understand the structural controls on vein formation; characterise whole rock and trace element geochemistry of veins, vein stages, host rock, volcanic rocks, and alteration in order to develop potential vectors towards mineralisation; and date, using a range of geochronological methods, the veins, host rocks and alteration.

Research focussed on the samples and observations collected during his 2019 fieldwork, including observation

of the veins underground in order to test structural observations from the 3D interpretation of geology and structure, and to compare textural and paragenetic observations to those made from core. Visual inspection of the host rocks at San Sebastian can readily distinguish two types of alteration: near surface weathering, and at depth, a broad volume of hardened and bleached mudstone. Staining with sodium cobaltinitrite indicates that this bleaching alteration is dominated by K-feldspar. It also reveals a third alteration domain spatially related to the main veins and which overprints the broader potassium alteration. Thus, there are three alteration events recognised at San Sebastian: 1) a pre-mineral broad event dominated by K-feldspar flooding; 2) syn-mineral vein-related alteration; and 3) post-mineral weathering.

Further analyses of hand sample descriptions, polished thin section descriptions, SEM analyses of mineralisation, potassium feldspar staining, SWIR (TerraSpec) data collection, pXRF (Olympus Vanta)

data collection, a carbon and oxygen (in carbonates) isotope study, a pilot Raman geo-thermometry study of the host rocks, and age dating of the regional volcanic rocks and hydrothermal alteration, are continuing. Rob presented a poster of his initial findings at the SEG Conference in Santiago in October. A third and final field season is planned for March 2020.

PORPHYRY RESEARCH

**Leader:** David Cooke

**Team members:** Michael Baker, Evan Orovan, Lejun Zhang

**Students:** Carlos Diaz, Victor Torres

**Collaborators:** Steve Garwin, David Kelley, Doug Kirwin, Santiago Vaca

General research into porphyry copper, gold and molybdenum and related deposits continued throughout 2019, with Master of Economic Geology research students Carlos Diaz and Victor Torres making significant advances towards the completion of their theses.

Carlos Diaz is researching the Cascabel porphyry deposit cluster in Ecuador, supported by SolGold. Cascabel contains the world-class Alpala Cu-Au porphyry deposit, with a maiden mineral resource estimate of 1.08 Gt @ 0.68% CuEq. In 2019, Carlos completed his field mapping, drill core logging and sampling at the Alpala, Tandayama and Aguinaga prospects to facilitate comparisons of the three prospects, and to build new models for the magmatic and metallogenic evolution of the Cascabel district that are intended to help to guide ongoing exploration in the district and broader region. Carlos has now completed drafts of several thesis chapters and all his geochronological and geochemical data have now been acquired. Thesis submission is planned for mid-2020.

Victor Torres’ research into the Soledad tourmaline breccia complex in the Cordillera Negra of central Peru continued throughout 2019. This research project is supported by Chakana Copper Corp. In 2019, Victor logged new drillholes in the district and completed geochronological analyses of several stratigraphic units in the district, along with detailed petrographic and mineral chemistry analyses. Writing of

the thesis is underway, with an intended submission date late in 2020.

TASMANIAN TIN GRANITES

**Leader:** David Cooke

**Team members:** Nathan Fox, Wei Hong, Sebastien Meffre, Jay Thompson, Lejun Zhang

**Collaborators:** Mostafa Fayek, David Huston, Roland Maas

This PhD study by Wei Hong was completed in 2017 and provided critical insights into magmatic-hydrothermal features in tin granites, including diffuse tourmaline patches, tourmaline-quartz filled miarolitic cavities and tourmaline orbicules, and quartz-K-feldspar-tourmaline-bearing unidirectional solidification textures. It also assessed

the geodynamic setting, timing and origins of tin granites in the eastern and western Tasmanian terranes.

2019 saw the publication of an *American Mineralogist* article that documented the characteristics, origins and significance of unidirectional solidification textures from the Heemskirk granite. Final corrections to a *Mineralium Deposita* article that summarises the boron and oxygen isotope systematics of tourmaline and quartz from magmatic-hydrothermal textures in Sn granites were made late in 2019, with a final publication date scheduled for early 2020.

Professor Khin Zaw (with CODES hat) was one of the leaders of a Myanmar Applied Earth Sciences Association post-conference field trip in November 2019. He is discussing rocks in the Mogok Metamorphic Belt, which are known to bear gold, copper and gemstones (rubies and sapphires).



Looking forward

Program 1 will continue to deliver a diverse range of projects into 2020, as exemplified by the ‘Power of pyrite’ project which continues to innovate in the field of pyrite mineral chemistry. A number of the Program 1 projects are driven by graduate student research projects that have reached, or in 2020 will enter, critical stages in data acquisition and scientific advancement. These projects, and the students who drive them, are the lifeblood of this Program, as they continue to generate quality research outcomes including theses, peer-reviewed publications and models for the development of mineralised hydrothermal systems in a diverse range of environments.

Postgraduate research projects continuing into 2020 include Rob Davidson’s work on the San Sebastian epithermal deposit, Mexico; Yi Sun’s project on the Lepanto QPG veins, Philippines; Carlos Diaz’ project on the Cascabel porphyry deposit in Ecuador; and Victor Torres’ project on the Soledad tourmaline breccia complex in central Peru.

A number of journal articles from across the Program are also nearing completion or have been submitted for publication in 2020. This, in addition to the expected completion of several graduate student theses, indicate that it will again be another excellent year for scientific reporting of Program 1 outcomes to the wider academic community.

## Program Two

# Geometallurgy, geoenvironment and mining



### Objective

- Create an integrated, cross-disciplinary geometallurgical research platform that delivers fundamental knowledge, tools and methods to the global mining industry for optimising sustainable and profitable mineral extraction.
- Develop more effective approaches to the definition of mineralogy, element deportment and texture using new technologies that can be linked to mineral processing performance and waste management, at a range of scales.
- Provide improved attributes or indices of processing performance that can be embedded into block models to define processing domains, which can be exploited in mine planning and optimisation.
- Deliver new cross-discipline geometallurgical education, training and awareness.



### Introduction

**Program 2: Geometallurgy, geoenvironment and mining** addresses some of the challenges the minerals industry faces in the accurate prediction of processing performance and variability in performance due to the limited number of samples that can be tested for metallurgical parameters. Significant technical and operational risks exist where ore bodies are poorly characterised. The discipline of geometallurgy seeks to efficiently integrate and use mineralogical and geochemical characterisation tools to undertake deposit-wide characterisation in order to maximise ore body knowledge.

Through a holistic approach, geometallurgy activities identify attributes that contribute to the realised value of a resource, and enable ore variability to be factored into the flowsheets, infrastructure design, and the production and quality forecasts over the life-of-mine. This includes variability in traditional attributes, such as grade, as well as less traditional factors, such as hardness (crushability, grindability), mineral species and abundance, mineral liberation, metallurgical recovery, concentration of deleterious elements, acid generating potential, neutralising potential and smelter enabling characteristics.

Over the past 15 years, CODES has established itself as a national centre for geometallurgical research, spurred on mainly by an increased interest in the discipline by the minerals industry. This increase in industry involvement led to the large AMIRA P843 and P843A (GeM<sup>III</sup>) projects collaboratively run with the JKMRC, University of Queensland, from 2005 to 2013. In these projects, an array of geometallurgical methods and

protocols were developed in the areas of mineralogy, comminution, heap leaching and flotation – and were tested on case study sites culminating in the publication of a series of technical reports released to the AMIRA sponsors.

The outcomes of the GeM<sup>III</sup> project provided a solid foundation for further research, particularly in relation to understanding mineralogical and textural controls on processing performance. Further research in this field is active both within the current AMIRA P1202 Module 4 project (described under the TMVC section) and as part of CRC ORE's (Cooperative Research Centre for Optimising Resource Extraction) remit, of which CODES is an Essential Research Participant.

CRC ORE aims to support mining sector growth through implementation of technological innovations in minerals characterisation, extraction and processing. Fundamental to CRC ORE's research is the concept of Grade Engineering®, which provides the ability to improve mill feed quality by implementing specific technological levers at critical points in the extraction and processing circuit. CRC ORE's research is organised into five programs: Define, Separate, Extract, Control and Operate. Project P1:006 ('Predictive geometallurgical controls on grade by size fractionation'), which operates at CODES, sits within Program 1 – Define.

This P1:006 project aims to evaluate the geological controls that influence the preferential partitioning of ore phases between different size fractions during early comminution stages (blasting, crushing). The tendency for some ores to naturally fractionate ore minerals into finer size fractions, termed natural deportment, is fundamental to effective Grade Engineering® levers that upgrade ores by size-based screening. Using a range of deposit and mineralisation styles, P1:006 will evaluate the geometallurgical drivers that influence natural grade by size deportment. The workflow will integrate existing geological, geochemical, mineralogical and metallurgical data sets with innovative new technologies for mapping mineralogy and geochemistry in drill cores to provide



(TOP) Dr Julie Hunt, leader of Program 2, giving a presentation during the 2019 CODES Annual Review in November. (BOTTOM) Cover of the special issue of Economic Geology, published in 2019, that focussed on geometallurgy and was co-edited by Dr Julie Hunt and Associate Professor Ron Berry from CODES.

predictive indices relating to the amenability of ore domains to Grade Engineering® levers.

Additional geometallurgical research activities at CODES are being carried out under the Optimising Geometallurgical Prediction and Minimising Geoenvironmental Risks themes within the ARC Industrial Transformation Research Hub – Transforming the Mining Value Chain (TMVC). The largest of these projects is the major AMIRA P1202 Module 4 sub-project which includes four PhD projects and six study sites. The project will develop new workflows for ore characterisation, specifically in porphyry-epithermal transition zones. This and several other stand-alone geometallurgy sub-projects within the TMVC Research Hub are described in the TMVC section of this report.

OPPOSITE PAGE: (TOP) Fieldwork in western Tasmania: TMVC PhD student Sibebe Nascimento taking samples from Haulage Creek for her PhD into reprocessing opportunities for mine waste in Macquarie Harbour. (BOTTOM) TMVC PhD student Annah Moyo working in the lab at UTAS on her project, which looks at how to control acid and metalliferous drainage at legacy mine sites in Tasmania using industrial waste materials.



The Renison Processing Plant in western Tasmania uses gravity concentration for the recovery of tin; here some of the shaking tables used in this process are shown. The picture was taken during the November 2019 'Geometallurgy' Masters course.



Dr Angela Escolme (left) and Alina Gaibor (BHP) during a fieldwork campaign to review drill core at the Spence porphyry deposit, Chile, as part of the AMIRA P1202 Module 4 project.

## Highlights

- New appointments to the Program's senior team members in 2019 include Dr Julie Hunt (Postdoctoral Research Fellow – Geometallurgy), who is Program Leader and leader for CRC ORE Project P1:006, and Dr Angela Escolme (role change to Researcher and Lecturer in Geology and Geometallurgy) who continues as Deputy Leader and leader of AMIRA Project P1202 Module 4. Dr Clare Miller will take up her appointment as Researcher and Lecturer in Geology and Geoenvironment, and generate new geoenvironmental research initiatives, in early 2020.
- The Master of Economic Geology short course on Geometallurgy (KEA711) was held for the fifth time in November 2019 and attended by a high turnout of 25 students. The course was coordinated by Dr Hunt and Dr Escolme and included a number of guest speakers.
- Publication of an *Economic Geology* Special Issue dedicated to Geometallurgy, co-edited by Dr Hunt, Associate Professor Ron Berry, Dr Megan Becker (University of Cape Town) and Dr Regina Baumgartner

(Teck Resources) with articles by Dr Escolme (featured on the issue's front cover) and Dr Cassady Harraden (Corescan).

- Completion of Honours thesis by Le Xi K'ng, titled 'Geochemical and mineralogical characterisation of tailings: Evaluating the potential for reprocessing the Bobadil Tailings, Rosebery' (sits within TMVC Theme 3).
- Completion of Honours thesis by Johanna van Balen titled 'Mineralogical and geochemical properties of tailings at Copper Mines Tasmania: Opportunities for metal recovery' (sits within TMVC Theme 3).
- TMVC PhD student Sibebe Nascimento received an award for a best student presentation at the SGA conference, Glasgow (August 2019).
- Dr Hunt and MSc student Nathaly Guerrero attended the CRC ORE Annual Assembly in Brisbane October where Dr Hunt gave an oral presentation on research project updates and Nathaly Guerrero gave a poster presentation summarising her work to date.
- Dr Hunt gave an oral presentation at SGA 2019, Glasgow, and Dr

Escolme and PhD students Javier Merrill (TMVC) and Angela Rodrigues (Monash-based) presented oral presentations at SEG 2019, Santiago.

### Technology transfer

Dr Escolme and Dr Scott Halley (Mineral Mapping) presented three workshops during 2019 for the AMIRA P1202 Module 4 sponsor group covering new developments and case studies in using whole rock geochemistry to understand mineralogy.

Dr Hunt and MSc student Nathaly Guerrero also participated in project development meetings and the CRC ORE annual assembly in Brisbane.

Dr Escolme also gave a public seminar in Hobart called 'Copper rocks! Red metal and green energy' as part of the 'Science in the Pub' initiative where she discussed the importance of the critical metal copper and its primary sources.

### Short courses

Dr Hunt and Dr Escolme co-ordinated the Master of Economic Geology short course on Geometallurgy (KEA711) in November 2019, the fifth time the course has been run at CODES. This year the course had 25

participants: 16 Masters students, two industry participants and seven other students, with attendees travelling from as far afield as the USA and the Philippines. Guest speakers included Dr Toni Kojovic (SimSAGE), Dr Teresa McGrath (Curtin University), Joe Pease (Mineralis), Clint Bowker (Bureau Veritas), Dr Luke Keeney (CRC ORE), Sefton Darby (KPMG), Dr Kathy Ehrig (BHP), Karyn Gardner (Newcrest Mining Ltd) and Associate Professor Steinar Ellefmo (NTNU). Participants made an excursion to the ALS Metallurgy Lab, Burnie, and processing plants on Tasmania's West Coast at Hellyer (Hellyer Gold Mines Pty Ltd) and Renison Bell (Bluestone Resources) where they were given extensive tours by the company representatives.

### Conferences

In 2019 research outcomes from Themes 2 and 3 of the ARC TMVC Hub, which has substantial crossovers with CODES Program 2, were presented by staff and students at international conferences, including SGA 2019 in Glasgow (Sibebe Nascimento) and SEG 2019 in Santiago (Dr Angela Escolme, Javier Merrill and Angela Rodrigues (Monash)). Presentations given were on a range of topics including:

- 'Geoenvironmental characterisation of the King River Delta: A combined geophysical, geochemical and mineralogical approach' by TMVC PhD student Sibebe Nascimento, which was awarded a Best Student Presentation prize at SGA 2019, Glasgow.
- 'Quantitative textural assessment of hyperspectral imagery of drill core to guide sample selection' from TMVC student Javier Merrill's PhD research (AMIRA P1202 Module 4).
- 'Automated mineral classification from hyperspectral imagery through semantic segmentation' from Angela Rodrigues' (Monash) PhD research (AMIRA P1202 Module 4).
- Dr Hunt was co-author on a keynote presentation on the changing face of metal extraction, SGA 2019, Glasgow.
- Dr Escolme presented research on approaches to predicting quantitative mineralogy from whole rock geochemistry.

## The program team

### LEADER

JULIE HUNT

### DEPUTY LEADER

ANGELA ESCOLME



### TEAM MEMBERS:

Ron Berry, David Cooke, Jonathan Cloutier, Matthew Cracknell, Leonid Danyushevsky, Sebastien Meffre, Paul Olin, Michael Roach

### PHD STUDENTS:

Takeshy Coaquira, Kyle Eastman, Laura Jackson, Javier Merrill, Annah Moyo, Sibebe Nascimento, Angela Rodrigues (Monash), Yi Sun

### MASTERS STUDENT:

Nathaly Guerrero

### HONOURS STUDENTS:

Le Xi K'ng, Johanna van Balen

### COLLABORATORS:

**ALS GLOBAL**  
Shengli Zhao

### BHP

Mario Avendaño, Alina Gaibor, Simon Gatehouse

### CENTRAL SCIENCE LABORATORY (UTAS)

Sandrin Feig, Karsten Goemann

### COPPER MINES OF TASMANIA

Geoff Cordery

### CORESCAN

Neil Goodey, Cassady Harraden

### CRC ORE

Luke Keeney, Paul Revell, Greg Wilkie

### CSIRO

Louise Fisher, Carsten Laukamp, Mark Pearce

### CURTIN UNIVERSITY

Teresa McGrath

### FMG

Cameron Quinn, Dana Olafson

### MERDEKA COPPER GOLD

Julian Bartlett, Rob Taube

### MINALYZE

Annelie Lundström, Mark Manly, Angus Tod

### MINERAL RESOURCES TASMANIA

Ralph Bottrill, David Green, Andrew McNeill, Carol Steyn

### MMG

Steve Scott

### NEWCREST MINING

Karyn Gardner, Anthony Harris, Mary Harris

### RIO TINTO

Paul Agnew, Debora Araujo, Adam Pacey, Michael Whitbread

### OLYMPUS AUSTRALIA

Dane Burkett, Jake Jarvinen

### OREXPLORE

Rob Downard, Russell McChesney

### TERRACORE

Paul Linton

### TRUSCAN

Shaun O'Brien

### CARL ZEISS MICROSCOPY

Shaun Graham

## Project

Geological controls on grade by size fractionation (CRC ORE P1:006)

*NB. The majority of geometallurgy and geoenvironment activities are reported in the TMVC section of this annual report.*

## Project summary

### GEOLOGICAL CONTROLS ON GRADE BY SIZE FRACTIONATION (CRC ORE P1:006)

**Leader:** Julie Hunt (joined June 2019)

**Team members:** Ron Berry, Matthew Cracknell, Angela Escolme, Michael Roach

**Student:** Nathaly Guerrero

**Collaborators:** Luke Keeney, Paul Revell, Greg Wilkie

This is a CODES–CRC ORE (Cooperative Research Centre for Optimising Resource Extraction) collaborative project and is focussed on understanding the geological controls on grade by size fractionation. In some rocks, mineral phases naturally preferentially fractionate into specific size fractions when the rock is broken. This propensity can be exploited and has the potential to generate an upgraded ore stream through rejection of lower-grade, larger-sized particles. Thus, reducing the amount of energy and water usage in later grinding and processing steps. It can also be used to upgrade very low-grade ore or mineralised waste leading to a reduction in the amount of material sent to waste dumps. The project began in 2016 but had a change of staff and students at CODES in 2019 with the departure of researcher Dr Nathan Fox and two students, and the appointment of researcher Dr Julie Hunt and the arrival of new student Nathaly Guerrero. Karla Morales will join as a Masters student in January 2020.



*CODES Honours student Johanna van Balen undertaking fieldwork at Princess Creek Tailings Storage Facility for her research on the mineralogical and geochemical properties of tailings dams in Tasmania, which sat within Program 2 and TMVC Theme 3. With her is Stuart Isles, an IMAS student who acted as skipper on the field trip.*

Research within this project is directed towards identifying predictors for pre-concentration from intact rocks and drill core and is divided into an over-arching research stream and two Masters projects. One Masters project is focussed on grade by size deportment of gold using the Gramalote and Telfer deposits as examples; this is being undertaken by Nathaly Guerrero. The second is directed towards establishing a library of mineralisation styles that show a tendency for pre-concentration in early comminution stages and will begin in 2020. Within the main research stream there are several projects:

- A project on grade by size fractionation of gold at the Carosue Dam project, WA, which was completed in 2019.
- Grade by size fractionation of copper and gold at a Chilean porphyry deposit is ongoing.
- The commencement of a library of grade by size fractionation response for various mineralisation styles at different deposit types (e.g., porphyry, Sedex, VHMS, fault-related) will begin in early 2020 with the ultimate aim of early prediction of amenability for pre-concentration.

As part of the project, researchers and students are testing equipment for its suitability to assist with predicting grade by size response. In 2019 this included measurement of elements and mineralogy (e.g., portable XRF, micro XRF, bench-scale XRF, hyperspectral

SWIR & TIR) and rock hardness (e.g., Equotip). In 2020 this will be expanded to include geological structures (e.g., automated systems for RQD), petrophysical parameters, 3D views (e.g., XRT), geochemistry (e.g., photon assay) and additional mineralogy equipment (e.g., LIBS). This work will be done in conjunction with a range of equipment suppliers and labs (e.g., CSIRO, Minalyze, Orexplore, Hylogger, TerraCore, Corescan and TruScan).

## Looking forward

The year ahead will see the major projects under Program 2 and the TMVC (CRC ORE P1:006 and AMIRA P1202 Module 4) begin to move towards their completion in mid-2021. Dr Hunt, Dr Escolme and Dr Miller will be developing a major new research initiative to succeed these projects. Dr Miller will also be working closely with Mineral Resources Tasmania in 2020 as part of the Mining Sector Innovation Initiative Program (MSIIP) that will include three Honours projects at sites around Tasmania. A new Masters student will also join the CRC ORE research team.

*OPPOSITE: CODES Masters student Nathaly Guerrero taking hardness measurements using Equotip while working at the CRC ORE facilities in Brisbane.*



## Program Three

# Sedimentation, tectonics and Earth evolution



### Objective

This program aims to understand the formation and evolution of sedimentary basins, including their metamorphic and deformation histories, within the broader context of geodynamic processes and Earth evolution through time. Our goal is ultimately to develop new and refined genetic and exploration models for diverse sediment-hosted mineral systems across all time periods of Earth history.



### Introduction

**Program 3: Sedimentation, tectonics and Earth evolution** encompasses all aspects of sedimentary basin geologic history and the development of life on Earth, including how cycles of marine geochemistry profiles and craton amalgamation may influence the location and timing of sediment-hosted mineral systems. This has a direct impact on the search for, and understanding of, a vast array of ore types, including sedimentary exhalative (SEDEX) Zn-Pb-Ag, Broken Hill-type Ag-Pb-Zn, sediment-hosted orogenic Au, and Zambian-style Cu-Co-Au.

### Highlights

Ongoing projects within Program 3 include the Kansanshi gold project, funded by Kansanshi Mining, the ARC Linkage project entitled 'Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia' and 'Mineral chemistry vectoring: uncovering Northwest Queensland's hidden potential' supported by the Geological Survey of Queensland as part of the Strategic Resources Exploration Program.

### Publications in 2019

During 2019, Program 3 researchers published a number of papers, including a series of papers co-authored by Dr Indrani Mukhujee, Professor Ross Large, Dr Jeff Steadman and Professor Leonid Danyushevsky on the implications of changes in pyrite chemistry for the formation of sediment-hosted base metal deposits and the evolution of ocean chemistry over geological time. A book chapter was published by Associate Professor Shaun Barker on the use of carbon and oxygen isotopes for exploration of carbonate-hosted ore deposits, intended as a 'how to' guide for explorers.

*Mineral Resources Tasmania geologist Grace Cumming sampling Proterozoic sequences in northwestern Tasmania for the 'Building Tasmania' project.*



▶ *OPPOSITE PAGE: (TOP) L-R: Former CODES Honours students Josh Denholm and Ben Kowaluk pictured with CODES PhD students Joseph Knight and Tom Schaap on day four of a six-day hike along Tasmania's South Coast Track in April 2019. Tom was attempting to reach outcrops for palaeomagnetic sampling to be used for his research connected with the Lachlan Orogen project. (BOTTOM) Geology consultant Nick Oliver with geologists from Glencore and the Geological Survey of Queensland inspecting rocks surrounding the Mary Kathleen uranium deposit, northwest Queensland, as part of the Program 3 project looking into uncovering northwestern Queensland's hidden potential.*

# The program team

**LEADER** SHAUN BARKER  
**DEPUTY LEADER** JEFF STEADMAN

## TEAM MEMBERS:

Ron Berry, Stuart Bull, Jonathan Cloutier, David Cooke, Matthew Cracknell, Leonid Danyushevsky, Ross Large, Peter McGoldrick, Sebastien Meffre, Indrani Mukherjee, Karin Orth, Michael Roach, Robert Scott, Sasha Stepanov, Irina Zhukova

## PHD STUDENTS:

Alexander Cherry, David Douth, Alex Farrar, Umer Habib, Jacob Heathcote, Max Hohl, Christopher Leslie, Elena Lounejeva, Thomas Schaap, Tristan Wells

## MASTERS STUDENTS:

Chloe Cavill, Batbayar Enkhbold, Brendan Hardwick, Corey Jago, Sitthinon Kultaksayos, George Maroa, Peerapong Sritangsirikul

## HONOURS STUDENTS:

Hamish Cowie, Darcy James, Verity Kameniar-Sandery

## COLLABORATORS:

### AUSTRALIAN NATIONAL UNIVERSITY

Janaina Avila, Trevor Ireland, Marc Norman

### CENTRAL SCIENCE LABORATORY (UTAS)

Sandrin Feig, Karsten Goemann

### CSIRO

James Austin

### CURTIN UNIVERSITY

William Collins

### FIRST QUANTUM MINERALS

Tim Ireland, Louis van Heerden

### FLINDERS UNIVERSITY

John Long

### GEOLOGICAL SURVEY OF NSW

John Greenfield, Robert Musgrave

### GEOLOGICAL SURVEY OF QUEENSLAND (DEPARTMENT OF NATURAL RESOURCES, MINES AND ENERGY)

Vladimir Lisitsin



### GEOSCIENCE AUSTRALIA

David Huston

### IMEX CONSULTING

Mark Arundell

### INSTITUTE FOR MARINE AND ANTARCTIC STUDIES (IMAS)

Jacqui Halpin, Joanne Whittaker

### MACQUARIE UNIVERSITY

Elena Belousova

### MINERAL RESOURCES TASMANIA

Ralph Bottrill, Clive Calver, Grace Cumming, John Everard, Andrew McNeill, Mike Vicary

### MONASH UNIVERSITY

Jacob Mulder

### RUSSIAN ACADEMY OF SCIENCE, RUSSIA

Valeriy Maslennikov

### TASMANIAN INSTITUTE OF AGRICULTURE (UTAS)

Ross Corkrey

### UNIVERSITY OF DELHI, INDIA

Mihir Deb

### UNIVERSITY OF MELBOURNE

Roland Maas

### UNIVERSITY OF MISSOURI, USA

Ray Coveney

### UNIVERSITY OF PORTSMOUTH, UK

David Loydell

### UNIVERSITY OF TORONTO, CANADA

Dan Gregory

### UNIVERSITY OF QUEENSLAND

Rick Valenta

### UNIVERSITY OF WESTERN ONTARIO, CANADA

Nigel Blamey

### US GEOLOGICAL SURVEY, USA

Karen Kelley, John Slack

### YUKON GEOLOGICAL SURVEY, CANADA

Patrick Sack



## Projects

### Trace elements in ancient oceans

### Kansanshi gold

### Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia

### Building Tasmania: The Cambrian and beyond

### Ore deposit cycles and ocean/atmosphere conditions

### Mineral geochemistry vectoring: Uncovering Northwest Queensland's hidden potential

## Project summaries

### TRACE ELEMENTS IN ANCIENT OCEANS

**Leader:** Ross Large

**Team members:** Leonid Danyushevsky, Indrani Mukherjee, Jeff Steadman, Sasha Stepanov, Irina Zhukova

**Collaborators:** Ross Corkrey, Trevor Ireland, John Long, David Loydell, Valeriy Maslennikov

This project uses the trace element content of sedimentary pyrite through time to interpret changes in the trace element content of past oceans and relationships to atmospheric oxygen. This study combines the results from two totally different methods to estimate atmosphere oxygen concentrations during the Precambrian and Phanerozoic. Firstly, measurements of oxygen concentrations in sedimentary halite fluid inclusions by Nigel Blamey and colleagues at the University of Western

Ontario. Secondly, measurement of the Se/Co ratio in 2037 sedimentary pyrite grains from 310 black shale samples spread throughout the Precambrian determined by the CODES research team. By combining these two approaches we have derived the following relationship:

Atmosphere O<sub>2</sub>% = 8.5 x log (Se/Co<sub>pyrite</sub>) + 16.2; R<sup>2</sup> = 0.94

The oxygen curve revealed by this relationship suggests that atmospheric oxygen in the Archean varied from <1–8%, with a median value of 4%, and in the Proterozoic from <1–21% with a median value of 8%. The broad first order trend is one of increasing O<sub>2</sub> of <1–20% from 3500 to 1850 Ma followed by a general decrease to around 1–5% at 1000 Ma, but with a spike around 1400 Ma. Oxygen rises gradually through the Ediacaran to reach a maximum of 20–25% by the early Cambrian. These estimates of atmospheric oxygen are very different to the current published view that oxygen was very low (less than 1%) throughout most of the Archean and Proterozoic. The results are to be published in *Precambrian Research* (Steadman et al., in press).

An additional study of S-isotopes in sedimentary pyrite and their relationship to trace elements in the global ocean has shown the influence of major Large Igneous Province (LIP) events on past ocean chemistry and S-isotope cycles through time. This study has been submitted as a chapter in a book to be published by the American Geophysical Union, titled *The Deadly Kiss of LIPS*.

### KANSANSHI GOLD

**Leader:** Robert Scott

**Student:** Jacob Heathcote

**Collaborators:** Tim Ireland, Louis van Heerden

This research project commenced in early 2014 and is funded by Kansanshi Mining Plc (KMP), a subsidiary of First Quantum Minerals. PhD student Jacob Heathcote has been researching the origins, distribution, mineral associations and paragenesis of gold at the Kansanshi Cu-Au deposit in

NW Zambia. Key results from this study highlight the importance of (i) exsolution (i.e. chemical unmixing of minerals precipitated at higher temperatures) and recrystallisation, and (ii) variations in host rock composition, in determining certain aspects of metal and element distribution at the deposit.

### ORE DEPOSITS AND TECTONIC EVOLUTION OF THE LACHLAN OROGEN, SE AUSTRALIA

**Leaders:** Sebastien Meffre, David Cooke, Matthew Cracknell, Joanne Whittaker

**Team members:** Ron Berry, Michael Roach, Jeff Steadman

**Students:** Umer Habib, Corey Jago, Christopher Leslie, Peerapong Sritangsirikul, Thomas Schaap, Tristan Wells

**Collaborators:** Mark Arundell, Elena Belousova, William Collins, John Greenfield, David Huston, Roland Maas, Robert Musgrave, Marc Norman

This ARC Linkage project, aimed at understanding the geology, tectonic evolution and ore deposits of the Lachlan Orogen in southeastern Australia, has been running for the past three years. In 2019 the final data sets were collected and collated, including 1800 zircon analyses, 13000 chlorite and epidote analyses and 80 pyrite trace element maps, together with paleomagnetic, Re-Os and other geochemical data. These data sets form the basis of models for the Lachlan Orogen, including a new statistical analysis of ore deposit prospectivity undertaken by Dr Matthew Cracknell and a new computer-based plate tectonic model developed by Thomas Schaap that is able to rotate all of the project data, including the prospectivity map, back to their original positions prior to tectonism and deformation.



Dr Indrani Mukherjee, who is working on Program 3's 'Trace elements in ancient oceans' project, is seen here presenting the results of her research at the CODES Annual Review in November 2019.

## BUILDING TASMANIA: THE CAMBRIAN AND BEYOND

**Leaders:** Sebastien Meffre, Robert Scott

**Team member:** Ron Berry

**Student:** Darcy James

**Collaborators:** Ralph Bottrill, Clive Calver, Grace Cumming, John Everard, Jacqui Halpin, Andrew McNeill, Jacob Mulder, Mike Vicary

This project aims to:

- document the stratigraphic, depositional, sedimentological provenance and geochronological links between Tasmania and north-western America;
- define Tasmania's place within the Nuna Supercontinent;
- provide new insights into the Cambrian tectonic setting of the Gondwana Pacific margin; and
- refine the depositional age of turbidites comprising the Oonah Formation and their correlation with Mesoproterozoic turbidites exposed on King Island.

In 2019 the results of this project were published in a new paper (Mulder et al. 2019, <https://doi.org/10.1016/j.earscirev.2019.103041>). The paper presented a new stratigraphy for the Neoproterozoic of Tasmania based on detrital zircon geochronology and revised the tectonic history of the island

through that period. The research also showed that detrital zircons can be used to revise the existing geological maps of western Tasmania. This work led Mineral Resources Tasmania staff to use this technique for their current mapping campaigns.

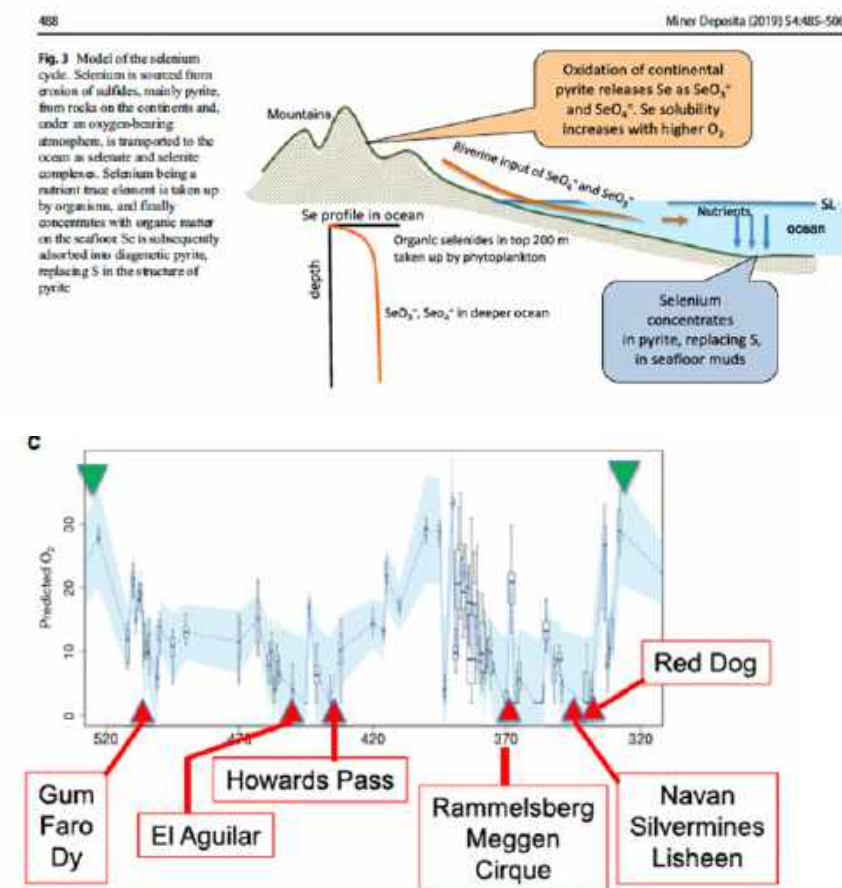
## ORE DEPOSIT CYCLES AND OCEAN/ATMOSPHERE CONDITIONS

**Leader:** Ross Large

**Team members:** Sebastien Meffre, Indrani Mukherjee, Jeff Steadman

**Collaborators:** Janaina Avila, Ross Corkrey, Ray Coveney, Mihir Deb, Dan Gregory, Sean Johnson, Karen Kelley, Valeriy Maslennikov, Patrick Sack, John Slack

The relationship between basin-hosted ore deposits and atmospheric oxygen was further investigated with a focus on sedimentary Cu deposits and sediment-hosted Zn-Pb-Ag deposits in 2019. A major breakthrough in quantifying the sedimentary pyrite proxy, based on the Se/Co ratio in pyrite, in terms of % O<sub>2</sub> in the atmosphere has led to a revolutionary understanding of oxygen trends. When compared to the timing of sediment-hosted Cu and Zn-Pb-Ag through Earth history, it becomes clear that sedimentary copper deposits have formed during periods of above average atmospheric oxygen, whereas Zn-Pb-Ag deposits have formed during periods of below average atmospheric oxygen. This work was published in *Mineralium Deposita* during 2019.



(TOP) Diagram from an article co-authored by Professor Ross Large and CODES colleagues in *Mineralium Deposita* showing that the selenium cycle from continent to ocean is controlled by atmospheric oxygen (see the 'Ore deposit cycles and ocean/atmosphere conditions' project). The article was titled 'Atmosphere oxygen cycling through the Proterozoic and Phanerozoic'. (BOTTOM) This diagram published during 2019 in *Mineralium Deposita* by Professor Ross Large and colleagues shows the relationship between predicted atmospheric oxygen determined from sedimentary pyrite, and the timing of major sediment-hosted zinc deposits. Stratiform zinc deposits form in sedimentary basins during periods of very low atmospheric oxygen (see the 'Ore deposit cycles and ocean/atmosphere conditions' project).

## MINERAL GEOCHEMISTRY VECTORING: UNCOVERING NORTHWEST QUEENSLAND'S HIDDEN POTENTIAL

**Leader:** Shaun Barker

**Team members:** Jonathan Cloutier, David Cooke, Peter McGoldrick, Robert Scott, Jeff Steadman

**Student:** Max Hohl

**Collaborators:** James Austin, Vladimir Lisitsin, Rick Valenta

Throughout 2019, the project team focussed on collecting new samples from the Lady Annie copper deposit and Starra IOCG deposit as part of the mineral chemistry 'footprint' studies being carried out to identify mineral chemistry vectors towards ore. A new PhD student (Max Hohl) joined the research team to work on the Starra IOCG deposit.

One of the key findings revealed by the project to date is a distinctive and systematic trend in the chemistry of pyrite associated with mineralisation throughout many of the IOCG deposits of northwest Queensland, which shows a distinct transition from high Co-low Ni to high Ni-low Co pyrite with time. This signature is similar to IOCG deposits from South America, suggesting that it may be a distinctive signature of IOCG deposits more broadly, which could be used by explorers to test whether pyrite encountered in drill core is likely to be associated with an IOCG mineral system.

Detailed study of carbonate-hosted copper mineralisation at the Lady Annie deposit reveals that copper mineralisation is associated with a late generation of carbonate which crosscuts earlier formed oscillatory zoned dolomite. This carbonate has a distinctive 'fingerprint' of high Mn, which is a common signature of mineralisation-associated carbonate cements in many types of carbonate-hosted ore deposit. Work is continuing to establish how far this elevated Mn signature in carbonate cements can be traced away from the Lady Annie Deposit.



Folded outcrop of alternating lenticular bands of pale to dark grey sandstone and siltstone from the Oonah Formation exposed along the shoreline 5 km northwest of Burnie. These rocks were being examined as part of the 'Building Tasmania' project.

## Looking forward

2020 will see the beginning of the Characterising pyrite chemistry of black shales hosting stratiform Zn-Pb-Ag: Application to mineral exploration' project, led by Professor Ross Large, Dr Indrani Mukherjee and Dr Jeff Steadman (see description in Program 1 section, with which this project has crossovers). This project will be focussing on developing new exploration tools for stratiform Zn-Pb-Ag deposits, and is being supported by Anglo American, First Quantum Minerals, the Geological Survey of Queensland, the Geological Survey of South Australia, DGO Ltd, Glencore, Red Metal, Rio Tinto, Sandfire Resources and Teck Resources. 2020 will see the continuation of the northwest Queensland mineral chemistry project, with exciting results anticipated from all of these new and ongoing initiatives.

# Program Four Magmatic and volcanic processes



## Objective

This program investigates volcanic processes, products, and architectures, magma fertility, and the roles of mantle and crustal processes in magmatic-hydrothermal mineral systems.

## Introduction

**Program 4: Magmatic and volcanic processes** conducts fundamental research about magma genesis, ascent and eruptions in a range of tectonic settings, and subaerial and submarine environments. Some of our research provides end users with a magmatic and volcanic framework to determine the most prospective regions for exploration and for targeting buried ore deposits.

We have an international profile in magmatic and volcanic processes research, which is reflected in the collaborative network of industry, research institutions, volcano observatories, oceanographic institutes and other universities that we work with.

## Highlights

### Student achievements

2019 was the year of PhD graduations! It was a fantastic year with five PhD graduations and three PhD submissions within Program 4: Daniele Vergani, Jodi Fox, Sam Holt, Brian McNulty and Naomi Potter all graduated in 2019. David Douch, Matt Ferguson and Adam Abersteiner submitted their theses for examination in 2019. We wish all of these students the very best in their future careers.

Daniele Vergani's research was conducted in collaboration with the Observatory of Piton de la Fournaise on Reunion Island, Indian Ocean. His research topic was focussed on three different eruptive phases of the 2007 eruption of Piton de la Fournaise. Daniele is currently writing up his research while working as a geologist.

*OPPOSITE PAGE: (TOP) The Evolution Mining core yard at Cowal, NSW, with CODES Honours student Claudia Jenkins examining core on a stormy day. Claudia was working in the 'Volcanology research related to ore deposits' project. (BOTTOM) Cruise Chief Scientist Associate Professor Jo Whittaker (IMAS), examines basalt and mafic volcanoclastics that have been dredged up from the seafloor during the 30-day voyage to the Coral Sea on board the RV Investigator. Dr Karin Orth from CODES worked alongside Jo on this voyage.*

Jodi Fox's PhD research on complex volcanic architecture produced by basaltic submarine and emergent volcanism in intraplate settings was completed in 2019. Jodi's research on Heard Island (Australian Antarctic Territory) is the basis of one paper in progress, and she is extending this research in her postdoctoral appointment working with Dr Rebecca Carey, Dr Jacqui Halpin and Associate Professor Jo Whittaker at IMAS in 2020.

Sam Holt's PhD research on explosive eruption dynamics in Hawaii was completed in 2019. The first paper from his research was also published in 2019, titled 'Eruption and fountaining dynamics of selected 1985–1986 high fountaining episodes at Kilauea volcano, Hawai'i, from quantitative vesicle microtexture analysis' in the *Journal of Volcanology and Geothermal Research*.

Brian McNulty completed his PhD research during 2019 on the lithological setting and geochronology of the West Block area at the Myra Falls VHMS district on Vancouver Island, Canada. Brian's research has advanced the overall understanding of the H-W member stratigraphy, the nature of hydrothermal alteration, and the temporal relationship of felsic host rocks at Myra Falls. These advancements have implications for the geology, genesis and explorations of the Myra Falls district VHMS deposits, as well as for mineral exploration throughout Vancouver Island.

Naomi Potter is also a 2019 PhD graduate. Her thesis is titled 'The origin and evolution of intrusive and extrusive carbonatites'. While completing her PhD Naomi also published her Honours research with Rebecca on Etna volcano, Italy, in 2019. This research paper is in the *Journal of Volcanology and Geothermal Research* and is titled 'Eruption dynamics of the 23 February 2013 event at Mt. Etna'. Naomi is working as a spectral geologist in Western Australia and we wish her the best in her future career.

David Douch's PhD project (see summary in Program 1) on the controls on gold mineralisation at the Invincible gold deposit has provided a wealth of new understanding on the volcano-sedimentary Neoarchaeon Black Flag

and Merougil Groups, and concluded that the conglomerates found therein are the product of diapiric uplift related to the intrusion of large granite batholiths rather than conventional tectonic models of regional deformation. David submitted his PhD research for assessment in 2019.

Matt Ferguson's PhD thesis 'Late stage magmatic evolution of A-type rocks around and to the southeast of Olympic Dam, South Australia', was submitted in 2019 and contained three published papers:

- Insights into magma histories through silicate-oxide crystal cluster: Linking the Hiltaba Suite intrusive rocks to the Gawler Range Volcanics, Gawler Craton, South Australia.
- From magma to mush to lava: crystal history of voluminous felsic lavas in the Gawler Range Volcanics, South Australia.
- Association between zircon and Fe-Ti oxides in Hiltaba event magmatic rocks, South Australia: atomic- or pluton-scale processes?

Adam Abersteiner submitted his PhD in 2019 and by the time of submission he had published nine papers in high-ranked journals as the first author, and 12 papers as a co-author. It is such an exceptional result! The Chair of Examiners, Associate Professor Ron Berry, commented: "I have never heard of a PhD candidate who published 9 papers during his candidature". After submission Adam received a prestigious APR Internship (Australian Institute of Mathematics & Science and BHP Olympic Dam) to work on sulfur isotopes in Olympic Dam. His project aims to elucidate isotopic variations in sulfur and lead in sulfate and sulfide minerals across the Olympic Dam U-Cu-Au-Ag super giant deposit in South Australia.

### Awards

Dr Rebecca Carey won the 2019 Tasmanian Young Tall Poppy Scientist of the Year Award for her research on volcanology in modern and ancient terrains and her outstanding ongoing efforts to communicate her science to the wider community. She was presented with the award in a ceremony at the Sandy Bay campus



In August 2019 Dr Karin Orth took part in a 30-day voyage to the Coral Sea on board the RV Investigator to study hotspot dynamics; here the group of expeditioners and crew are pictured in the bow of the ship. (Photo taken by Huw Morgan, CSIRO. © Copyright CSIRO Australia.)

on 15 October. These awards, which are run by the Australian Institute of Policy and Science (AIPS), recognise outstanding early-career researchers' efforts within their chosen field, with particular emphasis on the work they have undertaken to spread the word about the importance of their science to the broader community.

CODES PhD student Adam Abersteiner received the Peter W. Smith CSL Postgraduate Award from UTAS for producing the most outstanding peer-reviewed publication in the past 12 months by a UTAS student making extensive use of the Central Science Laboratory.

#### Major funding awards

This year has been highly successful for our Program 4 team in the acquisition of different types of research funding for our fundamental and applied research.

#### Australian Research Council Linkage Grant with Geological

#### Survey of NSW and Industry

**Partners:** Dr Rebecca Carey was successful as Chief Investigator in receiving funding for an ARC Linkage project titled *Exploration targeting from next-generation volcanic facies reconstruction (2020–2023)*. Dr Martin Jutzeler will be senior research fellow on this project along with CIs Professor Ray Cas, Professor David Cooke, Associate Professor Sebastien Meffre and Associate Professor Shaun Barker. The project aims to reconstruct the architecture of the volcanic host at Cowal mine, NSW, and Waihi mine in New Zealand. It will be based on traditional facies analysis augmented with the development of an automated image analysis technique based on crystal size distribution. Expected outcomes of this project include next-generation techniques for volcanic facies analysis, and predictions of where hydrothermal alteration is most prospective for mineralisation.

#### Australian Research Council Discovery Grant:

Dr Rebecca Carey was successful as Chief Investigator in receiving funding for an ARC Linkage project titled *Exploration targeting from next-generation volcanic facies reconstruction (2020–2023)*. Dr Martin Jutzeler will be senior research fellow on this project along with CIs Professor Ray Cas, Professor David Cooke, Associate Professor Sebastien Meffre and Associate Professor Shaun Barker. The project aims to reconstruct the architecture of the volcanic host at Cowal mine, NSW, and Waihi mine in New Zealand. It will be based on traditional facies analysis augmented with the development of an automated image analysis technique based on crystal size distribution. Expected outcomes of this project include next-generation techniques for volcanic facies analysis, and predictions of where hydrothermal alteration is most prospective for mineralisation.

**Australian Research Council Discovery Grant:** Professor Vadim Kamenetsky was successful in his application, with Professor Penny King (ANU), for a grant of \$497,000 (covering the period 2020–2023). The project title is *Impact of hot gas on volcanic rocks and ore-forming processes*, and the project will be administered by the ANU.

#### Australian Antarctic Science

**Program:** In 2019 Dr Rebecca Carey was successful with two project grants with the Australian Antarctic Science Program. The first grant, *Opening of the Tasman sea and the separation of Australia and Antarctica: temporal and isotopic constraints to further test the deep-seated Balleny plume vs. tectonic reorganization models*, will support research by Dr Carey and Associate Professor Jo Whittaker (IMAS) to elucidate hot spot volcanism related to the Balleny mantle plume and its role in the separation of Australia and Antarctica.

The second grant, *The re-awakening of a mantle plume – the nature and petrogenesis of Neogene volcanism on the Central Kerguelen Plateau*, will support research on the Kerguelen Plateau by Dr Trevor Falloon, with Dr Jodi Fox as his postdoctoral researcher.

**ANZIC IODP grant:** Dr Rebecca Carey and Dr Martin Jutzeler were also successful with a grant from the Australia and New Zealand International Consortium of the International Ocean Discovery Program, *Volcanic architecture and eruption behaviour at Site U1347 Izu-Bonin-Mariana rear-arc, IODP Leg 350*.

#### International workshops/presentations

In 2019 Dr Rebecca Carey co-led a postgraduate-level volcanology field trip to New Zealand with Honours students from UTAS and PhD students from the University of Hawaii. This year's field trip included PhD student Jodi Fox, and Honours students Acacia Clark and Imbi Simpson. They were extremely lucky with the weather and were able to have a clear blue skies trip over Tongariro Volcanic Complex. Further, they were able to access forestry areas around Lake Taupo to examine in detail the products of the 181 AD eruption of Taupo volcano.

Dr Martin Jutzeler participated in the IODP-ANZIC Ocean Planet Decadal Plan Workshop at Canberra in April 2019. This three-day workshop with Australian and New Zealand geoscientists aimed at developing new scientific themes and goals for

the next decade of ocean drilling with the International Ocean Discovery Program (IODP). The workshop outcomes from our region will be bundled up with international partners by IODP to propose a new decadal plan of research in the deep sea.

#### International visitors

Two international high-profile volcanologists visited CODES/Earth Sciences in 2019: Professor Bruce Houghton from the University of Hawaii, who worked together with Dr Rebecca Carey, Dr Martin Jutzeler, Dr Karin Orth and Honours students Imbi Simpson and Acacia Clark; and Dr David Lund from the University of Connecticut, USA, who will be working with Dr Carey and Associate Professor Zanna Chase (IMAS) on relationships between glacial-interglacial cycles and mid-ocean ridge volcanic and hydrothermal activity.

#### Voyages

In 2019, our team developed a series of proposals to the CSIRO–Marine National Facilities to obtain ship-time on board the RV *Investigator*, the national ocean-going research flagship. The RV *Investigator* is 94 m in length and can host up to 40 scientists for up to two months at sea. Various science can be achieved onboard, with a strong focus on geosciences through acquisition of high-resolution multibeam bathymetry, sub-bottom profiling, seismic reflection, deep-water camera footage, sediment coring, and dredging. Its availability to Australian researchers is based on a competitive basis through an annual proposal process.

In 2019, Dr Martin Jutzeler obtained ship-time funding for four voyages for 2020–2022, three as lead Chief Scientist and two of which will have Dr Rebecca Carey as co-chief scientist. Further, Dr Carey obtained funding for a voyage in 2021 as Chief Scientist. Altogether, the five voyages are worth \$18.7M for a total of 174 days at sea. To secure these voyages is a considerable achievement for our team, and a mark of trust and confidence from the Marine National Facilities. These voyages have a strong international contingent of collaborators from New Zealand, the UK, the USA, Germany and

Indonesia. Three of the expeditions have a combined volcanology and sedimentary volcanology focus, whereas two voyages address landslides on the continental shelf, and are detailed in the 'Sedimentary volcanology' project summary below.

This year our Program 4 team also participated in two voyages on the RV *Investigator*. In January, Dr Rebecca Carey, Dr Martin Jutzeler, Dr Karin Orth, Associate Professor Jo Whittaker (IMAS), PhD student Tom Schaap and three Earth Sciences undergraduate students had a highly successful research voyage on board the RV *Investigator* to the Tasman Sea. The purpose of the voyage was to collect carbonate and volcanic rocks from a hypothesised age progressive (80 Ma to present) volcanic chain in the Tasman Sea to date the timing of volcanism and volcano submergence. This data will be used to test the hypothesis that the Balleny mantle plume played a significant role in the plate tectonic breakup between Tasmania and Antarctica.

In August 2019, Dr Karin Orth participated in a 30-day voyage on board the RV *Investigator* to the Coral Sea to look at 'Hotspot dynamics in the Coral Sea: connections between the Australian plate and deep Earth'. The team were highly productive with over 50 dredges of seamounts, plateaux and trenches in the Coral Sea, and those rocks will be studied in 2020 funded by a new ARC Discovery grant.

#### Publications in 2019

During 2019, 18 papers were published in international peer-reviewed journals by researchers within Program 4; nine of them by the igneous petrology, geochemistry and studies of Olympic Dam group led by Professor Vadim Kamenetsky, and nine by the volcanology group led by Dr Rebecca Carey. The majority of these articles were published in A\* and A journals.

# The program team

**LEADER** REBECCA CAREY

**DEPUTY LEADER** VADIM KAMENETSKY

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Sharon Allen, Shaun Barker, Heidi Berkenbosch, Ron Berry, Stuart Bull, Jonathan Cloutier, Leonid Danyushevsky, Paul Davidson, Trevor Falloon, Jodi Fox, Bruce Gemmell, David Green, Martin Jutzeler, Maya Kamenetsky, Ross Large, Charles Makoundi, Jocelyn McPhie, Sebastien Meffre, Paul Olin, Karin Orth, Robert Scott, David Selley, Jeff Steadman, Jay Thompson, Khin Zaw

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**UNIVERSITY OF NEWCASTLE, NSW**  
Hannah Power

**UNIVERSITY OF NEW HAMPSHIRE, USA**  
Alexander Proussevitch

**UNIVERSITY OF NOTRE DAME, USA**  
Anthony Simonetti

**UNIVERSITY OF OREGON, USA**  
Ilya Bindeman

**UNIVERSITY OF OTAGO, NEW ZEALAND**  
James White

**UNIVERSITY OF OTTAWA, CANADA**  
Mark Hannington

**UNIVERSITY OF OXFORD, UK**  
Michael Cassidy, Ekaterina Kiseeva

**UNIVERSITY OF SOUTHAMPTON, UK**  
Robert Marsh, Rex Taylor

**UNIVERSITY OF SYDNEY**  
David Airey, Samantha Clarke, Tom Hubble, Michael Kinsela,  
Maria Seton

**UNIVERSITY OF UTRECHT, NETHERLANDS**  
Erik Van Sebille

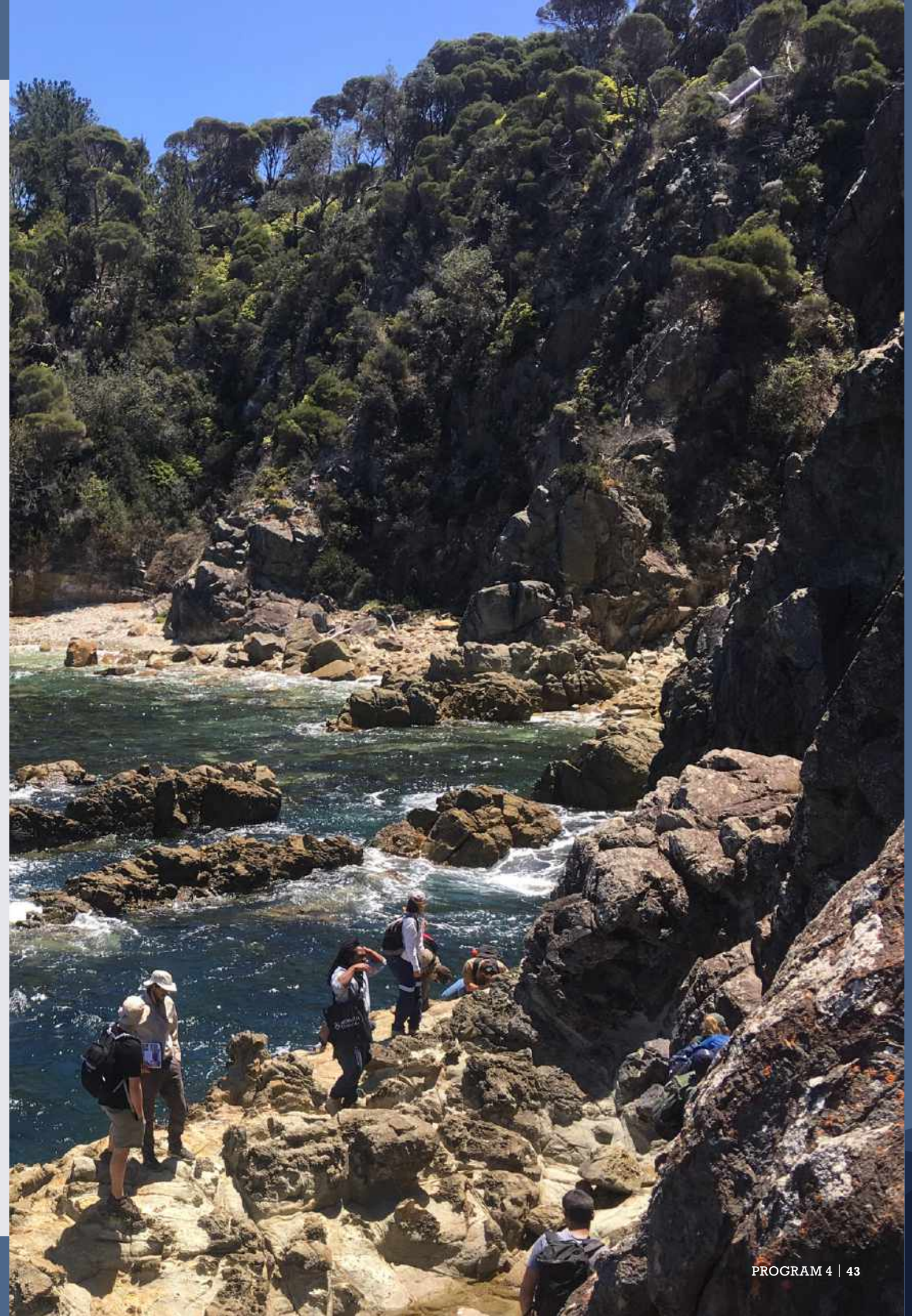
**UPPSALA UNIVERSITY, SWEDEN**  
Abigail Barker

**VANDERBILT UNIVERSITY, USA**  
Kristen Fauria

**WESTERN WASHINGTON UNIVERSITY, USA**  
Sue DeBari

**WOODS HOLE OCEANOGRAPHIC INSTITUTION, USA**  
Daniel Fornari, Adam Soule

*Dr Martin Jutzeler (in black tee-shirt)  
teaching part of the CODES/Monash  
'Volcanic Processes, Products,  
Successions and Resources' short  
course at Merimbula, NSW, during  
December 2019.*



# Projects

Volcanology research related to ore deposits

Subaerial and submarine volcanology and natural hazards

Sedimentary volcanology

Stability of the continental shelf

Pegmatites and pegmatite-related ores

Kimberlites and flood basalts: Linking primary melts with mantle and crustal sources

A melt inclusions pursuit into identity of carbonatite magmas and their economic potential

Melt-fluid evolution, magmatic immiscibility and budget of chalcophile and noble metals in basaltic magmas

Olympic Dam

Subduction magmatism in the Southwest Pacific

Mantle characteristics of the East Antarctic margin

Volcanic-hosted mineralisation – modern

Volcanic-hosted mineralisation – ancient



Program 4 leader Dr Rebecca Carey (right) with CODES Honours students Acacia Clark (left) and Imbi Simpson pictured at Ruapehu volcano while on a joint University of Hawaii/UTAS volcanology field trip to New Zealand in 2019.

## Project summaries

### VOLCANOLOGY RESEARCH RELATED TO ORE DEPOSITS

**Leader:** Rebecca Carey

**Team members:** Sharon Allen, Jonathan Cloutier, Bruce Gemmell, Martin Jutzeler, Ross Large, Jocelyn McPhie, Sebastien Meffre, Paul Olin, Karin Orth, Robert Scott, David Selley, Jeff Steadman

**Students:** Justin Burns-Nichols, David Douth, Matt Ferguson, Claudia Jenkins

**Collaborators:** Ray Cas, Matthew Crawford, Kim Denwer, Rob Duncan, Leon Grimbeek, Ned Howard, Andrew McNeill, Gary Sparks

We have an array of projects focussed on understanding the volcanology of mineralised successions around the world, including those on the modern-day seafloor. Our current research in this theme provides constraints on the physio-chemical factors for seafloor ore deposits, and the paleoenvironment setting of ancient volcanic-hosted mineralised deposits. In 2020–2021 our research will include voyages to modern mineralising volcanic systems to add new knowledge of modern

volcanic architectures to ancient mineralised volcanic successions.

This year two Honours students have started with us – Justin Burns-Nichols and Claudia Jenkins, both UTAS BSc graduates. Justin and Claudia are working with Dr Martin Jutzeler, Professor Ray Cas and Dr Rebecca Carey together with Evolution Mining geologists to further understand the volcanic architectures of Ordovician successions at Cowal.

### SUBAERIAL AND SUBMARINE VOLCANOLOGY AND NATURAL HAZARDS

**Leader:** Rebecca Carey

**Team members:** Sharon Allen, Trevor Falloon, Martin Jutzeler, Jocelyn McPhie, Paul Olin, Karin Orth

**Students:** Acacia Clark, Jodi Fox, Sam Holt, Fumihiko Ikegami, Stephanie Morrish, Naomi Potter, Imbi Simpson, Fan Tan, Daniele Vergani

**Collaborators:** Daniele Andronico, Costanza Bonadonna, Cathy Busby, Fabio Caratori-Tontini, Ray Cas, Maya Coussens, Grace Cumming, Nathan Daczko, Cornel de Ronde, Andrea DiMuro, Robert Duncan, John Everard, Richard Fiske, Daniel Fornari, Yoshi Goto, Julie Hollis, Bruce Houghton,

Maria Janebo, Sean Johnson, Michael Manga, Gerrit Olivier, Tim Orr, Matthew Patrick, Christopher Phillips, Ryan Portner, Michael Rosenberg, Maria Seton, Jack Simmons, Adam Soule, Kenichiro Tani, Rex Taylor, James White, Joanne Whittaker, Simon Williams, Richard Wysoczanski

2019 was a year of exciting research projects, student graduations, research outputs and acquisition of multiple research voyages and new funding for the volcanology team. First, congratulations to Jodi Fox, Daniele Vergani, Sam Holt and Naomi Potter who completed their PhD research and graduated in 2019. We look forward to working with them as they continue to write up research for journals in 2020. Congratulations to Jodi Fox who is now a postdoctoral fellow and will be working with Dr Rebecca Carey, Dr Jacqui Halpin and Associate Professor Jo Whittaker in 2020 on Kerguelen and Antarctic-related research.

Together we published 14 journal articles, including two articles by our PhD students Sam Holt and Naomi Potter. Two of our publications were in the high impact journal *Geophysical Research Letters*, and a further three in the journal *Geology*.

Other highlights included a successful Australian Research Council Discovery

Grant awarded to Dr Rebecca Carey to research offshore East Australian volcanism and geodynamics together with Associate Professor Jo Whittaker (IMAS), Dr Maria Seton (University of Sydney), Dr Simon Williams (Northwest University, Xi'an, China), and Professor Nico Coltice (Laboratoire de Geologie de Lyon: Terre, Planetes, Environnement, France). This project will begin in mid- to late 2020.

The sub-projects within 'Subaerial and submarine volcanology and natural hazards' also achieved excellent progress:

#### SUBMARINE VOLCANISM

One of the common observations of large magnitude silicic volcanic eruptions on land is that lava effusion often occurs after the climactic high intensity phase. In 2015 the Havre project team were able to demonstrate that this was also the case with the 2012 Havre eruption, but the exact dynamics of this transition had yet to be determined.

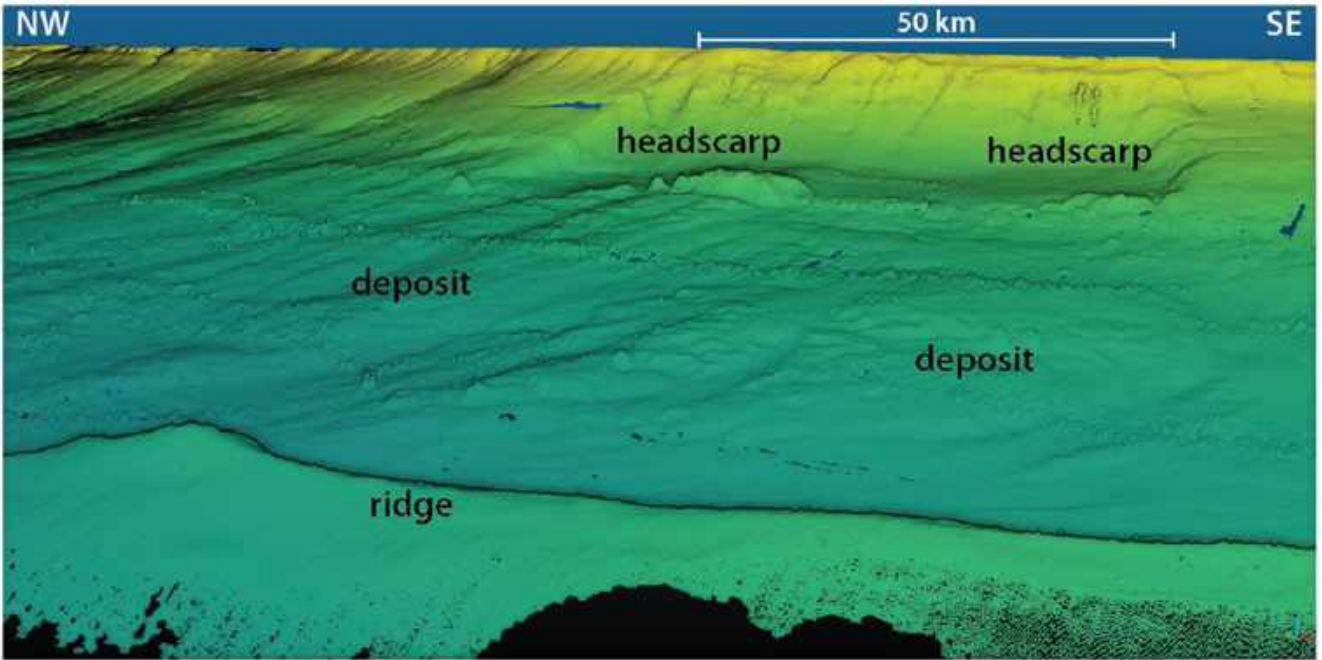
In 2019 Acacia Clark focussed her Honours project on understanding the transitions of eruptive style at Havre. Her project included looking through tens of hours of video footage from the remotely operated vehicle to discover and examine possible transitional units

between the high intensity and lava effusion phase and, where these units existed, to place them in the existing stratigraphic framework. Acacia quantitatively studied the vesicles and crystals in the products of these units in order to assess eruption dynamics during magma ascent and lava emplacement processes. Acacia received first-class Honours; her thesis is titled 'Transitions in eruptive style during the 2012 Deep Submarine Silicic Eruption of Havre Volcano, Kermadec Arc, New Zealand'.

The wider Havre group have continued publishing research with three publications in 2019 in prestigious geological journals including *Geology*. Dr Rebecca Carey and Dr Martin Jutzeler will return to Havre to follow up on some exciting research on the volcanic architecture of the volcano and to assess the disturbance and recovery of the hydrothermal systems and the biological communities with the RV *Investigator* in 2020 and 2021.

#### Tonga submarine eruption

On 7 August 2019, a 195 km<sup>2</sup> raft of andesitic pumice was produced at 200 m below sea level at an unnamed submarine volcano in the Tonga Islands (Southwest Pacific Ocean). This eruption and the pumice raft made headline news, not because it was a



A 3D view of a huge submarine landslide off western Tasmania. Dr Martin Jutzeler will take part in a planned voyage to investigate this in March 2022. The undated landslide is estimated to have covered 450 km<sup>2</sup>.

particularly large eruption but because there were a number of yachts that intersected the raft and filmed what looked like a vast moonscape – but on the surface of the ocean. Dr Martin Jutzeler, Dr Rebecca Carey, Professor Jocelyn McPhie and collaborators from the National Oceanography Centre, UK, tracked the dispersed raft with satellite imagery and then modelled the predicted path of the raft including its future arrival in Australia. This research was published in a highly prestigious journal, *Geophysical Research Letters*.

#### Miocene submarine volcanism in the Izu-Bonin rear arc

In 2019 Dr Martin Jutzeler and co-PI Dr Rebecca Carey obtained a grant from the Australia and New Zealand Consortium to the International Ocean Discovery Program (ANZIC) to carry out geochemical analyses on pumice-rich deposits drilled in the Izu-Bonin rear-arc. This study follows on Martin's participation in the deep-sea drilling IODP expedition 350 in 2014. This study will reconstruct the volcanic architecture of a deep-water submarine succession ranging from the Miocene to Pliocene using a stratigraphically continuous sequence of sedimentary facies. Analyses will include volcanic micro-texture characterisation, glass composition and volatile content.

#### TARAWERA VOLCANO, NEW ZEALAND

New PhD student Hannah Moore arrived in late 2019 and will be conducting her research on understanding the drivers of large magnitude eruptions of basaltic magma, using the Tarawera 1886 eruption as the archetypal example. Hannah is conducting this research with Dr Rebecca Carey and Dr Martin Jutzeler. We are looking forward to a 1–2-month field campaign on Tarawera volcano in 2020.

#### TAUPO VOLCANO, NEW ZEALAND

Imbi Simpson conducted her Honours research on a cryptic transitional unit between two major eruptive phases of the 181 AD large magnitude eruption of Taupo volcano, New Zealand. The purpose of this research was to elucidate the timing, eruption intensity and vent location for this transitional phase in order to further understand how large magnitude silicic eruptions

transition between vastly different eruptive styles. Imbi completed this research in 2019.

#### HOT SPOT VOLCANISM: KERGUELEN PLATEAU

Big Ben volcano on Heard Island is one of three hotspot volcanoes globally. Jodi Fox is now a postdoctoral researcher at IMAS leading the study of the geological history of Heard and McDonald Islands on the Kerguelen Plateau together with Professor Jocelyn McPhie, Dr Trevor Falloon, IMAS collaborators and international researchers from Oregon State University and Oxford University. Rebecca, Jodi and Trevor recently were awarded an Australian Antarctic Science Program research grant to support Jodi to study legacy rock and International Ocean Discovery Program samples to unravel the complex spatial-temporal and geochemical patterns of volcanism across the Kerguelen Plateau since 30 Ma that are difficult to explain with current 'point source' plume models. Further, Jodi will work with tsunami modellers at New Zealand's National Institute for Water and Atmospheric Research in order to understand how the sector collapse of Big Ben may have triggered tsunami in the Indian Ocean and potential impacts.

#### HOTSPOT VOLCANISM: THE 2018 ERUPTION OF KILAUEA VOLCANO

In 2019 adjunct researcher Dr Gerrit Olivier (Institute of Mine Seismology) and Dr Rebecca Carey published their research on the onset of the 2018 eruption of Kilauea volcano using seismic velocity data in the prestigious journal *Geophysical Research Letters*. The eruption was preceded by significant damage of the magma plumbing system that potentially drove greater permeability of the system moving magma from the summit to the East Rift Zone.

#### HOTSPOT VOLCANISM: 2007 ERUPTION OF PITON DE LA FOURNAISE VOLCANO, REUNION ISLAND

Piton de la Fournaise volcano on Reunion Island in the Indian Ocean is a hotspot volcano, with magma fed from a mantle plume and erupting at the surface. The 2007 eruption of Piton de la Fournaise is one of the larger eruptions of this volcano in human

history. CODES PhD student Daniele Vergani has graduated but is writing up his projects on lava–water interaction explosions, lava fountaining and the eruption and collapse of the summit caldera.

#### HOT SPOT VOLCANISM: THE BALLENY MANTLE PLUME

Associate Professor Joanne Whittaker (IMAS) and Dr Rebecca Carey led a ship voyage to the Tasman Sea and Southern Ocean in 2018/2019 to dredge a hypothesised age progressive chain of large 15x30 km seamounts that extend from the Lord Howe Rise to the south of Tasmania. Dr Karin Orth, Dr Martin Jutzeler and four Earth Sciences students participated in the two-week voyage. The voyage was highly successful, with 16 dredges of 13 seamounts and around 30 seamounts mapped in this region. An age-progressive chain would be convincing evidence of the Balleny Mantle Plume, and the exact timing of volcanism would place constraints on the role of the plume on the separation of Tasmania and Cape Adare, Antarctica.

The 2019 voyage collected hundreds of kilograms of rocks for study. Over the 2019–20 summer Fu Rong Mah completed a Dean's Summer Research Scholarship with Dr Karin Orth, and Dushyendra Asaithamby (IMAS) began his Masters program with Associate Professor Jo Whittaker and Dr Jodi Fox from IMAS. Their research is focussed on the geomorphologies of a suite of these seamounts coupled with geochemistry and geochronological studies to further understand whether they are related to mantle plume volcanism or from another tectonic process.

#### HOT SPOT VOLCANISM: OFFSHORE EAST AUSTRALIAN VOLCANISM

In August 2019, Dr Karin Orth participated in a 30-day research voyage to the Coral Sea; the voyage was led by Associate Professor Jo Whittaker (IMAS), Dr Maria Seton (University of Sydney) and Dr Simon Williams (Northwest University, Xi'an, China). The purpose of the voyage was to collect rocks from a hypothesised volcanic plateau near Papua New Guinea and the trails of Tasmanid and Lord Howe Chain seamounts in the

Coral Sea in order to understand the timing and expression of volcanism in eastern offshore Australia. The voyage was highly successful, with 54 dredges and hundreds of kilograms of rocks, but unfortunately they suffered the loss of three dredges when they were hung up on the seafloor. This research will be supported by an ARC Discovery grant awarded to Dr Rebecca Carey and Associate Professor Jo Whittaker at UTAS, Dr Maria Seton (University of Sydney) and other international collaborators.

#### SURTSEY INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Eruptions from 1963 to 1968 off the southern coast of Iceland created the island of Surtsey, famous for spectacular jets of ash and steam. The eruption was very carefully recorded, except for events close to the vent and under water. Drill core recovered by drilling in 1979 and in 2017 has greatly advanced understanding of the near-

vent eruption processes and the rate and consequences of hydrothermal alteration during the past ~55 years. A paper describing the drilling operations and summarising the results to date has been published in *Scientific Drilling*. A manuscript on the characteristics of the three 2017 drill cores has been accepted by *Surtsey Research* and will be published early in 2020: McPhie, J., White, J.D.L., Gorny, C., Jackson, M.D., and Gundmundsson, M.T. 'Lithofacies from the 1963-1967 Surtsey eruption in SUSTAIN drill cores SE-2a, SE-2b and SE-03'.

#### SEDIMENTARY VOLCANOLOGY

**Leader:** Martin Jutzeler

**Team members:** Stuart Bull, Rebecca Carey, Jocelyn McPhie, Karin Orth

**Collaborators:** Mirzam Abdurrachman, Cathy Busby, Ray Cas, Michael Cassidy, Cornel de Ronde, Sue DeBari, Raymond Duraiswami, James

Gill, Jens Karstens, Steffen Kutterolf, Emily Lane, Michael Manga, Robert Marsh, Abdul Muhari, Adam Soule, David Tappin, Christian Timm, Erik van Sebille, Sebastien Watt, James White, Joanne Whittaker, Richard Wysoczanski

The Sedimentary Volcanology sub-theme encompasses research on eruption, transport and deposition dynamics in modern and ancient volcanic successions. Sub-projects include:

#### CALDERA-FORMING SUBMARINE VOLCANISM

Widespread seafloor waveforms, called sediment waves, surround many modern submarine silicic caldera arc volcanoes. Many of these sediment waves have been attributed to caldera-forming eruptions in a recent study published by Dr Martin Jutzeler. In the Kermadec arc, two volcanoes have sediment waves that form gigantic fanning out, upward-



*CODES collaborator and volcanologist Michael Zelenski performing measurements of temperature and composition of gas-air mixtures emitted through skylights and fractures in the roofs of lava tubes. This photograph accompanied an article in the journal Terra Nova (2019) by Professor Vadim Kamenetsky and colleagues entitled 'High-temperature gold-copper extraction with chloride flux in lava tubes of Tolbachik volcano (Kamchatka)'.*

migrating cyclic steps and anti-dune deposits, suggesting extreme fluxes of deposition from supercritical density currents directly linked with caldera-forming volcanism. In 2019 Dr Martin Jutzeler and co-PI Dr Rebecca Carey were successful in obtaining time on the RV *Investigator* for a 29-day voyage they will lead in October 2020. The aim of this voyage is to link the behaviour of deep submarine eruptions with the morphology of their deposits using seismic reflection and sediment coring at several calderas in the Kermadec arc, north of New Zealand. The high-resolution seismic transects will enable new ore vectoring strategies for exploration in Australia and provide essential data to propose an IODP expedition to drill these calderas.

#### ANAK KRAKATAU VOLCANO, INDONESIA

In December 2018 Anak Krakatau volcano dramatically collapsed with

part of its newly built cone falling into the surrounding shallow ocean basin. The 2018 collapse created a tsunami in the Sunda Strait, killing more than 400 people in Java and Sumatra. In 2019 Dr Martin Jutzeler and Dr Rebecca Carey were successful in obtaining ship-time for a 38-day voyage in October 2021 on board the RV *Investigator*. Our team will investigate the submarine deposits of the volcanic landslide using bathymetry, seismic reflection, deep-tow cameras and sediment coring to understand the sedimentary mechanisms that produced the tsunami, and reconstruct the eruption and tsunami sequence.

#### PROVENANCE OF VOLCANIC SEDIMENT OFFSHORE OF ANTARCTICA

Dr Martin Jutzeler was an onshore participant in the two-month ocean drilling IODP 379 expedition in the Amundsen Sea (western Antarctica). The expedition was facilitated by the

RV *JOIDES Resolution* (USA) and led by K. Gohl and J. Wellner. Dr Jutzeler requested samples of sandy to pebbly material from ice-rafted debris, and possible turbidites and tephra fallout. This study will reconstruct the provenance of volcanic sediment by chemical fingerprinting using the LA-ICP-MS and the microprobe.

#### STABILITY OF THE CONTINENTAL SHELF

**Leader:** Martin Jutzeler

**Team member:** Stuart Bull

**Collaborators:** David Airey, Michael Clare, Samantha Clarke, Tom Hubble, Claire Kain, Michael Kinsela, Vanessa Lucieer, Scott Nichol, Hannah Power, Maria Seton, Joanne Whittaker

#### WESTERN TASMANIA SUBMARINE SLIDE

In 2019 Dr Martin Jutzeler and IMAS colleagues were successful in an application for a 42-day voyage in March 2022 on board the RV *Investigator*. The team will investigate the submarine deposits of a giant (450 km<sup>3</sup>) submarine landslide off the western Tasmania shelf. This landslide is undated and has never been formally identified before; its features suggest that it is a recent event (Pleistocene to Holocene?). They will map, image and sample the landslide from its headscarp on the continental shelf to its distal deep-sea deposits, using seismic reflection, coring and deep-tow cameras. Our team will identify the offshore continuation of the Mt Read Volcanics, with implications for improving the geological map of Tasmania and possible identification of further ore deposits offshore. Moreover, the study will contribute to risk mitigation and tsunami hazard assessment for shelf-initiated tsunamis and map the benthic habitat of the western Tasmanian shelf.

#### QLD AND NSW NEOGENE SLIDES

Numerous Neogene landslides are spread along the passive margin of the eastern Australian seaboard. Our team will collaborate with Tom Hubble (University of Sydney) to characterise the architecture of the landslides and canyons that dissect the continental shelf. This study will emphasise the influence of plate tectonics for triggering mass wasting events, and will contribute to tsunami hazard assessment for shelf-initiated tsunamis.

#### PEGMATITES AND PEGMATITE-RELATED ORES

**Leader:** Paul Davidson

**Collaborators:** Karen Appel, Adolf Rericha, Rainer Thomas, Olaf Tietz

This initiative examines melt-melt immiscibility in felsic silicate melts, in the formation of pegmatites and pegmatite-related ore deposits. Pegmatites are noted for the presence of giant crystals, sometimes including rare minerals and gems, and are prime sources of several rare elements, even though their major element chemistry differs little from the standard haplogranitic melts, which are generally accepted to be their parental magmas. Therefore, it can be inferred



A two-day-old pumice raft as viewed by the crew of SV *Finely Finished* in August 2019, in the Tonga region, Southwest Pacific Ocean. This 195 km<sup>2</sup> raft extended to the horizon and consisted of a 15–30-cm-thick layer of freshly erupted pumice clasts. Dr Martin Jutzeler has studied this pumice raft extensively. (Photo courtesy Shannon Lenz.)

that something in their origin favours extremely efficient partitioning, which would explain the high rare element concentrations (up to ore grade). Moreover, such processes need not be restricted to pegmatites, or even terrestrial processes.

We published two papers in 2019. 'The enhanced element enrichment in the supercritical states of granite-pegmatite systems' was published in *Acta Geochimica*, by Rainer Thomas, Paul Davidson and Karen Appel. In that paper we demonstrated that supercritical fluids have a greater significance in the generation of pegmatites, and for ore-forming processes related to granites, than is usually assumed.

During the year we also published a paper in the journal *Berichte Der Naturforschenden Gesellschaft Der Oberlausitz*, titled 'Eine außergewöhnliche Einschlussparagenese im Quarz von Steinigtwolmsdorf/Oberlausitz' by Rainer Thomas, Paul Davidson, Adolf Rericha and Olaf Tietz. The paper addresses the genesis of quartz veins in the Lausitz Block. Based on fluid and melt inclusions in the quartz of

Steinigtwolmsdorf, the formation of this vein is attributed to magmatic, high-temperature hydrothermal fluids. During this process, two silicate melts with different water content are formed. A third paper, titled 'Emerald from the Habachtal: New observations', by Rainer Thomas, Paul Davidson, and Adolf Rericha, has been accepted for publication by *Mineralogy and Petrology*.

#### KIMBERLITES AND FLOOD BASALTS: LINKING PRIMARY MELTS WITH MANTLE AND CRUSTAL SOURCES

**Leader:** Vadim Kamenetsky

**Team members:** Maya Kamenetsky, Jay Thompson

**Student:** Adam Abersteiner

**Collaborators:** Elena Demonerova, Kathy Ehrig, Karsten Goemann, Alexander Golovin, Alexei Ivanov, Graham Pearson, Thomas Rodemann, Igor Sharygin, Zdislav Spetsius

This project is aimed at understanding the relationship between kimberlites and diamonds, flood basalts and magmatic sulfides, and chromitites and related PGE mineralisation, by linking



Professor Bruce Houghton (University of Hawaii, second from left) and Dr Rebecca Carey (third from left) led a joint University of Hawaii/UTAS volcanology field trip to New Zealand in 2019. CODES Honours students Imbi Simpson (second from right) and Acacia Clark (centre in aqua jacket) took part. The group is pictured here at Ruapehu volcano.

mantle structure, phase and chemical composition, isotope evolution and temperature to the melting processes.

Genetic constraints for primitive magmas (kimberlites, shoshonites) in a number of continental magmatic provinces (South Africa, Siberia and NW Canada) were presented in four publications in high-impact journals (*Lithos* and *Contributions to Mineralogy and Petrology*) during 2019.

A renowned example of a sill kimberlite complex (Benfontein, Kimberley cluster, South Africa) provided us with an excellent opportunity to examine the emplacement and evolution of intrusive kimberlite magmas. We have undertaken a detailed petrographic and melt inclusion study of the Benfontein sills and reported new perovskite and baddeleyite U/Pb ages ( $85.7 \pm 4.4$  Ma and  $86.5 \pm 2.6$  Ma, respectively) in *Lithos*. The Lower Sill is characterised by carbonate-rich diapirs, which intrude into oxide-rich layers from underlying carbonate-rich levels. The general paucity of xenogenic mantle material in the Benfontein sills is attributed to its separation from the host magma during flow differentiation during lateral spreading. The low viscosity is likely responsible for non-explosive emplacement of the Benfontein sills, while the rhythmic layering is attributed to multiple magma injections. Analyses of secondary inclusions in olivine and primary inclusions in monticellite, spinel, perovskite, apatite and interstitial calcite are largely composed of Ca-Mg carbonates and, to a lesser extent, alkali-carbonates and other phases. These inclusions probably represent the entrapment of variably differentiated parental kimberlite melts, which became progressively more enriched in carbonate, alkalis, halogens and sulfur during crystal fractionation.

Our published study (in *Contributions to Mineralogy and Petrology*) of the unique sulfide mineral djerfisherite ( $K_6(Fe,Ni,Cu)_{26}S_{26}Cl$ ) revealed two plausible mechanisms for its formation. Djerfisherite, occurring in the groundmass of many kimberlites, kimberlite-hosted mantle xenoliths, and as a daughter inclusion phase in diamonds and kimberlitic minerals may form through replacement of pre-existing Fe-Ni-Cu sulfides by djerfisherite, which is attributed to

precursor sulfides reacting with metasomatic K-Cl bearing melts/ fluids in the mantle or the transporting kimberlite melt. The second scenario envisages direct crystallisation of djerfisherite from the kimberlite melt in groundmass or due to kimberlite melt infiltration into xenoliths. The occurrence of djerfisherite in kimberlites and its mantle cargo from several localities worldwide provides strong evidence that a common kimberlite melt was enriched in K and Cl. This led to suggestions that kimberlites originated from melts that were more enriched in alkalis and halogens relative to their whole-rock compositions.

Adam Abersteiner has submitted his PhD thesis for examination; it is based on nine published papers.

**A MELT INCLUSIONS PURSUIT INTO IDENTITY OF CARBONATITE MAGMAS AND THEIR ECONOMIC POTENTIAL**

**Leader:** Vadim Kamenetsky

**Team members:** Maya Kamenetsky, Jay Thompson

**Student:** Naomi Potter

**Collaborators:** Anton Chakhmouradian, Karsten Goemann, Thomas Rodemann, Victor Sharygin

This project aims to understand primary compositions of mantle-derived carbonatite magmas and carbonate-rich components in association with alkali silicate magmas. The study is based on a set of representative samples from renowned occurrences of carbonatites.

In 2019, we continued research on perovskite accumulations in the Afrikanda alkaline-ultramafic complex (Kola Peninsula, NW Russia) and had our paper accepted for publication in *Contributions to Mineralogy and Petrology*. We aimed to understand the development of the perovskite-rich zones in the olivinites, clinopyroxenites and silico-carbonatites by studying polyminerale inclusions hosted in perovskite and magnetite. The abundance of inclusions varies across the three perovskite textures, with numerous inclusions hosted in the fine-grained equigranular perovskite, fewer inclusions in the coarse-grained

interlocked perovskite and rare inclusions in the massive perovskite. A variety of silicate, carbonate, sulfide, phosphate and oxide phases are assembled randomly and in variable proportions in the inclusions. These observations reveal that the inclusions are not *bona fide* melt inclusions, but represent host media trapped during subsolidus sintering of magmatic perovskite. The continuation of the sintering process resulted in the coarsening of inclusion-rich subhedral perovskite into inclusion-poor anhedral and massive perovskite. We advocate the importance of inclusion studies for interpreting the origin of oxide minerals and their associated economic deposits and suggest that the formation of large-scale accumulations of minerals in other oxide deposits may be a result of annealing of individual disseminated grains.

With three papers published, Naomi Potter was admitted to the degree of Doctor of Philosophy.

**MELT-FLUID EVOLUTION, MAGMATIC IMMISCIBILITY AND BUDGET OF CHALCOPHILE AND NOBLE METALS IN BASALTIC MAGMAS**

**Leader:** Vadim Kamenetsky

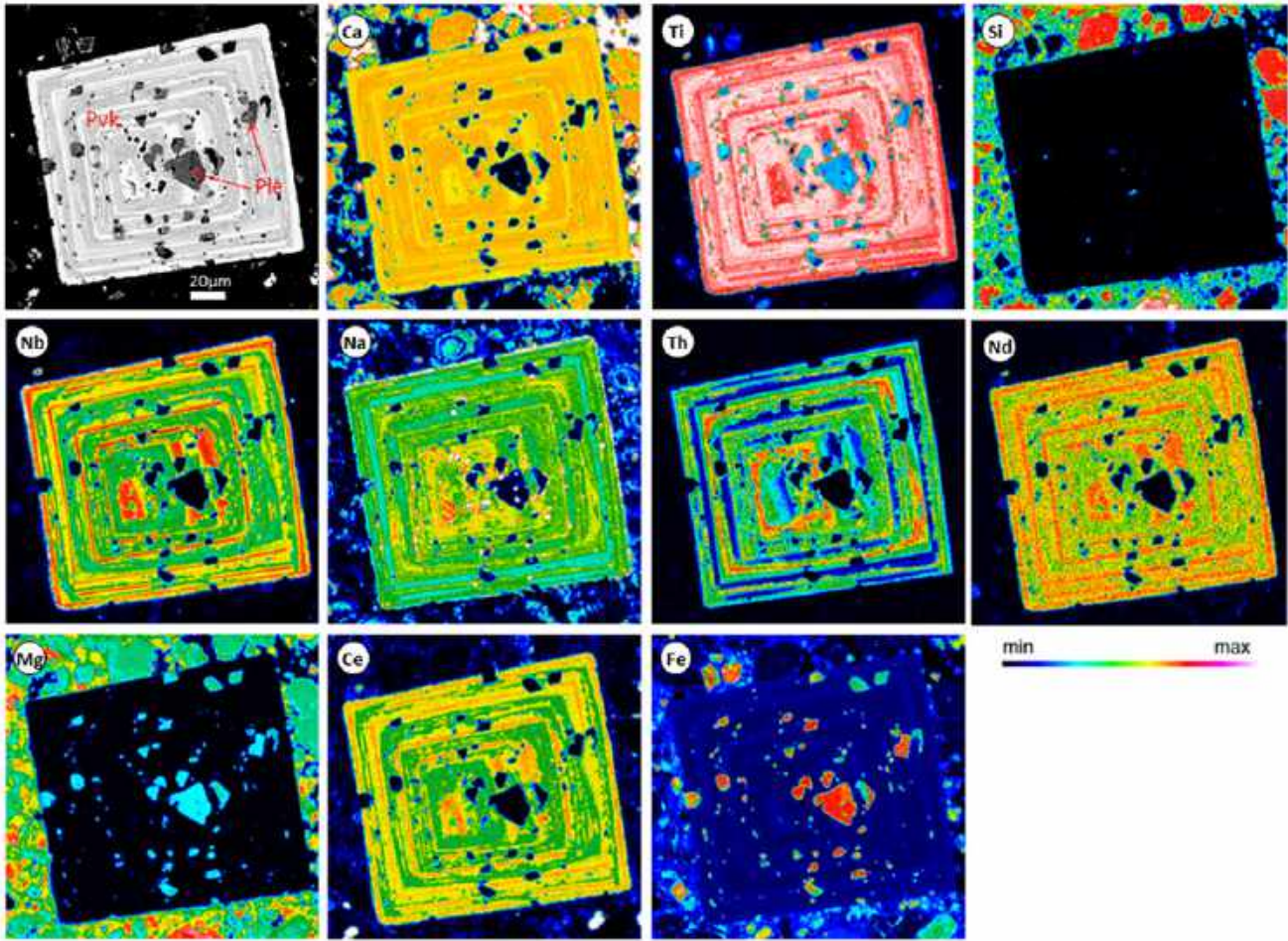
**Team member:** Maya Kamenetsky

**Student:** Adam Abersteiner

**Collaborators:** Alexander Belousov, Ilya Chaplygin, Kathy Ehrig, Pavel Nesterenko, Victor Sharygin, Michael Zelenski, Liudmila Zhitova

This research aims to establish the initial metal abundances in common primitive magmas, and the mechanisms of separation of immiscible liquids and fluids from the silicate melt, through studies of melt and fluid inclusions in minerals.

Subvolcanic environments in supra-subduction zones are renowned for hosting epithermal deposits that often contain electrum and native gold, including bonanza examples. Our study published during 2019 in *Terra Nova* examines mineral assemblages and processes occurring in shallow-crust volcanic settings using materials from recent eruptions (2012–2013) of the basaltic Tolbachik volcano in



Back-scattered electron (BSE) image of an oscillatory zoned perovskite grain from Adam Abersteiner's PhD, which examined kimberlites and diamonds and was submitted in 2019. Electron microprobe (EMP) X-ray element maps show brighter layers to be more enriched in Nb, Na, Th and light rare earth elements (LREEs – Ce, Nd) compared to darker zones, which are more Ca- and Ti-rich.

the Kamchatka arc. The Tolbachik eruptive system is characterised by an extensive system of lava tubes. After cessation of magma input, the tubes maintained the flow of hot oxidised gases that episodically interacted with the lava surfaces and sulfate-chloride fumarolic assemblage on these surfaces. The gas-rock interaction had strong pyrometamorphic effects that resulted in the formation of molten salt, oxidised (tenorite, hematite, Cu-rich magnesioferrite) and skarn-like silicate mineral assemblages. By analogy with experimental studies and metallurgical practices we propose that this naturally occurring smelting process was responsible for extraction of metals from the basaltic wall rocks and deposition of Cu-, Fe- and Cu-Fe-oxides and native gold.

Near-magmatic temperature and efficiency of metal smelting in the post-eruptive environment are facilitated by elevated oxygen fugacity, which is caused by ingress of air into episodically emptied magmatic plumbing systems and consequent

oxidation of fluids and metals. We further argue that metal build-ups, although initially sub-economic, accompany and postdate every stage of magma injection and eruption. Metal accumulations scattered vertically and laterally in shallow magmatic conduit can be upgraded by coupled dissolution and re-deposition in successive volcanic cycles. It is also anticipated that long-lived volcanic systems, processing tens to hundreds of cubic km of magmas to the surface, are capable of attaining high gold endowments by scavenging precursor, fumarole-style accumulations of metals.

**OLYMPIC DAM**

**Leader:** Vadim Kamenetsky

**Team members:** Maya Kamenetsky, Jocelyn McPhie

**Student:** Adam Abersteiner

**Collaborators:** Cristiana Ciobanu, Nigel Cook, Christian Dietz, Kathy Ehrig, Karsten Goemann, Roland Maas, Danielle Schmandt

This project is building on existing knowledge related to economic geology at Olympic Dam through a combination of petrological, geochemical and geochronological research initiatives. Two publications by our colleagues at the University of Adelaide (Schmandt et al. in *Minerals Engineering* and *Canadian Mineralogist*) and an accepted paper by McPhie et al. (*Australian Journal of Earth Sciences*) present new outcomes of the ARC Linkage project 'The supergiant Olympic Dam U-Cu-Au-REE ore deposit: towards a new genetic model'.

Professor Jocelyn McPhie and co-authors explored an Fe oxide-copper-gold prospect Acropolis, which is ~20 km from Olympic Dam, South Australia. Prospective Fe oxide-apatite±sulfide veins occur in Mesoproterozoic and Paleoproterozoic volcanic and granitoid host units beneath unmineralised sedimentary formations. We have produced a geological map and history of the prospect using data from 16 diamond drill holes, including LA-ICP-MS and

high-precision CA-TIMS ages. The oldest unit is megacrystic granite of the Donington Suite (~1850 Ma). A non-conformity spanning ~250 my separates the Donington Suite and felsic lavas and ignimbrites of the Gawler Range Volcanics (GRV; 1594.03 ± 0.68 Ma). The GRV were intruded by granite of the Hiltaba Suite (1594.88 ± 0.50 Ma) and felsic dykes (1593.88 ± 0.56 Ma; same age as the Roxby Downs Granite at Olympic Dam). The felsic dykes are weakly altered and lack Fe oxide-apatite-sulfide veins, suggesting that they post-date the main hydrothermal event. If correct, this relationship implies that the main hydrothermal event at Acropolis was ~1594 Ma and pre-dated the main hydrothermal event at Olympic Dam. The GRV at Acropolis are the same age as the GRV at Olympic Dam and ~3 to 7 my older than the GRV exposed in the Gawler Ranges. The gravity and magnetic anomalies coincide with sections through the GRV, Hiltaba Suite and Donington Suite that contain abundant Fe-oxide veins. The GRV, Hiltaba Suite and Donington Suite are unconformably overlain by the Mesoproterozoic Pandurra Formation or Neoproterozoic Stuart Shelf sedimentary formations. The Pandurra Formation shows marked lateral variations in thickness related to paleotopography on the underlying units and post-Pandurra Formation pre-Neoproterozoic faults.

Our PhD student Adam Abersteiner was successful in winning the Internship funding (APR Intern), provided by BHP Billiton Olympic Dam Corporation and the Australian Government. His project studying sulfur isotopes in Olympic Dam samples should contribute to the overall genetic story of the supergiant Olympic Dam deposit.

### SUBDUCTION MAGMATISM IN THE SOUTHWEST PACIFIC

**Leaders:** Trevor Falloon, Leonid Danyushevsky

**Collaborators:** Julien Collot, Roland Maas, Martin Patriat

This project is an ongoing investigation of magma generation processes in subduction zones and back-arc basins

in the southwest Pacific, and their links with the tectonic evolution of this region.

In 2019, a paper was published in collaboration with IFREMER and the University of Melbourne on the subduction initiation processes at the southern termination of the North Fiji Basin, as inferred from trace element and isotopic compositions of modern volcanic rocks in this region. Research focus during 2019 was on understanding the processes leading to formation of adakite magmas in the modern subduction zones. This study is based on samples from active adakite volcanoes within the underwater section of the Hunter Ridge. A paper is planned for publication in 2020.

### MANTLE CHARACTERISTICS OF THE EAST ANTARCTIC MARGIN

**Leaders:** Trevor Falloon, David Green

**Collaborator:** Anders McCarthy

The petrology of dredged mantle rocks along the East Antarctic margin at Seamount B, offshore Terre Adélie, coupled with new interpretations of multichannel seismic reflection transects have revealed the evolution of magma-poor rifted margins along the Antarctic-Australia rift system. This study represents only the second locality, along with the Iberia–Newfoundland margins, where the importance of exhumed mantle domains along ocean-continent transition zones can be clearly identified. Research so far has revealed how the Antarctic margin is formed of cold and fertile subcontinental mantle which has been variably overprinted by high-pressure melt percolation. A 50–100-km-wide domain along the Australian-Antarctic margins might be formed of exhumed subcontinental mantle with sporadic volcanic additions. Seamount B offers a key starting point from which we can explore, with the help of IODP drilling and dredging expeditions, a variety of petrological and tectonic problems, from the lack of rift-related subsidence to the origin of mantle heterogeneity. This research is being prepared for publication in *G<sup>3</sup>*.

### VOLCANIC-HOSTED MINERALISATION – MODERN

**Leader:** Rebecca Carey

**Team member:** Martin Jutzeler

**Collaborators:** Fabio Caratori-Tontini, Cornel de Ronde, Michael Manga, Adam Soule, Christian Timm

### UNDERSTANDING THE ACTIVITY OF HYDROTHERMAL SYSTEMS AFTER ERUPTION – HAVRE VOLCANO, KERMADEC ARC

Dr Rebecca Carey and Dr Martin Jutzeler with New Zealand and US colleagues have secured a research voyage on the Australian ship, the RV *Investigator*, to Havre volcano in the Kermadec Arc, New Zealand, to further understand the recovery dynamics of the infant hydrothermal systems that have been produced since the 2012 large magnitude eruption. These hydrothermal systems were active when visited by remotely operated vehicle *Jason* in 2015 and the new voyage will use the *Jason* again to deploy an array of thermal blankets across the caldera and other fluid monitoring equipment, and use fluid sampling equipment to understand how hydrothermal systems renew after eruptions. This voyage is likely to take place in 2021.

### BLACK SMOKER CHIMNEYS AT BROTHERS VOLCANO, NEW ZEALAND

In 2019, Heidi Berkenbosch, along with co-authors Cornel de Ronde, Chris Ryan, Andrew McNeill, D. L. Howard, J. Bruce Gemmell, and Leonid Danyushevsky, published a paper in *Economic Geology* entitled ‘Trace Element Mapping of Copper- and Zinc-Rich Black Smoker Chimneys from Brothers Volcano, Kermadec Arc, Using Synchrotron Radiation XFM and LA-ICP-MS’. The research has demonstrated that the chimneys have trace element differences in rings indicating that (1) seawater ingress into the chimney interiors occurs despite it vigorously discharging 274°C fluids at the time of sampling, and (2) that during these periodic seawater incursions, rapidly changing chemical gradients within the chimney wall induce the instantaneous precipitation

of metals from the vent fluid. Thus, the trace element rings are a proxy for the secular evolution of vent fluid compositions.

### VOLCANIC-HOSTED MINERALISATION – ANCIENT

**Leader:** Jonathan Cloutier

**Team members:** Shaun Barker, Ross Large, Charles Makoundi, Sebastien Meffre, Khin Zaw

**Collaborators:** Mohd Basril Iswadi Basori, Ben Cooke, David Green, Scott Halley, Chun Kit Lai, Andrew McNeill, Terry P. Mernagh, Steve Piercey, Mike Vicary

**Student:** Zebedee Zivkovic

### SE ASIA

VHMS research in SE Asia, particularly in Myanmar, was continued in 2019. The Myanmar VHMS deposits include the Bawdwin deposit in the Shan-Tanintharyi Belt and other VHMS systems (e.g., Leymyetna in the Indo-Myanmar Ranges and Mahar San in the Central Volcanic Belt). The Bawdwin deposit is located in Namtu Township, Northern Shan State, Myanmar. The deposit occurs as sub-vertical pipes in a rhyolitic volcanoclastic pile of Cambro-Ordovician age. The geological, isotopic and mineralogical characteristics of the Bawdwin deposit are comparable to the Rosebery-style polymetallic VHMS deposit in Tasmania. The Bawdwin mine was one of the largest producing volcanic-hosted polymetallic (Pb-Zn-Cu-Ag-Co-Ni-Ba) deposits in the world before World War II. Three ore lenses, Meingtha, Chinaman and Shan, from south to north, occur as sub-vertical pipes in a rhyolitic volcanoclastic pile of Cambrian age. They lie along N–S and NW–SE trending major rift structures in which dome-shaped rhyolite intrusions were emplaced. Current exploration activities by Myanmar Metals at Bawdwin (<https://myanmarmetals.com.au/>) have delineated new ore lenses in the area and the deposit will become the world’s third largest producer of lead and ninth largest producer of silver when production re-starts in 2022. Our ongoing studies on reconstruction of assembly and breakup of equatorial SE Asian Gondwana demonstrate that the

formation and location of the Bawdwin and the Rosebery deposits were related to rifting on the northern margin of Gondwana during the Cambro-Ordovician.

The Mahar San VHMS deposit is located in the Kawlin–Wuntho area, northern Myanmar. It consists of polymetallic pods of massive sulfide ore lenses containing pyrite, chalcopyrite and chalcocite with galena, sphalerite, covellite, bornite and tennantite. The mineralisation is hosted in a complex of intermediate volcanic and volcanoclastic rocks of probable Miocene age. A collaborative research project of the Mahar San deposit was set up with researchers from Kyushu University, Japan, during Professor Khin Zaw’s visit there in June–July 2019. The aim of the research is to understand the alteration, fluid characteristics and origin of the deposit. Researchers interested in pursuing this VHMS research in Myanmar should contact Professor Khin Zaw.

### TASMANIA

Associate Professor Shaun Barker is leading a project entitled ‘Lithogeochemical fertility indicators for VHMS deposits’ initiated in June 2019 as a Masters by Research project being undertaken by Zebedee Zivkovic. In this project, we are examining the lithogeochemical characteristics of different stratigraphic rock packages in the Mount Read Volcanics in order to evaluate whether distinctive geochemical signatures exist within the units which host VHMS mineralisation. We are taking advantage of recent improvements in geochemical assay methods in order to resolve variations in Zr/Hf ratios and other ratios of geochemical elements of volcanic units across the province. Low Zr/Hf ratios have been demonstrated to be associated with horizons that are host to mineralisation. These variations are inferred to be related to fractionation of the underlying magma chamber and the associated build-up of hydrothermal fluids. If this hypothesis is correct, it suggests that the lithogeochemistry of VHMS host rock packages could be used to fingerprint prospective horizons and thus guide exploration activities.

We are working across the Mount Read Volcanics, re-assaying historic

MRT rock-chip samples as well as collecting new samples from historic drill holes with the aim of testing the validity of this approach, and identifying potential prospective horizons. The lithogeochemical studies will be coupled with mineral chemistry (particularly zircon chemistry) in the upcoming year in order to evaluate whether a zircon fertility index for VHMS mineralisation can be developed.

The implications of this study go beyond VHMS systems in the Mount Read Volcanics and may speak to a whole host of magmatic-hydrothermal deposits. As such, we are also conducting a review of global crustal geochemistry to compare with known mineralised data sets to test the method’s ability to characterise other mineralisation systems and attempt to develop a more robust magmatic fertility indicator that can be used in a variety of exploration settings.

Dr Charles Makoundi is currently working on downhole hyperspectral mineralogy and multi-element analysis for the Mt Julia (Henty) and Rosebery VHMS deposits in the Mount Read Volcanic Belt to characterise the types of alteration minerals downhole and their relationships with precious and base metal distribution; he is doing this in collaboration with Dr Jonathan Cloutier and Professor Khin Zaw (CODES) and David Green and Dr Andrew McNeill (Mineral Resources Tasmania). The project is linked with a submitted ARC Linkage project entitled ‘Geochemical, isotopic, and hyperspectral investigation of volcanic-hosted massive sulphide deposits of eastern Australia and southeast Asia: Enhancing the exploration potential and discovery for a low-carbon world’ led by Dr Jonathan Cloutier.

### NEWFOUNDLAND

Dr Jonathan Cloutier concluded a project initiated at the Memorial University of Newfoundland with collaborator Professor Steve Piercey. The research undertaken looked at the use of SWIR spectral reflectance in VHMS exploration. The project was focussed on the precious metal-bearing, bimodal-felsic volcanogenic massive sulfide Lemarchant deposit (1.24 Mt at 0.58% Cu, 5.38% Zn, 1.19% Pb, 1.01 g/t Au, and 59.17

g/t Ag). The Lemarchant deposit is located within the Exploits subzone of the Appalachian orogen of central Newfoundland, Canada, and consists of two mineralised lenses hosted in the felsic rocks of the Bindons Pond formation. Mineralisation consists of sphalerite, chalcopyrite, galena, pyrite and pyrrhotite with subordinate sulfosalts (i.e., tetrahedrite-tennantite), bornite, stromeryite, electrum, bladed barite, Ca-Fe-Mg-Mn-carbonate, and has enrichments in epithermal suite elements (i.e., Au, As, Bi, Co, Cr, In, Mo, Ni, Sb, Se, Te). These features are interpreted to be the result of a shallow-water hydrothermal system with both VMS and epithermal features. Alteration is associated with zones of weak to intense chlorite-carbonate, chlorite, white mica, and quartz alteration below the massive and semi-massive sulfide lenses. For this project, a new lithology normalised spectral alteration index (SAI) for white mica and chlorite was developed by integrating lithogeochemistry with VSWIR reflectance in order to map and characterise the alteration intensity surrounding the deposit. In addition, depth ratio parameters (2200D/2340D vs 2250D/2340D) were used to characterise mineralogical changes and zonation. The use of hyperspectral reflectance coupled with geochemical alteration proxies permitted the identification of areas of intense alteration, the chemical affinities of the minerals, and their relationships to alteration processes (i.e., seawater alteration versus silicification), which would not be possible using geochemistry alone. A manuscript summarising this project was recently accepted in *Economic Geology* and will be published in 2020.



(ABOVE) Program 4 leader Dr Rebecca Carey presenting research results at the 2019 Annual Review in Hobart. (OPPOSITE) CODES PhD student Jodi Fox oversees Honours students Acacia Clark and Imbi Simpson during the field trip to New Zealand as part of a joint University of Hawaii/UTAS volcanology field trip in 2019. They are logging tephra sections at Taupo.

## Looking forward

2019 has been a fantastic year, but 2020 is pitched to deliver further exciting research and student achievements. The volcanology group are in preparation for Dr Martin Jutzeler and Dr Rebecca Carey's research voyage to the Kermadec Arc in October 2020. Currently we are planning the seismic and coring details, applying for permits and also looking for opportunities for students and teachers to sail with us on the voyage. We are excited to announce that two new PhD students with UTAS scholarships will be joining us in 2020, and their research will focus on the data and samples from this voyage.

Our ARC Linkage project is set to launch in April 2020. We have a new PhD student, Gilles Ngoran from Cameroon, who will be starting to work with us in 2020 on this exciting project. Dr Rebecca Carey's ARC Discovery project on the offshore Eastern Australian volcanism will also begin, and a new PhD student will be working with Associate Professor Jo Whittaker (IMAS), Dr Karin Orth and Dr Rebecca Carey on this project. Rebecca, Jo and Dr Jodi Fox (IMAS) will also begin the analytical programs on rocks from Heard Island and the Tasman Sea seamounts.

Professor Vadim Kamenetsky and his collaborator Professor Penny King (RSES, ANU) are recruiting postdocs and PhD students to work on the ARC Discovery project *Impact of hot gas on volcanic rocks and ore-forming processes*. However, they have had to defer the start of the project to at least July 2020. It is unlikely that they will get the research team assembled prior to 2021.



# Program Five

## Analytical research



### Objective

- Analytical research underpins much of our most innovative research across the fundamental to applied spectrum.
- New developments in analytical research generated by CODES Analytical Laboratories provide the basis for CODES' global leadership in micro-analytical techniques specifically applied to mineral exploration, U/Pb geochronology, mineral processing, ore genesis, igneous geochemistry and volcanology, and waste management.
- CODES Analytical Laboratories also provide analytical services to government, academia and industry.



### Introduction

**Program 5: Analytical research** explores and develops novel analytical and data interpretation techniques based on the latest technological and algorithmic developments, such as a number of high spatial resolution microprobes and advanced data-reduction algorithms. This helps in the understanding, exploration and exploitation of deep Earth resources.

Current research projects focus predominantly on expanding the capabilities of laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) for geological applications, analytical data reduction, and the development of new, user-friendly software packages. In 2019, a significant proportion of research activities were focussed on developing algorithms for quantification of images of elemental distribution in multi-mineral assemblages and deconvoluting time-resolved data.

The analytical projects using LA-ICP-MS include in-situ multi-element analysis and imaging of element distribution within minerals; in-situ isotope analysis, focussing on a range of U/Pb dating applications and Pb isotope measurements; development of calibration standards; and technological developments aimed at improving the capabilities of the laser microprobes.

Many of the projects involve close collaborations with national and international research groups and equipment manufacturers.

*OPPOSITE PAGE: (TOP) Laboratory Analyst Terrie Sawyer at work in the CODES clean laboratory, where she is preparing ultra-pure water to be used in sample preparation for solution ICP-MS analysis. (BOTTOM) Al Cuisson, Lapidary Manager, cutting rock to ready it for examination by CODES staff.*

### Highlights

#### Research

New algorithms have been developed for quantification of LA-ICP-MS images of multi-mineral assemblages.

#### Equipment

Discussions began with Agilent on a collaborative project which would involve installation of triple-quad 8900 ICP-MS instrument at the CODES Analytical Laboratories

#### Software

A new version of LADR, the data reduction software for LA-ICP-MS, has been released. This version is capable of advanced data reduction for U/Pb dating of a wide range of minerals.

#### Staff

The team welcomed Terrie Sawyer as a Laboratory Analyst specialising in bulk rock analysis using solution ICP-MS. Prior to joining CODES Analytical Laboratories Terrie worked in the United Kingdom.

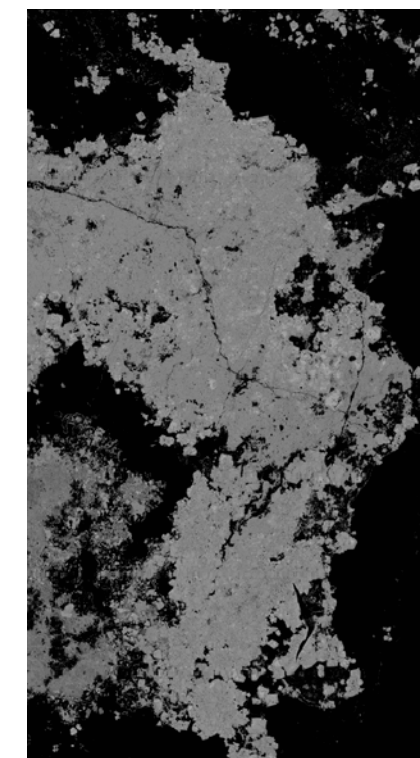
Dr Paul Olin has been appointed to the position of Deputy Leader of CODES Analytical Laboratories.

In February 2019 Sasha Stepanov moved to a research position at the Chinese University of Geosciences (Wuhan), and in August 2019 Jay Thompson took up a position with NASA in Houston, USA.

#### Conferences

Team members were involved in a number of major conferences and workshops in 2019, including a Workshop on Laser Ablation data reduction (during the TANG<sup>2</sup>O meeting in Hobart), the North American Workshop on Laser Ablation (NAWLA 2019) and related short course on the application of LA-ICPMS (USA); and the Goldschmidt Conference. In total, team members produced over 20 conference abstracts.

Keynotes at NAWLA and Goldschmidt focussed on the latest developments in the geological applications of laser ablation and in particular on the accurate analysis of major elements. The short course at NAWLA summarised the main developments in LA-ICP-MS over the past decade.



*Dr James Tolley's entry in the 2019 CODES Photo Competition: 'Textural variation in magnetite'.*

# The program team

**LEADER** LEONID DANYUSHEVSKY  
**DEPUTY LEADER** IVAN BELOUSOV

## TEAM MEMBERS:

Shaun Barker, Matthew Cracknell, Angela Escolme, Elena Lounejeva, Sebastien Meffre, Paul Olin, Terrie Sawyer, Jay Thompson, James Tolley,

## PHD STUDENTS:

Bridie Le'Gallais, Nanda Mrabawani, Xin Ni Seow, Jay Thompson

## HONOURS STUDENTS:

Josh Denholm, Matthew Vincent

## COLLABORATORS:

**AGILENT TECHNOLOGIES**  
 Fred Fryer

**CENTRAL SCIENCE LABORATORY, UTAS**  
 Karsten Goemann

**IOWA STATE UNIVERSITY, USA**  
 Sam Houk

**LAURIN TECHNIC**  
 Michael Shelley

**MOSCOW STATE UNIVERSITY, RUSSIA**  
 Pavel Plechov



## NORRIS SCIENTIFIC

Ashley Norris

## TELEDYNE CETAC TECHNOLOGIES

Damon Green, Ciprian Stremtan

## TOFWERK

Olga Borovinskaya, Michael Cubison, Martin Rittner, Martin Tanner

## UNIVERSITÉ DU QUEBEC À CHICOUTIMI, CANADA

Dany Savard

## UNIVERSITÉ GRENOBLE ALPES, FRANCE

Valentina Batanova, Alexander Sobolev

## UNIVERSITY OF BRISTOL, UK

Jon Blundy

## UNIVERSITY OF KIEL, GERMANY

Dieter Garbe-Schönberg

## UNIVERSITY OF MELBOURNE

Roland Maas

## UNIVERSITY OF TECHNOLOGY SYDNEY

David Clases, Philip Doble



Professor Leonid Danyushevsky (front wearing sunglasses) pictured in Milan where he was invited to present part of a short course entitled 'Fluids in the Earth' at the University of Milano-Bicocca, Italy, during September 2019. He has been participating in the delivery of this short course for the past ten years.

## Projects

Fundamentals of ICP-MS

Fundamentals of laser ablation

Calibration standards for LA-ICP-MS

LA-ICP-MS instrumentation development

U/Pb dating

LA-ICP-MS data reduction software

Interpretation of LA-ICP-MS time-resolved signals

## Project summaries

### FUNDAMENTALS OF ICP-MS

**Leaders:** Leonid Danyushevsky, Jay Thompson

**Team members:** Ivan Belousov, Paul Olin

**Collaborators:** Olga Borovinskaya, Fred Fryer, Sam Houk, Martin Tanner

This project is aimed at better understanding the physical processes that occur in ICP-MS, in order to improve its performance and the range of applications for laser ablation. The main focus in 2019 continued to be on improving our understanding of robust plasma conditions and developing methods for quantitative analyses of trace elements in minerals, without using matrix-matched reference materials. The work focussed on understanding the impact of particle size distribution of elemental fractionation in the ICP.

### FUNDAMENTALS OF LASER ABLATION

**Leader:** Leonid Danyushevsky

**Team members:** Paul Olin, Jay Thompson, James Tolley

**Students:** Nanda Mrabawani, Xin Ni Seow

**Collaborators:** David Clases, Philip Doble, Damon Green, Michael Shelley, Ciprian Stremtan

This project aims to gain a better understanding of laser ablation processes, leading to improved analysis of geological materials, especially sulfide minerals.

In 2019, research continued within the project, which is jointly funded by Laurin Technic. The focus was on characterisation of aerosol transport as a function of gas pressure in the ablation cells. Key research activities focussed on:

- Developing approaches to quantitative analyses of plagioclase, alunite and apatite for a wide range of trace elements. This research is part of Nanda Mrabawani's and Xin Ni Seow's PhD projects in the TMVC.
- Developing algorithms for quantification of images of trace-element distributions in multi-mineral assemblages.



The CODES Lapidary Technician Michele Chapple-Smith using a Nikon optical microscope to examine heavy mineral separates.

- Developing algorithms for quantification of compositions of micro-inclusions in minerals using ICP-TOF-MS.
- Testing of the performance of the very fast washout ablation cell Cobalt developed by Teledyne Cetac Technologies.

### CALIBRATION STANDARDS FOR LA-ICP-MS

**Leaders:** Ivan Belousov, Leonid Danyushevsky

**Team members:** Paul Olin, Jay Thompson

**Collaborators:** Valentina Batanova, Jon Blundy, Dieter Garbe-Schönberg, Karsten Goemann, Pavel Plechov, Dany Savard, Alex Sobolev

This project is aimed at the development and characterisation of new calibration reference materials for LA-ICP-MS analysis of various geological materials.

Calibration standard STDGL3 for sulfide analysis is being distributed to several analytical laboratories worldwide. A manuscript describing this new reference material is in preparation.

A manuscript describing the composition of an olivine reference material has been accepted for publication in *Geostandards and Geoanalytical Research*.

Collaboration continued in 2019 with the University of Kiel and the Université du Québec à Chicoutimi on characterising pressed nano-particle pellets of sulfide minerals. A collaboration continues with the University of Bristol and Moscow State University on the characterisation of plagioclase reference material.

LA-ICP-MS  
INSTRUMENTATION  
DEVELOPMENT

**Leader:** Leonid Danyushevsky

**Team members:** Paul Olin,  
Jay Thompson

**Collaborators:** Olga Borovinskaya,  
Michael Cubison, Martin Rittner,  
Michael Shelley, Martin Tanner

This project tests, designs and develops new instrumentation to ensure continuing advances in geological LA-ICP-MS applications. Example developments include ablation cells, the interface between the laser and the mass-spectrometer, and testing new types of laser microprobes and mass-spectrometers. In 2019, activities formed part of the technological developments within the TMVC Research Hub. The main focus was on developing operating conditions for ICP-TOF-MS and modifications to the ablation cell designs.

U/PB DATING

**Leader:** Jay Thompson

**Team members:** Leonid  
Danyushevsky, Ivan Belousov

**Collaborator:** Roland Maas

This project investigates the causes of limitations to U/Pb dating of minerals by LA-ICP-MS, with the aim of enhancing laboratory practices and instrumentation parameters to lower systematic errors and improve precision. Zircon is the primary mineral

investigated; however, ongoing investigations for apatite, uraninite and monazite are currently underway.

A paper describing the application of time-of-flight mass-spectrometer to U/Pb dating is in the final stages of completion.

Throughout the year the focus was on identification of multiple populations of zircons of similar ages in igneous samples.

LA-ICP-MS DATA  
REDUCTION SOFTWARE

**Leader:** Leonid Danyushevsky

**Team members:** Ivan Belousov,  
Paul Olin, Elena Lounejeva

**Collaborator:** Ashley Norris

This project aims to develop comprehensive, user-friendly LA-ICP-MS data processing software, capable of:

- quantification of data acquired using multiple calibration standards and a range of internal standard elements;
- quantification of images depicting distribution of major and trace element concentrations in fine-grained multi-mineral aggregates of sulfides, silicates, phosphates and carbonates; and
- identification of mineral phases in, and sizes of, micro inclusions in minerals.

Activities in 2019 were directed towards developing algorithms for advanced U/Pb dating applications and for quantitative gold deportment in rock samples.

INTERPRETATION OF  
LA-ICP-MS TIME-RESOLVED  
SIGNALS

**Leader:** Shaun Barker

**Team members:** Matthew Cracknell,  
Sebastien Meffre

This project is evaluating the use of changes in signals during single LA-ICP-MS analyses to identify inclusions within minerals, and the potential to improve the speed and consistency

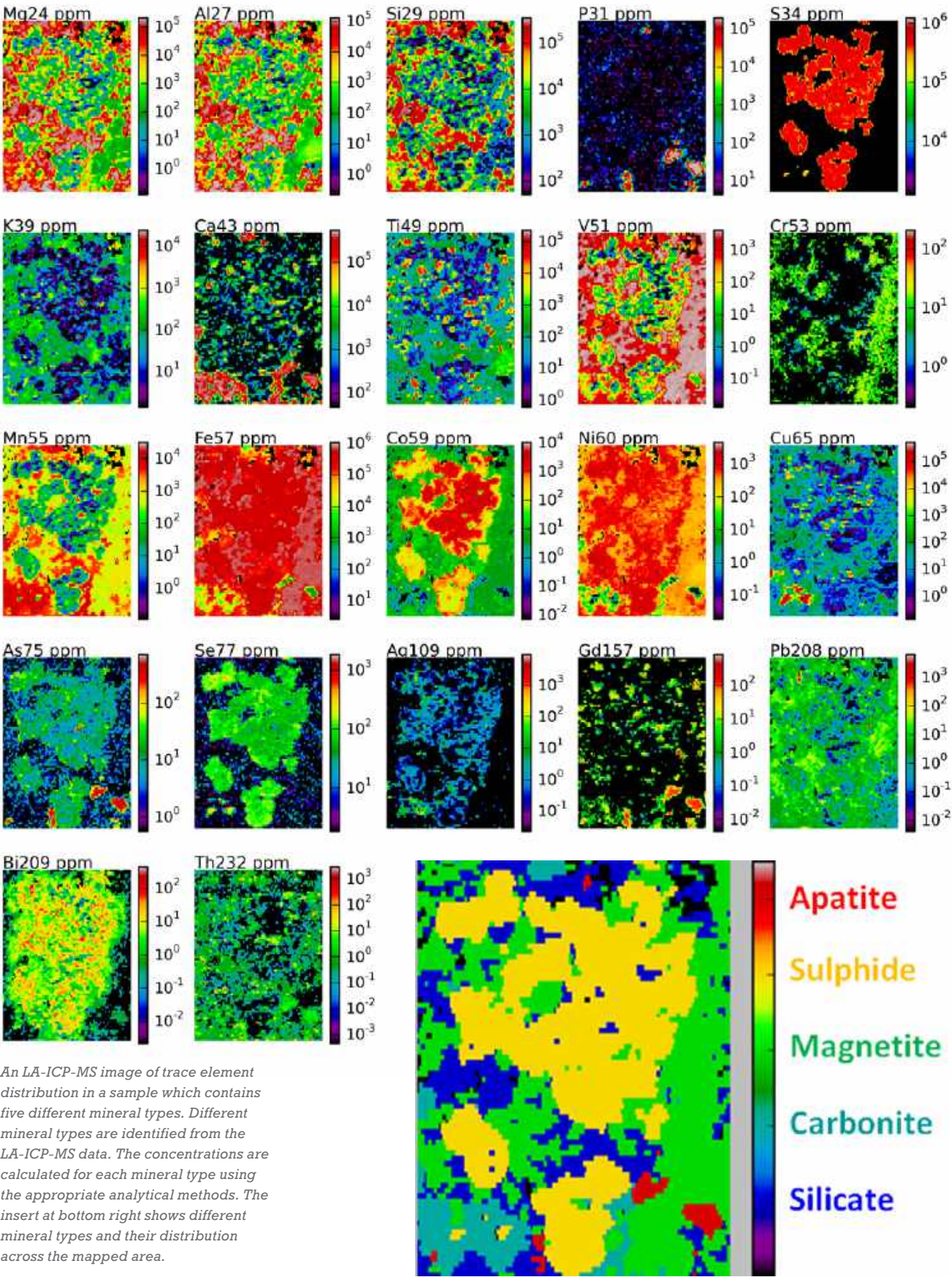
of LA-ICP-MS signal interpretation and processing. Each laser ablation ICP-MS point or line analysis contains an enormous amount of information, typically 30–40 elemental masses collected every 0.5 to 1 second during a single “sweep” over the mass spectrometer, over a 60-second interval. This means that every analysis yields between 1800 and 2500 data points. With hundreds of analyses collected on a daily basis, this data-rich environment presents an opportunity to apply new approaches including data analytics and machine learning to obtain more information from the data sets that the CODES Analytical Laboratories produce.

During 2019, our focus has been on developing workflows in open-source software packages in order to rapidly normalise LA-ICP-MS data signals, and to use machine learning approaches to automatically identify and classify LA-ICP-MS signals. In 2020, we plan to further develop and test these methods, and in particular focus on automatic mineral inclusion identification and classification.

Looking forward

The team will further develop its analytical research in 2020, and continue working in close collaboration with the TMVC Research Hub. Developments are expected to include:

- Investigating the applicability of triple-quad ICP-MS instrument for routine geological applications.
- Continue collaboration with Bristol, Grenoble, Kiel and Quebec universities and Moscow State University on the characterisation of a wide range of mineral reference materials.
- Continue developing advanced data-processing algorithms for imaging elemental distributions in minerals by LA-ICP-MS.



# Program Six

## Geophysics and computational geosciences



### Objective

This program addresses the challenges associated with technological advances in automated data acquisition and imaging methods across the geosciences. It seeks solutions to issues associated with managing, processing, visualising and interpreting minerals industry data sets at all stages from exploration to mining and mineral processing to waste management.

### Introduction

**Program 6: Geophysics and computational geosciences** focuses on the applications of new methods for data collection, data analysis, data integration, data-driven decision making, and novel visualisation techniques. It includes a diverse range of projects that focus on three-dimensional geophysical interpretation, seismic array studies, geodata analytics, data visualisation, exploration targeting and geoscience education.

Modern minerals industry activities are undertaken in highly data-rich environments characterised by a wide range of quantitative and qualitative information. There have been significant recent advances in areas such as geophysical data acquisition, geophysical data processing and inversion, multi-element geochemical analyses, and a range of new optical and infrared imaging techniques. The challenge is to be able to effectively integrate all of these diverse data streams using new methods and workflows that can effectively transform data into information and knowledge. The ultimate aim of this data synthesis process is to facilitate more informed decision making at all stages in the mineral exploration, extraction and processing sequence.

### Highlights

**From a geophysical perspective, 2019 highlights for Program 6 include:**

- Preparation of publications from Esmail Eshaghi's PhD study on geologically constrained geophysical models for western and northwestern Tasmania.
- Generation of new 2D and 3D models of the deep electrical structure of Tasmania derived from

*OPPOSITE PAGE: (TOP) Taking a break: CODES PhD student Alex Farrar undertaking horseback-supported fieldwork at San Juan, Argentina, March 2019. (BOTTOM) CODES PhD student Alex Farrar taking notes during a fieldwork trip to San Fernando, Chile, in September 2019 for his Program 6 research on the formation of giant porphyry copper deposits in the Central Andes.*

magnetotelluric measurements by Tom Ostensen in his PhD study.

- New PhD student Alex Farrar presented a summary of his work mapping and interpreting deep-rooted crustal-scale structures, called trans-lithospheric faults (TLF), to staff and students at the Universidad Austral de Chile.
- PhD student Umer Habib has discovered an overall Devonian overprint from the Palaeomagnetic analysis of the Cambrian and Ordovician rocks of Victoria and New South Wales. He has also analysed central Victorian Cambrian volcanic rocks that have yielded magmatic ages between 522–515 Ma, which correlates with a hypothesised (first) west-dipping subduction zone.
- Honours student Joseph Behans evaluated the geophysical signature of the bonanza-grade gold mineralisation at Fosterville in Victoria and provided recommendations for application of the most appropriate geophysical methods.
- Professor Anya Reading was presented with the UTAS Vice-Chancellor's Leadership Award in November for her 'significant and lasting contributions to STEM education and University outreach'.

**In the field of computational science and data visualisation, the major achievements of 2019 were:**

- Congratulations to Shawn Hood for his thesis submission and graduation with a number of peer-reviewed papers published in distinguished journals such as *Chemical Geology*.
- Dr Matthew Cracknell co-authored two papers in *Economic Geology*, the first with Cassady Harraden (Corescan) detailing the collection of geotechnical information from Corescan mineral maps and Digital Surface Models, and the second with Daniel Gregory (University of Toronto) and CODES researchers exploring the use of machine learning to classify ore deposit styles from pyrite trace element data.
- PhD student Tom Schaap presented his G-plates-based tectonic reconstructions of the Lachlan Orogen at the ASEG conference in Perth.

- In July, PhD student Steve Kuhn published a key chapter of his thesis in *Ore Geology Reviews* that compared classification and clustering methods for geochemical domaining. This important contribution also assesses the response of models to variations in spatial distributions of field observations.

**In the area of technology transfer major highlights were:**

- In July, Dr Matthew Cracknell delivered a short course for CODES staff and students exploring data analytics methods for geochemical data processing and interpretation.
- Also in July, Professor Anya Reading gave an invited talk at the International Union of Geodesy and Geophysics 27th General Assembly in Montreal, Canada. She spoke on the topic of 'Insights from data-driven research methods in the solid Earth and spatial sciences'.
- Dr Matthew Cracknell and Dr Shawn Hood collaborated with Michael Gazely (RSC) and Juan Carlos Ordóñez Calderón (Kinross Gold Corporation) to develop and deliver 'Machine Learning for Geologists' workshops at the AusIMM PACRIM and Mining Geology conferences. These workshops aim to provide geologists with an introduction to machine learning and were well received by participants.
- In September Dr Michael Roach presented talks and workshops on geological visualisation methods at the University of Uppsala, Sweden, University College, Dublin, and to the Geological Survey of Ireland.
- In November Professor Anya Reading gave a keynote speech and was a panellist at the Women in Data Science event at Stanford University, USA; the title of her talk was: 'Maximising insight from machine learning investigations in the geosciences'.

# The program team

**LEADER** MICHAEL ROACH  
**DEPUTY LEADER** MATTHEW CRACKNELL

## TEAM MEMBERS:

David Cooke, Anya Reading (Physics)

## PHD STUDENTS:

Alex Farrar, Umer Habib, Shawn Hood, Stewart Jackson, Stephen Kuhn, Stephen Meyer (Physics), Peter Morse, Thomas Ostensen, Thomas Schaap, Tobias Staal (CODES/IMAS)

## HONOURS STUDENT:

Joseph Behan

## COLLABORATORS:

**CORESCAN**  
 Cassady Harraden

**CSIRO OCEANS AND ATMOSPHERE FLAGSHIP**  
 Mark Hemer

**FIRST QUANTUM MINERALS**  
 Mike Christie, Tim Ireland, Chris Wijns

**GEOLOGICAL SURVEY OF SOUTH AUSTRALIA**  
 Kate Robertson, Stephan Thiel

**GHD**  
 Hugh Tassell



**GRANGE RESOURCES**  
 Gilbert Charles

**INSTITUTE OF MARINE AND ANTARCTIC STUDIES (IMAS)**  
 Jacqueline Halpin, Joanne Whittaker

**INSTITUTE OF MINE SEISMOLOGY**  
 Gerrit Olivier, Brian Salmon

**KINROSS GOLD CORPORATION**  
 Juan Carlos Ordóñez Calderón

**MINERAL RESOURCES TASMANIA**  
 Daniel Bombardieri, Mark Duffett

**MITRE GEOPHYSICS**  
 John Bishop

**RSC MINING & MINERAL EXPLORATION**  
 Michael Gazely

**UNIVERSITY OF SOUTH AUSTRALIA**  
 Tom Raimondo

**UNIVERSITY OF TORONTO, CANADA**  
 Daniel Gregory

**WESTERN MINING SERVICES**  
 Jon Hronsky



Dr Michael Roach (right, seated) demonstrating the AusGeol Virtual Library of Australia's Geology at the CODES booth, SEG Conference, Santiago, in October 2019.

## Projects

Integrating geology and geophysics for resources targeting

Geodata analytics, visualisation and decisions

Geological visualisation and virtual education

Magnetotelluric imagery of the Earth's crust and mantle

The lithosphere of East Antarctica from combined geology and geophysics

Application of passive seismic methods to assess the stability of mine tailings dams

## Project summaries

### INTEGRATING GEOLOGY AND GEOPHYSICS FOR RESOURCES TARGETING

**Leader:** Matthew Cracknell

**Team member:** David Cooke

**Student:** Alexander Farrar

**Collaborators:** Mike Christie, Jon Hronsky

New CODES PhD candidate Alex Farrar, generously supported by First Quantum Minerals, aims to solve the mysteries surrounding geodynamic and structural controls, in particular the presence of trans-lithospheric faults (TLF), on the formation of giant porphyry copper deposits in the Central Andes. The Central Andes offers an excellent case study region due to its prolific metal production, well-documented geologic evolution and distinct spatial and temporal mineralisation events. Alex will use information that describes the location,

timing, grade and structural setting of both economic and non-economic porphyry Cu deposits, combined with detailed structural mapping to answer the following research questions:

- What role does the inherited geologic architecture play in the localisation of giant porphyry camps and how do we best interpret it within multiple data sets and across scales representative of their length?
- Can proxies for pre-existing geologic architecture, i.e. TLF, be identified in the field to increase the level of confidence in the existence of structures?
- How does the evolution of the regional stress field focus, store and then release fertile magmas that form porphyry camps and can the paleo-stress fields be modelled in geographic space and through geological time?
- What are appropriate methods for transferring the information in geodynamic models to supervised machine learning methods for predicting porphyry mineralisation and how are the outputs best communicated?

We look forward to following Alex's progress over the next few years as he tackles this exciting and ambitious project.

### GEODATA ANALYTICS, VISUALISATION AND DECISIONS

**Leader:** Anya Reading

**Student:** Peter Morse

This project expands the scope of research undertaken within CODES and the Discipline of Earth Sciences into geodata analytics and innovative visualisation strategies. During 2019, PhD student Peter Morse continued computational work on both colour usage and interactive volumetric visualisation tailored to data sets in geoscience. Innovations progressed in 2019 include 2.5D compositing for the rapid reconnaissance of 3D volumetric data with a paper being submitted late in the year.

### GEOLOGICAL VISUALISATION AND VIRTUAL EDUCATION

**Leader:** Michael Roach

**Collaborator:** Tom Raimondo

This project continues to refine and develop methods for effective geological visualisation and explores how these methods can be applied for research, education at professional, postgraduate and undergraduate levels, and for public outreach.

A main focus of new work in 2019 was on the development of a virtual tour of the Savage River mining operations in western Tasmania in conjunction with Grange Resources. This project is part of a collaboration with Dr Tom Raimondo at the University of South Australia supported by a grant from the AusIMM Education Endowment Fund.

The Savage River tour uses a range of immersive media including 360-degree imagery, 360-degree video, 3D photo-realistic models, conventional video, and high-resolution imagery. The tour has been initially designed as a tool for tertiary and professional education but will be later modified for outreach purposes. It documents the entire Savage River operation from exploration and mining geology to mining operations, metallurgy and environmental management. Grange Resources have kindly provided access to their entire site and many Grange employees have participated in video interviews to accompany the virtual material. This tour will be published online in 2020.

### MAGNETOTELLURIC IMAGERY OF THE EARTH'S CRUST AND MANTLE

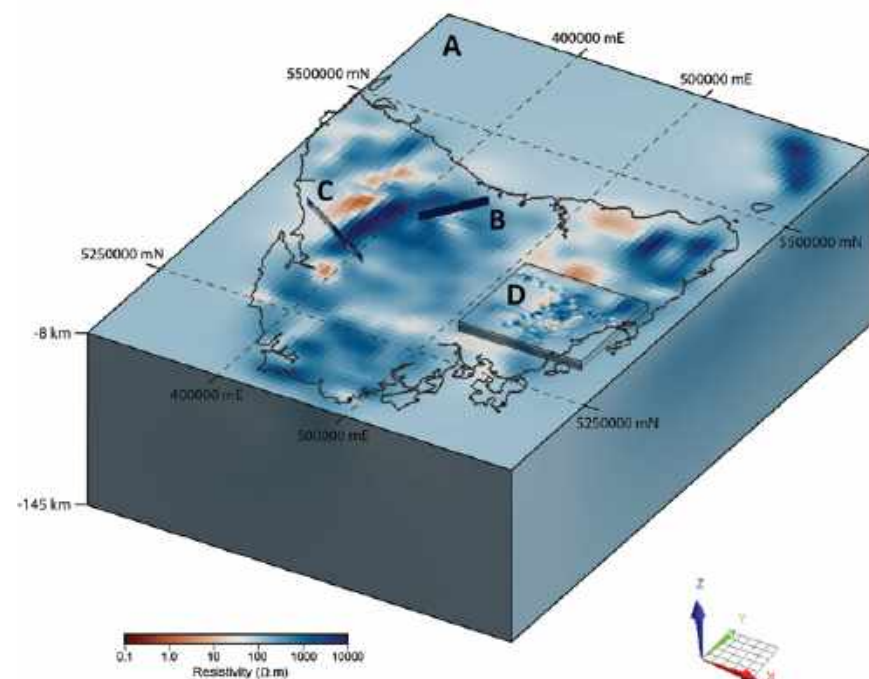
**Leader:** Anya Reading

**Team members:** Matthew Cracknell, Michael Roach

**Student:** Thomas Ostensen

**Collaborators:** John Bishop, Mark Duffett, Kate Robertson, Stephan Thiel

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) is a national initiative



Orthographic projected oblique view from the southeast showing 2D and 3D resistivity models generated over the course of Thomas Ostersen's PhD research project. Model A) provides state-scale resistivity structure at a horizontal resolution of 5 km and was derived from the national AusLAMP MT survey. The two 2D transect models B) and C) focus on shallow crustal structure across major crustal boundaries in western and northern Tasmania. The high-resolution 3D model D) in eastern Tasmania represents the output of a joint inversion process investigating the electrical structure of the Lemont geothermal prospect.

charged with mapping the electrical resistivity structure of the Australian lithosphere. AusLAMP data acquisition took place across Tasmania in 2016 and was a collaborative effort involving staff and students from UTAS, Geoscience Australia, Mineral Resources Tasmania and the University of Adelaide. Through 2018 the AusLAMP data set was used to generate Tasmania-wide and regional 3D electrical resistivity models of the subsurface. In 2019 the computational phases of the project concluded with two further major results: 1) geoelectric transects across the west and northwest of Tasmania and 2) a collaboration with John Bishop resulting in an improved geoelectric model for the midlands of Tasmania that combines AusLAMP and industry data from KUTh Energy Ltd. The Tasmanian midlands is prospective for geothermal energy and the new 3D images will inform the next phase of data collection for this resource.

Final interpretation, including integration with updated geophysical data sets for Tasmania, is now complete. AusLAMP resistivity models yield insights into the regional-scale resistivity structure for the Tasmanian crust and uppermost lithospheric mantle. The models confirm the presence of the Tamar Conductivity Anomaly as a shallow- to mid-crustal arcuate structure between the Tamar and Coal River valleys, coincident

with the inferred boundary between the uniformly resistive East Tasmania Terrane and the more electrically complex West Tasmania Terrane. In the mid- to upper-crust, highly resistive zones of the model are spatially correlated with areas of voluminous Devonian granite intrusion (Eastern Tasmania, South West Cape and the central west). Areas of anomalously low resistivity at this depth are spatially correlated with outcropping Cambrian metamorphic complexes bounding the Dundas-Fossey Trough.

Advanced 3D visualisation was employed to investigate relationships between the newly determined conductivity structures at depth, and crustal architecture such as granite bodies. This will inform understanding of tectonic evolution and both mineral and geothermal prospectivity for Tasmania.

## THE LITHOSPHERE OF EAST ANTARCTICA FROM COMBINED GEOLOGY AND GEOPHYSICS

**Leader:** Anya Reading

**Student:** Tobias Staal

**Collaborators:** Jacqueline Halpin, Joanne Whittaker

The continental land mass of East Antarctica is one of the least

understood regions on Earth. This is due to the ice cover, several km thick in places, and the rock outcrops being restricted to the coastal regions. It is also a region that is very limited in the available geophysics coverage (e.g. seismic tomography, airborne magnetics and gravity) but initiatives of the International Polar Year of 2007/08, and subsequent data compilations, have resulted in significant improvements. A number of continent-wide data sets were recently made available to the international community.

This project seeks to combine geological and geophysical data, including the use of statistical and



Professor Anya Reading received a Vice-Chancellor's Leadership Award in November 2019 for her STEM education and University outreach work.

probabilistic methods, to progress our understanding of the East Antarctic Lithosphere. A highlight of 2019 was the publication of a paper, by CODES/IMAS PhD student Tobias Staal and the project team, that used a multivariate method to constrain major boundaries in the deep lithosphere. Further achievements include the development and publication of open source software for joint geological and geophysical data analysis, and progress in areas of solid-Earth geophysics that link to interdisciplinary studies of the great ice sheets and outlet glaciers.

## APPLICATION OF PASSIVE SEISMIC METHODS TO ASSESS THE STABILITY OF MINE TAILINGS DAMS

**Leader:** Michael Roach

**Student:** Stewart Jackson

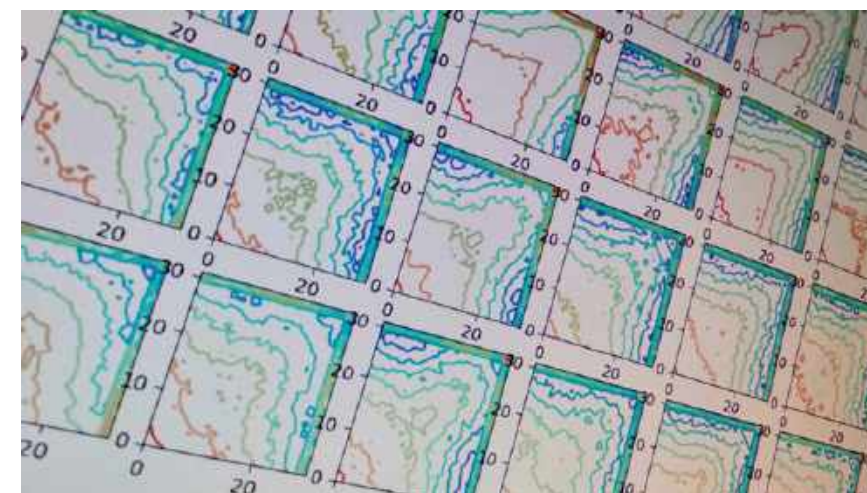
**Collaborators:** Gerrit Olivier, Hugh Tassell

All major mining operations have tailings storage facilities and recent tragic failures of major tailings dams highlight the need for new methods to assess the integrity and stability of this infrastructure. Drilling into existing dams is difficult and provides only localised information. Geophysical methods can provide three-dimensional coverage but existing techniques such as resistivity imaging, time-domain electromagnetics, seismic refraction and MASW often provide only limited depth of investigation and indirect proxies for important engineering parameters.

Passive seismic techniques have evolved rapidly over the past decade and now potentially provide new methods to better image the interior of large tailings storage facilities that may provide three-dimensional information that is more directly applicable to engineers. This project explores the application of a range of passive seismic methods for imaging the interior of mine tailings dams. In 2019 the focus has been on literature review and code development for forward and inverse modelling. Initial data acquisition trials, planned for mid-2019, were delayed and will now take place in 2020.



CODES/IMAS PhD student Tobias Staal giving a presentation at ISAES (the 13th International Symposium on Antarctic Earth Science) in South Korea, July 2019. His participation was sponsored by the Antarctic Gateway Partnership. (Photo: Korea Polar Research Institute.)



Arrangement of contour matrices containing textural patterns within the hyperspectral image of a rock sample, from the early stages of Javier Merrill's PhD research. Javier is working within Program 2 and the TMVC with data analytical support from Program 6.

## Looking forward

The computational and data science research undertaken in Program 6 will continue to provide a basis for the utilisation of new data analytical techniques within a wide range of CODES projects including the ARC TMVC Research Hub. The emphasis of this work, coordinated by Dr Matthew Cracknell, will be on unsupervised methods for aggregation, clustering and classification of geochemical data sets at a wide range of scales.

Geological visualisation activities in 2020 will focus on development of virtual education modules for undergraduate and professional education. This will include finalisation of the Savage River Mine virtual tour and digitisation of diverse UTAS sample collections that will form the basis for online educational resources for use in UTAS undergraduate units and in CODES Master of Economic Geology courses.

From a geophysical perspective, Tom Ostensen plans to complete his PhD project on the crustal and upper mantle electrical structure of Tasmania in 2020. Tom's new 3D electrical models will provide a fresh perspective on the intermediate and deep structure of Tasmania.

Undergraduate student Wei Heng will commence an Honours project that aims to assess ground-based geophysical methods, such as electromagnetics and ground penetrating radar, for rapid reconnaissance of mine waste to predict revegetation and rehabilitation success. This project will be supported by Mineral Resources Tasmania through the Mining Sector Innovation Program, and will sit within Theme 3 of the TMVC.

Dr Matthew Cracknell is currently planning the Geodata Analytics Master of Economic Geology short course to be held in November 2020. Given rapid advances and uptake of computation methods for processing and analysing geological data, this course will provide a timely and important addition to the Masters program. This course will bring together a number of key practitioners and researchers in the fields of signal and image processing, machine learning and statistical analysis. Participants will gain skills in the analysis and visualisation of geoscience data with a focus on providing a platform for rapid communication of outputs to geologists to help inform decision making.

*Sunset, San Pedro de Atacama, Chile,  
photographed by CODES PhD student  
Alex Farrar during fieldwork in 2019.*



# TMVC

## The ARC Research Hub for Transforming the Mining Value Chain



### Objectives

The Australian Research Council Research Hub for Transforming the Mining Value Chain (TMVC) aims to resolve some of the greatest challenges currently facing the minerals industry, by improving efficiencies along the entire mining value chain. Its principal objectives are to:

- Achieve real-time automated acquisition and interpretation of detailed mineralogical, textural and geochemical data in mine site core sheds that can be used immediately for 3D-modelling of geometallurgical and geoenvironmental parameters and ore zone footprints.
- Move the mining industry from the data-rich, but comparatively knowledge-poor, environment it currently works in, to a data-rich, knowledge-rich environment that allows for rapid decision making during the exploration and development phases of mining operations.
- Develop tools and protocols that allow near-instantaneous identification of proximity to ore zones, together with geometallurgical and geoenvironmental characterisation of ores and waste through automated core logging and spectral analyses of drill core. This will enable 3D exploration, mining and geometallurgy models to be developed that are continually updated as the exploration or resource drilling program continues.

### Introduction

The ARC Research Hub for Transforming the Mining Value Chain (TMVC) encompasses a wide array of activities from exploration, discovery, ore deposit characterisation, and environmental assessment, through to mining, ore processing and waste rock disposal. It sets out to improve efficiencies within this value chain, focussing on areas that will have a marked impact on the value of Australia's mineral resources. By helping to develop more efficient and environmentally sustainable practices throughout the mining value chain, it is anticipated that the TMVC's research outcomes will extend the lives of mines and create employment opportunities across Australia's regional mining centres.

The TMVC provides substantial benefits for the minerals industry through advanced mineral characterisation methods, and innovative technologies for their implementation, which can be applied much earlier in the mining value chain. This enhances decision making and maximises productivity and profitability at Australian mine sites.

The TMVC is housed within CODES at the University of Tasmania (UTAS) – the Administering Organisation. In addition to CODES, the industry partners involved in the Research Hub include BHP, Corescan, Newcrest Mining, and a consortium of global companies co-ordinated by AMIRA International. Other organisations affiliated with the initiative include Laurin Technic and RWTH Aachen University in Germany.

### Highlights

The additional industry funding secured to support the TMVC's largest sub-project, AMIRA P1202, has allowed

*OPPOSITE PAGE: Postdoctoral research fellow Francisco Testa looking for variations in hydrothermal alteration patterns in low sulfidation epithermal vein systems from the Cerro Negro district (Newmont-Goldcorp), Patagonia, Argentina, as part of his work within TMVC Theme 1. The photo was taken during fieldwork in February–March 2019.*

for the operational life of the TMVC to be extended to June 2021. The ongoing positive impacts of the TMVC research program are reflected in three new industry funders joining the Hub, with additional industry funding being secured from our existing and new industry partners. Two PhD students, one Masters student and three Honours students were also recruited to the TMVC in 2019.

Notable achievements during the year included Honours students Johanna van Balen and Le Xi K'ng, who worked on projects in western Tasmania, both being supported by Governor's Environmental Scholarships. Johanna also received an AusIMM Education Endowment Fund Premium Scholarship, while Le Xi also benefitted from an AusIMM, BHP and EIANZ Environment and Community Award. PhD student Sibeles Nascimento won a best student oral presentation prize for her presentation entitled 'Geoenvironmental characterisation of the King River Delta: A combined geophysical, geochemical and mineralogical approach' at SGA Glasgow in August. There were also several keynote and invited presentations and workshops at various conferences around the world across all the Hub themes.

The AMIRA P1202 project, which brings together all the research themes of the TMVC (early exploration, geometallurgical and geoenvironmental characterisation, data analytics and microanalytical innovation), expanded during the year with the sponsors group now consisting of 14 companies, six of which are involved in the optional Module 4. The project team successfully delivered sponsor review meetings in June and November (Hobart) and

October (Santiago), as well as recruiting several new students who either commenced during the year or will start in early 2020.

A new research agreement with AMIRA was signed late in 2019 for a one-year project on Resistate Indicator Minerals (RIMS). The major highlight for Theme 2 in 2019 was the publication of the *Economic Geology* special issue on geometallurgy in December, containing contributions from Dr Angela Escolme and Dr Cassidy Harraden.

The Theme 3 research team continued to make progress on various PhD student projects with bench-scale tests being initiated by Annah Moyo, further detailed characterisation of tailings samples from the King River delta being performed by Sibeles Nascimento, and the finalisation of Laura Jackson's study of Cadia.

2019 saw the completion of testing of the third prototype of the fast response laser ablation cell on biological samples by the Underpinning Technologies team, with results demonstrating that imaging of elemental distribution can be conducted at a speed up to ten times faster than what was possible with standard instrumentation. Research in the computational space saw the publication of several journal articles, as well as technology transfer through presentations and workshops, both nationally and internationally.

It was also another productive year for student completions, with the submission of six theses: two PhD and five Honours. Our publication outputs included 18 refereed journal articles, 34 conference presentations and 95 reports to industry.

*PhD student Sibeles Nascimento won a best student oral presentation award at SGA Glasgow in August 2019 for her presentation entitled 'Geoenvironmental characterisation of the King River Delta: A combined geophysical, geochemical and mineralogical approach'.*



# The program team

**LEADER** DAVID COOKE  
**DEPUTY LEADER** LEONID DANYUSHEVSKY

## TEAM MEMBERS:

**CODES:** Mike Baker, Shaun Barker, Ivan Belousov, Ron Berry, Matthew Cracknell, Angela Escolme, Bruce Gemmell, Wei Hong, Ben Kowaluk, Ross Large, Elena Lounejeva, Sebastien Meffre, Emmet O'Keefe, Paul Olin, Evan Orovan, Anya Reading, David Selley, Terrie Sawyer, David Selley, Francisco Testa, Jay Thompson, Lejun Zhang

**ENGINEERING, UTAS:** Danchi Jiang

**AMIRA INTERNATIONAL:** Adele Seymon

**BHP:** Kathy Ehrig

**CORESCAN:** Neil Goodey

**LAURIN TECHNIC:** Michael Shelley

**NEWCREST MINING:** Anthony Harris

**RWTH AACHEN UNIVERSITY:** Bernd Lottermoser

## PHD STUDENTS:

**CODES:** Ayesha Ahmed, Jing Chen, Takeshy Coaquira, Kyle Eastman, Amos Garay, Shawn Hood, Laura Jackson, Colin Jones, Stephen Kuhn, Erin Lawlis, Javier Merrill, Peter Morse, Annah Moyo, Nanda Mrabawani, Sibebe Nascimento, Josh Phillips, Xin Ni Seow, Emily Smyk, Yi Sun, Francisco Testa, Jennifer Thompson

**MONASH UNIVERSITY:** Angela Rodrigues

**UNIVERSITY OF THE PHILIPPINES:** Cleodette Lagata

**WAIKATO UNIVERSITY, NEW ZEALAND:** Rocky Barker

## MASTERS STUDENTS:

**CODES:** Batbayar Enkhbold

**LAKEHEAD UNIVERSITY, CANADA:** Emily Gorner, Patrick Hamilton, Andrew Jedemann, Joseph Vrzovski

## HONOURS STUDENTS:

**CODES:** Le Xi K'ng, Hugh Rivett, Johanna van Balen, Matthew Vincent

**LAKEHEAD UNIVERSITY, CANADA:** Mitch Marcelissen

**UNIVERSIDAD AUSTRAL DE CHILE:** Camila Arcos



## COLLABORATORS:

**AUSTRALIAN NATIONAL UNIVERSITY**

Trevor Ireland

**CONSULTANT**

Noel White

**COPPER MINES OF TASMANIA**

Geoff Cordery

**CORESCAN**

Ronell Carey, Cari Deyell, Cassady Harraden, Ekaterina Savinova

**CSIRO**

Carsten Laukamp, Michael Gazley

**CURTIN UNIVERSITY**

Fred Jourdan

**FIRST QUANTUM MINERALS**

Mike Christie, Tim Ireland, Chris Wijins

**GEOSCIENCE AUSTRALIA**

Simon Bodorkos

**HEFEI UNIVERSITY OF TECHNOLOGY, CHINA**

Shiwei Wang, Fan Yu, Taofa Zhou

**INNER MONGOLIA MINING TECHNOLOGY RESEARCH INSTITUTE LTD, CHINA**

Dapeng Ren, Zhongfei Yao

**IRISH CENTRE FOR RESEARCH IN APPLIED GEOSCIENCES (iCrag), IRELAND**

Murray Hitzman, Sean Johnson

**LAKEHEAD UNIVERSITY, CANADA**

Peter Hollings

**LEPANTO CONSOLIDATED MINING COMPANY**

Mervin Delos Santos, Leo Subang

**MINERAL MAPPING PTY LTD**

Scott Halley

**MINERAL RESOURCES TASMANIA**

Ralph Bottrill, John Everard, David Green, Andrew McNeill, Michael Reid, Clint Siggins, Carol Steyn

**MMG**

Steve Scott

**MONASH UNIVERSITY**

Laurent Ailleres, Robin Armit

**NEWCREST MINING**

Karyn Gardner, Mary Harris, Fiona Karaut, Paul Napier

**NEWMONT GOLDCORP**

Thomas Bissig, Patricio Brivodoro, German Escorza, Cesar Riveros

**NORRIS SCIENTIFIC**

Ashley Norris

**PEKING UNIVERSITY, CHINA**

Wenbo Li, Xueyuan Qiao, Bei Xu, Fanghua Zhang

**SIGNATURE GOLD**

Johnathan Robbeson, Jim Yaxley

**UNIVERSIDAD AUSTRAL DE CHILE**

José Piquer

**UNIVERSITY OF ALBERTA, CANADA**

Robert Creaser

**UNIVERSITY OF BRITISH COLUMBIA, CANADA**

Richard Friedman

**UNIVERSITY OF QUEENSLAND**

Anita Parbhakar-Fox

**UNIVERSITY OF MELBOURNE**

Roland Maas

**UNIVERSITY OF TASMANIA, SCHOOL OF TECHNOLOGY, ENVIRONMENTS AND DESIGN**

Christopher Lueg

**UNIVERSITY OF TASMANIA, CENTRAL SCIENCE LABORATORY**

Ashley Townsend, Thomas Rodemann

**UNIVERSITY OF THE PHILIPPINES**

Rosana Balangue

*The new core shed at Tujuh Bukit, Indonesia; this facility was built to process new core from the Upper High Grade Zone porphyry-epithermal target. This photo was taken in March 2019 by TMVC PhD student Kyle Eastman who is focussing on Tujuh Bukit in his research.*



# Projects

The TMVC is focussed on the country's highest earning precious metal, gold; the base metal, copper; and the main energy metal, uranium. Each of these commodities has its own scientific challenges, which the TMVC is tackling through three principal research themes. In addition, Underpinning Technologies, Knowledge Transfer and Training are essential parts of the TMVC, encompassing all research themes. The full scope of research activities gains considerably from the expertise, state-of-the-art facilities and technological developments within the TMVC, and benefits to end-users are assured through extensive, hands-on technology transfer and training programs.

## THEME 1: DETECTING PROXIMITY TO ORE (FOOTPRINTS)

- Pyrite footprints
- Geochemical and mineralogical vectors to ore, Bilihe–Hadamiao district, Inner Mongolia, China
- Magmatic-hydrothermal transition features in Sn granites of Tasmania
- Geological and geochemical vectors to low sulfidation epithermal gold mineralization, Cerro Negro district, Deseado Massif, Argentina
- Geochemical footprint and paragenesis of the Specimen Hill Au prospect, New England Orogen, Queensland
- Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits (AMIRA P1202) – Modules 1–3
- Timing relationships within porphyry-epithermal deposits
- Identifying unique Resistate Indicator Mineral (RIM) chemistry as a guide in prospectivity for sediment-hosted copper mineralisation (AMIRA P1206)

## THEME 2: OPTIMISING GEOMETALLURGICAL PREDICTION

- Characterising supergene copper mineralogy using hyperspectral techniques
- Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits (AMIRA P1202) – Module 4

## THEME 3: MINIMISING GEOENVIRONMENTAL RISKS

- Mineralogical domaining of low grade and no grade zones using automated drill core logging at Cadia
- Utilising industrial waste materials for AMD control
- Geometallurgy of historic mine waste: Evaluating options for reprocessing

# UNDERPINNING TECHNOLOGIES

- Development of the fast-throughput sample cell for laser ablation applications
- Corescan data feature extraction and classification for mineralogical and textural information analysis
- Integrating chemical and mineralogical data layers for element deportment
- Interpreting structural and geochemical patterns using machine learning
- Geological feature discovery from quantitative data integration (algorithm development)
- Method development for Laser Ablation ICP-MS applied to complex matrices

# Project summaries

## THEME 1: DETECTING PROXIMITY TO ORE (FOOTPRINTS)

### PYRITE FOOTPRINTS

**Leader:** David Cooke

**Team members:** Leonid Danyushevsky, Angela Escolme, Anthony Harris, Sebastien Meffre, Lejun Zhang

**Students:** Cleodette Lagata, Erin Lawlis

**Collaborators:** Rosana Balangue, Karyn Gardner, Fiona Karaut, Paul Napier

Analytical work on samples from the Runruno alkalic epithermal gold deposit, Philippines, was conducted during the year as part of a collaboration with Rosana Balangue and PhD student Cleodette Lagata of the University of the Philippines. These analyses aim to understand the timing and nature of gold mineralisation at Runruno to inform understanding of ore genesis and mineral processing. A manuscript on the geology and mineralisation of Lihir was accepted for publication in the Society of

Economic Geologists Special Publication on gold deposits. Erin Lawlis, as part of her PhD study, has interpreted results from additional pyrite samples from Lihir. These will form the basis of a new manuscript to be drafted in 2020.

## GEOCHEMICAL AND MINERALOGICAL VECTORS TO ORE, BILIHE–HADAMIAO DISTRICT, INNER MONGOLIA, CHINA

**Leader:** Lejun Zhang

**Team members:** Mike Baker, Wei Hong, Ben Kowaluk, Emmet O’Keefe

**Collaborators:** Wenbo Li, Xueyuan Qiao, Dapeng Ren, Bei Xu, Zhongfei Yao, Fanghua Zhang

This sub-project commenced in 2018 as a collaboration between CODES and Peking University. It aimed to develop a geological understanding of the Hadamiao Cu ± Au porphyry prospect in Inner Mongolia, China, with an emphasis on the evolution of hydrothermal fluids at the prospect in order to identify features indicative of the exploration potential of this type of intrusive complex.

An Honours thesis completed by Ben Kowaluk (November 2018) which established the paragenesis for alteration and mineralisation, characterised the breccias and veins, and analysed key magmatic hydrothermal transition textures to determine their exploration and genetic significance. Key alteration minerals were analysed by ICP-MS to test their potential for fertility and vectoring assessments.

During the second field campaign, the research team found a large zone of skarn alteration in the northeast of the Hadamiao Cu ± Au porphyry prospect. After some preliminary work done by the group, a new pilot study Honours project has been proposed to mainly investigate the mineralogy and paragenesis of the skarn alteration. The aims are to understand the genesis of the skarn, and to advance the overall understanding of the metallogeny of the district.

## MAGMATIC- HYDROTHERMAL TRANSITION FEATURES IN SN GRANITES OF TASMANIA

**Leader:** Evan Orován



Ralph Bottrill from Mineral Resources Tasmania is a collaborator on PhD student Colin Jones’ TMVC Theme 1 research project. Here Ralph is standing in front of tourmaline-bearing alkali feldspar granite at Bicheno on Tasmania’s East Coast during fieldwork with Colin in 2019.

**Team members:** Ivan Belousov, David Cooke, Wei Hong, Sebastien Meffre, Jay Thompson

**Student:** Colin Jones

**Collaborators:** Simon Bodorkos, Ralph Bottrill, John Everard, Trevor Ireland, Fred Jourdan, Roland Maas, Andrew McNeill

This project is focussed on aspects of granites in Tasmania, especially in how they relate to mineralisation. Petrogenetic questions involving the genesis of I- and S-type granites, pluton construction, and the magmatic-hydrothermal transition are being addressed. Colin Jones successfully completed his confirmation of candidature for his PhD, as well as most of his fieldwork and sample collection in 2019. He has completed a significant portion of his geochronology and whole-rock geochemistry analytical campaign, as well as finished O-isotope analyses on zircon at ANU. Colin published an extended abstract for the Sn-W-Critical Metals and Associated Magmatic Systems conference held in Tinaroo, Queensland, where he presented a poster on the geochronology of Bluestone Bay, Tasmania. David Cooke and Wei Hong also published extended abstracts for the Sn-W-Critical Metals and Associated Magmatic Systems conference and gave oral presentations

on aspects of the magmatic-hydrothermal transition in Tasmanian granites. Wei submitted a fluid inclusion manuscript to *Economic Geology* in 2019, which should be published in 2020. Colin gave an oral presentation at the Tasmanian Geoscience Forum in St Helens, Tasmania, where he also ran a conference field trip to Bluestone Bay, Freycinet.

## GEOLOGICAL AND GEOCHEMICAL VECTORS TO LOW SULFIDATION EPITHERMAL GOLD MINERALIZATION, CERRO NEGRO DISTRICT, DESEADO MASSIF, ARGENTINA

**Leaders:** David Cooke, Noel White

**Team members:** Bruce Gemmell, Francisco Testa, Lejun Zhang

**Collaborators:** Thomas Bissig, Patricio Brivodoro, German Escorza, Cesar Riveros

This sub-project aims to test and develop geological and geochemical vectors to low sulfidation epithermal gold mineralisation in the Cerro Negro district of Argentina by integrating TerraSpec and XRD analyses of clay mineralogy (illite, smectite, kaolinite) with vein textures and, where available, whole rock and mineral geochemistry to help

constrain the relative depths of vein segments within discrete fault blocks and proximity to ore.

Francisco Testa and Lejun Zhang conducted fieldwork in February and March 2019 focussed on the Eureka vein system within the district (currently being mined). Hydrothermal alteration mineral zones were detected by means of TerraSpec analyses (e.g., carbonate mineralogy), which aided vectoring towards mineralisation. Based on whole rock geochemistry, both lithologic units (immobile elements) and hydrothermal alteration zones (mobile elements) were detected. Some of the main achievements in the Silica Cap–Gato Salvaje vein systems include: the first documentation of paragenetic sequences, Ar/Ar ages on adularia to date the low sulfidation epithermal event, record textural features, mineralogical zonation, and quartz trace element chemistry, all used as proximity indicators towards mineralised quartz veins. The same analyses were conducted in the Silica Cap lithocap. Some of the major results include first Ar/Ar ages on alunite to date the overprinting advance argillic event, understanding of trace element substitution in HS quartz, which contrasted hydrothermal fluids responsible for the intense silicic alteration exposed on surface, and vector towards heat source, and most importantly provide a genetic model which explains the relationship between low-sulfidation epithermal mineralisation and overprinting lithocap alteration; the latter has proven to be applicable for other areas in the district.

The final report for the project will be provided to Newmont Goldcorp in 2020.

**GEOCHEMICAL FOOTPRINT AND PARAGENESIS OF THE SPECIMEN HILL AU PROSPECT, NEW ENGLAND OROGEN, QUEENSLAND**

**Leaders:** Lejun Zhang, Mike Baker  
**Student:** Hugh Rivett  
**Collaborators:** Jonathan Robbeson, Jim Yaxley

This Honours project completed by Hugh Rivett and sponsored by Signature Gold Ltd aimed to describe the geology and model the hydrothermal

alteration patterns present at the Specimen Hill intrusion-related Au-Cu prospect, Queensland. This will aid further exploration for similar styles of mineralisation in the northern New England fold belt by Signature Gold. This study focussed on several fundamental objectives, including using geological mapping and drill core logging to construct a cross-section to understand the geology, alteration, mineralisation characteristics and morphology of Specimen Hill. The alteration and mineralisation mineralogy, texture, and any zoning patterns from in-field observations, petrography observations and SEM (scanning electron microscope) were used to construct a plausible paragenesis for the prospect. Major and trace element chemistry analysis of key alteration minerals epidote, chlorite and pyrite by SEM and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) were utilised for vectoring potential and prospect fertility assessment. Pyrite chemistry and sulfur isotope analyses were used to understand the source and evolution process of hydrothermal fluids.

The results of this study indicated that there is significant skarn-style alteration and Au-Cu sulfide-bearing mineralisation within the prospect area. Six alteration and mineralisation stages were defined, with Cu and Au mineralisation related to the retrograde stage skarn alteration. Pyrite from retrograde stages was found to contain high Cu, Au, As, Zn. Paragenetic and geochronology results suggest several magmatic-hydrothermal-associated events occurred in the area. Epidote and chlorite geochemistry also suggest the Specimen Hill area is a fertile system.

**FAR-FIELD AND NEAR-MINE FOOTPRINTS: FINDING AND DEFINING THE NEXT GENERATION OF TIER 1 ORE DEPOSITS (AMIRA P1202) – MODULES 1–3**

**Leaders:** Mike Baker, Shaun Barker, David Cooke, Leonid Danyushevsky, Angela Escolme, Lejun Zhang

**Team members:** Ivan Belousov, Matthew Cracknell, Sebastien Meffre, Evan Orovan

**Students:** Camila Arcos, Kyle Eastman, Batbayar Enkhbold,

Patrick Hamilton, Andrew Jedemann, Mitch Marcelissen, Xin Ni Seow, Emily Smyk, Yi Sun

**Collaborators:** Laurent Ailleres, Robin Armit, Scott Halley, Peter Hollings, José Piquer, Mervin Delos Santos, Leo Subang, Noel White

AMIRA P1202 is being conducted in collaboration with researchers from Lakehead University, Monash University and the Universidad Austral de Chile. Building upon the results of the AMIRA P1153 project, this multi-year project is developing new methods for discovering porphyry and/or epithermal deposits through improved geochemical detection of far-field and near-mine ore deposit footprints. Analysis of the geochemical signals recorded in hydrothermal alteration halos will provide explorers with methods for assessing district fertility (how large?), vectoring information (how far, and in what direction?), as well as developing workflows for ore body characterisation in the near-mine environment. This will facilitate the presence, location and significance of porphyry and/or epithermal copper, gold and molybdenum deposits in an exploration tenement to be determined during the early stages of exploration. This approach has relevance to exploration involving drilling under post-mineralisation cover, or in areas where outcrop is limited or difficult to access.

Modules 1–3 of the project focus on three key alteration domains within the porphyry-epithermal system. These include the green rock and lithocap environments, and aspects of magmatic fertility. The main research outcomes will be the development of geochemical tools for testing the fertility of mineral districts, tools for vectoring to mineralised centres and depth assessments in lithocap environments. This will involve the use and analysis of key alteration minerals from green rock, white rock and lithocap environments. Cost-effective field-based methods will also be developed that can be applied by explorers who do not have access to suitable laboratory facilities for LA-ICP-MS analyses.

In 2019, the research team commenced or continued field campaigns at sites in Australia, Indonesia, the Philippines, South Korea and the USA. A number of



Dr Mike Baker taking notes on the rocks surrounding the Christmas porphyry Cu-Mo deposit, Dripping Springs Range, Arizona; fieldwork at the Christmas deposit was undertaken as part of Emily Smyk’s PhD study within the AMIRA P1202 project, TMVC Theme 1.

these field sites involved postgraduate students (Honours, MSc and PhD). Kyle Eastman, Emily Smyk and Yi Sun have continued their PhD studies on the Tujuh Bukit district (Indonesia), Christmas deposit (USA), and Lepanto district (Philippines), respectively. Patrick Hamilton and Andrew Jedemann have also continued their MSc studies on the Pemberton Hills deposit (Canada), while Camila Arcos has completed her Honours study of Central Chile green rocks and Mitch Marcelissen has commenced his study of the Mines Gaspé deposit (Canada). In late 2019 Batbayar Enkhbold commenced an MSc project on alteration chemistry at Mt Isa, with Mertkan Bozoglu to commence an MSc project on pyrite mineral chemistry early in 2020.

**TIMING RELATIONSHIPS WITHIN PORPHYRY-EPITHERMAL DEPOSITS**

**Leader:** Evan Orovan  
**Team member:** David Cooke  
**Student:** Erin Lawlis

**Collaborators:** Robert Creaser, Richard Friedman

This project involved using high-resolution geochronology (ID-TIMS on zircon and Re-Os on molybdenite) to constrain the magmatic and mineralising events at the largest known alkalic epithermal Au deposit (Lihir, Papua New Guinea) and a calc-alkalic porphyry district (Namosi, Fiji). Results from this project will help us better understand the volcano-magmatic construction of a porphyry district, from early volcanism, through emplacement of porphyry-related intrusions and then superimposition of a world-class epithermal Au deposit. All analytical work is complete (geochronology and Hf isotopes) and is currently being incorporated into two manuscripts to be submitted in early 2020.

**IDENTIFYING UNIQUE RESISTATE INDICATOR MINERAL (RIM) CHEMISTRY AS A GUIDE IN PROSPECTIVITY FOR SEDIMENT-HOSTED COPPER**

**MINERALISATION (AMIRA P1206)**

**Leader:** Shaun Barker  
**Team members:** David Cooke, Leonid Danyushevsky, David Selley  
**Collaborators:** Murray Hitzman, Sean Johnson

This one-year project began in late 2019, and is designed to provide a rapid assessment of whether the chemistry of resistate mineral phases (apatite, rutile and tourmaline) formed during the hydrothermal alteration associated with sediment-hosted copper mineralisation can be used to provide information on proximity to ore, and the fertility of the aquifer systems responsible for copper mineralisation. The project is supported by Anglo American; First Quantum Minerals; Independence Group; the Japan Oil, Gas and Metals National Corporation (JOGMEC); and Rio Tinto, and is utilising the world-leading expertise of the CODES Analytical Laboratories laser ablation ICP-MS instrumentation and TIMA “TIGER”



Dr Lejun Zhang investigates alteration assemblages at the Rincones de Araya porphyry Cu-Mo prospect, San Juan province, Argentina, February 2019.

automated SEM at iCrag to provide a quantitative, detailed assessment of the paragenesis and mineral chemistry of samples which are being analysed from throughout the Central African Copper Belt.

### THEME 2: OPTIMISING GEOMETALLURGICAL PREDICTION

#### CHARACTERISING SUPERGENE COPPER MINERALOGY USING HYPERSPECTRAL TECHNIQUES

**Leader:** Angela Escolme

**Team members:** Ron Berry, Sebastien Meffre

**Student:** Erin Lawlis

**Collaborators:** David Green, Carsten Laukamp

The major goals of this project are to develop a spectral library for supergene copper minerals which can be used to develop mineralogical models of supergene ore zones using automated hyperspectral techniques. It is anticipated that these models will inform predictive hydrometallurgical performance models for heap and dump leach operations. A suite of type mineral

specimens has been provided by CSIRO. The project is currently awaiting an Honours student to complete full mineralogical characterisation and collect the SWIR spectra in order to begin building a spectral library.

#### FAR-FIELD AND NEAR-MINE FOOTPRINTS: FINDING AND DEFINING THE NEXT GENERATION OF TIER 1 ORE DEPOSITS (AMIRA P1202) – MODULE 4

**Leaders:** David Cooke, Angela Escolme

**Team members:** Mike Baker, Shaun Barker, Ivan Belousov, Matthew Cracknell, Leonid



Morning light reaches base camp at Rincones de Araya, Argentina; the Rio Salinas alteration anomaly is visible in the background. This photo was taken by PhD student Kyle Eastman who was working as a field assistant on this trip in February 2019.

Danyushevsky, Sebastien Meffre, Evan Orovan, Lejun Zhang

**Students:** Takeshy Coaquira, Kyle Eastman, Javier Merrill, Angela Rodrigues

**Collaborators:** Laurent Ailleres, Robin Armit, Scott Halley, José Piquer

Details of the overall AMIRA P1202 project are outlined in the TMVC Theme 1 section of this annual report. The optional research module of P1202 (Module 4) is reported here in the Geometallurgy Theme, as it is the major geometallurgical research activity being conducted in the TMVC from year 4 onwards.

P1202 currently has six sponsors of Module 4 (BHP, FMG, Merdeka, Newcrest, Rio Tinto and Northparkes) with Rio Tinto and Northparkes joining the project in 2019. The Module 4 research initiative involves both near-mine exploration vectoring and geometallurgical assessments of the porphyry transition zone, where clay and mica alteration overprint early formed potassic alteration. The research team are working closely with Corescan at Module 4 sites to optimise mineralogical characterisation of the transition zone for exploration, evaluation and mining.

In 2019, the P1202 Module 4 research team continued research activities across several study sites, including field activities in Indonesia, Chile, Argentina, Fiji and Arizona. The research team are progressing well towards delivering on the project's objectives to the sponsor group (including algorithms for textural classification of hyperspectral imagery, and new white micas mineral chemistry data sets and exploration tools). PhD students Javier Merrill, Kyle Eastman,

Takeshy Coaquira and Angela Rodrigues (Monash) are continuing to generate exciting outcomes with impact through their case studies. Additional PhD students are expected to join the project in early 2020.

### THEME 3: MINIMISING GEOENVIRONMENTAL RISKS

#### MINERALOGICAL DOMAINING OF LOW GRADE AND NO GRADE ZONES USING AUTOMATED DRILL CORE LOGGING AT CADIA

**Leader:** David Cooke

**Team member:** Matthew Cracknell

**Student:** Laura Jackson

**Collaborators:** Ronell Carey, Mary Harris, Anita Parbhakar-Fox, Ekaterina Savinova

Geoenvironmental characterisation at the earliest life-of-mine stages is critical

for designing the most appropriate environmentally conscientious waste management strategies and storage facilities. However, geochemical tests typically used for predicting waste characteristics are texturally destructive, and therefore do not appropriately describe the geoenvironmental characteristics of the waste materials, and indeed how they might evolve regarding the role of secondary minerals in metal cycling within the surficial environment. In 2019, PhD student Laura Jackson developed and tested a field tool for determining AMD risk in drill core and for screening waste, as well as developing and testing hyperspectral and automated mineralogy assessment methods for kinetic leach columns. Laura's PhD thesis will be submitted in Q2 2020.

TMVC PhD student Sibele Nascimento taking a break from doing a geophysical survey at the King River delta in western Tasmania during 2019. Her research project 'Geometallurgy of historic mine waste: Evaluating options for reprocessing', sits within TMVC Theme 3.





*Buckets of red mud: bauxite refinery waste sourced from Bell Bay Aluminium in northern Tasmania is a potential acid mine/metalliferous drainage (AMD) ameliorant. PhD student Annah Moyo is researching its use in her project 'Utilising industrial waste materials for AMD control', which falls within TMVC Theme 3.*

## UTILISING INDUSTRIAL WASTE MATERIALS FOR AMD CONTROL

**Leader:** David Cooke

**Team member:** Sebastien Meffre

**Student:** Annah Moyo

**Collaborators:** Anita Parbhakar-Fox, Michael Reid, Clint Siggins, Carol Steyn

Cost-effective waste management of materials producing acid and metalliferous drainage (AMD) is essential for successful remediation. Considering this, using alkaline waste materials generated by other industrial processes represents a potential option for managing acid-forming mine wastes and is the focus of this sub-project being undertaken by PhD student Annah Moyo.

Mine waste materials were collected in early 2019 from six mine and smelter sites across Tasmania. Annah is currently assessing whether these acid-generating materials can be neutralised when combined with wastes from other industrial sites. An innovative series of bench-scale accelerated kinetic leach tests were initiated in 2019 and will continue for around 100 weeks to

assess whether green liquor dregs, wood ash, coal ash, red muds, and scallop, mussel and oyster shells can ameliorate acid drainage generated by oxidation of the mine wastes.

## GEOMETALLURGY OF HISTORIC MINE WASTE: EVALUATING OPTIONS FOR REPROCESSING

**Leader:** Matthew Cracknell

**Team member:** David Cooke

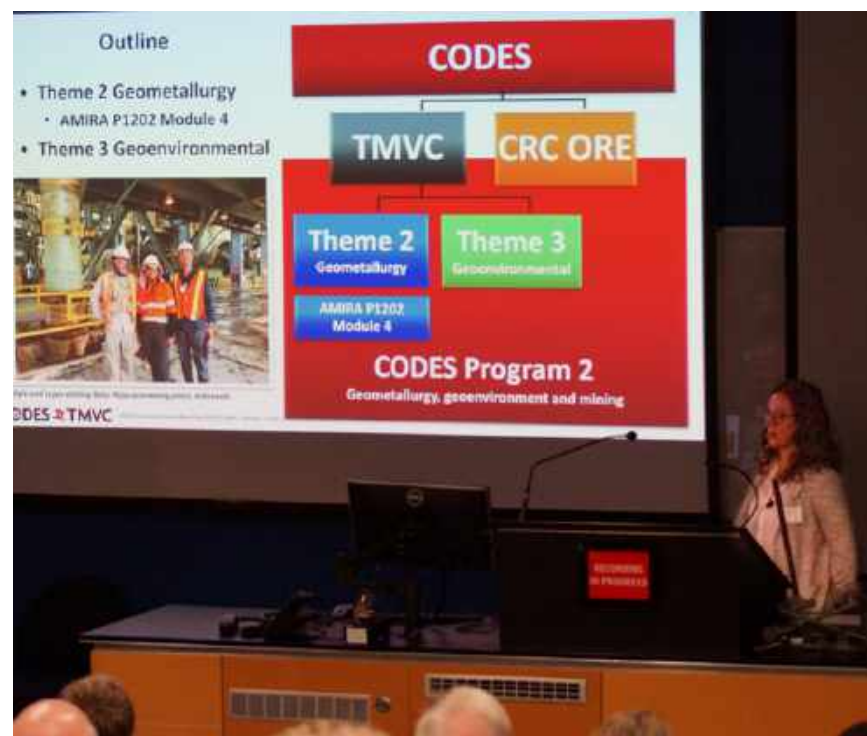
**Student:** Sibebe Nascimento

**Collaborator:** Anita Parbhakar-Fox

Strategic mine waste planning has only been actively pursued in the past decades, with historical mining operations having used inappropriate disposal methods by today's environmental standards. This can result in environmental degradation to downstream catchments. One such example is the King River delta/Macquarie Harbour, western Tasmania, and is the focus of this project. Approximately 100 Mt of mine tailings and slag materials have been discharged into the Queen and King rivers from the Mount Lyell copper mine, Queenstown, since the 1890s. Furthermore, the 2.5 km<sup>2</sup> King River delta contains approximately 10 Mt of

mine tailings, with a further 10 Mt of fine tailings deposited beyond it. Whilst the tailings properties and the geochemistry of Macquarie Harbour have been documented, the sulfide chemistry of individual minerals (i.e., pyrite) has yet to be detailed at the micro-scale. This research project aims to mineralogically and geochemically characterise tailings and slag materials in the riverine and deltaic systems and establish if reprocessing of these materials is an environmentally and economically viable rehabilitation option.

PhD student Sibebe Nascimento has spent 2019 characterising in detail the mineralogical and geochemical properties of the King River delta tailings. Preliminary results indicate that substantial cobalt and minor copper are present in pyrite and chalcopyrite phases and are likely target metals for metals recovery. At the recent SGA 2019 conference in Glasgow, Scotland, Sibebe was awarded a best student talk prize for her presentation detailing preliminary results from the integrated analysis of mineralogical, geochemical and geophysical observations across the delta. In 2020 Sibebe will finalise her mineralogical analysis of collected samples and will commence flotation and bio-oxidation test work to determine the best methodology to recover cobalt and other metals.



*Dr Angela Escolme explains the structure of the TMVC's work in Theme 2 and Theme 3 at the 2019 CODES Annual Review in November.*



*TMVC PhD student Xin Ni Seow with Qingling Xiao (Hefei University of Technology) examining drill core during the 2019 'Ores in Magmatic Arcs – Indonesia' short course.*

## UNDERPINNING TECHNOLOGIES

### DEVELOPMENT OF THE FAST-THROUGHPUT SAMPLE CELL FOR LASER ABLATION APPLICATIONS

**Leaders:** Leonid Danyushevsky, Michael Shelley

**Team members:** Ivan Belousov, Paul Olin

**Collaborator:** Ashley Norris

This project aims to develop a new sample cell capable of high-throughput applications using laser ablation instruments, which may involve LA-ICP-MS and/or LIBS. The instrumentation developed would be used for the scanning of large sections of drill half-core.

Stages within this project include prototype development and performance testing.

During 2019, testing of the third prototype of the fast response cell was completed using biological samples.

The testing has demonstrated that imaging of elemental distribution can be conducted at a speed up to ten times faster than what was possible with standard instrumentation, while maintaining the required limits of detection. Initial testing on geological materials has confirmed that the instrumentation is capable of quantitative characterisation of mineral micro-inclusions. Testing will continue in 2020 with the aim of developing quantitative methods for mineral analysis.

### CORESCAN DATA FEATURE EXTRACTION AND CLASSIFICATION FOR MINERALOGICAL AND TEXTURAL INFORMATION ANALYSIS

**Leader:** Matthew Cracknell

**Team members:** Ron Berry, Leonid Danyushevsky, Neil Goodey, Anthony Harris, Anya Reading

**Students:** Javier Merrill, Angela Rodrigues

**Collaborators:** Laurent Ailleres, Robin Armit, Ekaterina Savinova

CoreScan generates a range of drill core image products including Digital Surface Models (DSM), Red-Green-Blue (RGB) colour photographs and Visible-Near Infrared–Short Wave-Infrared (VNIR–SWIR)-derived mineral interpretations. Despite the rich geological information implicitly contained within these data, they are primarily used to provide percentages of identified minerals down hole to CoreScan customers. The aim of this project is to classify and extract mineralogical and textural features from CoreScan imagery, adding value to their data products. For example, the two-dimensional imagery generated by CoreScan contains information on the geometric characteristics and spatial arrangement of interpreted minerals, while there are key economic mineral species, such as sulfides, that do not have characteristic absorption features in VNIR–SWIR spectra and are therefore not identified accurately.

In 2019 a significant boost was the addition of PhD candidates Javier

Merrill (CODES) and Angela Rodrigues (Monash) to this project. The PhD projects are embedded within AMIRA P1202 Module 4 and are investigating novel approaches to obtaining numeric representations of mineral texture for geometallurgical domaining and the use of machine learning for improving hyperspectral mineral classifications. Dr Matthew Cracknell presented at PACRIM 2019 in Auckland, New Zealand, highlighting research on identification of sulfides and quantification of mineral textures in Corescan RGB photographs. In April and November, Matthew co-hosted one-day introduction to machine learning workshops as part of the AusIMM PACRIM 2019 (Auckland, New Zealand) and Mining Geology 2019 (Perth, Australia) conferences. The aim of these workshops was to introduce the fundamental concepts of machine learning and encourage uptake in the geoscience community. Matthew has also run a number of data analytics workshops for CODES/TMVC researchers.

INTEGRATING CHEMICAL AND MINERALOGICAL DATA LAYERS FOR ELEMENT DEPORTMENT

**Leaders:** Sebastien Meffre, Matthew Cracknell, Leonid Danyushevsky, Ron Berry, Shaun Barker

**Team members:** Ivan Belousov, Angela Escolme, Paul Olin

**Student:** Rocky Barker

This project aims to integrate mineralogical and chemical data from various spectral and analytical techniques in order to extract information on element deportment, mineral chemistry, mineral association and other mineral-based information, such as the ability to automatically recognise gold in solid solution, and gold in particles. Digital cameras, short-wave infrared spectrometry and laser Raman spectroscopy will be used to acquire mineralogical data, with chemical information being garnered from laser ICP-MS, pXRF and/or laser-induced breakdown spectroscopy (LIBS). During the year data obtained from samples from the Carlin Deposit were acquired testing and validating the ‘fast lines on unpolished cores’ technique



Shawn Hood, seen here presenting at PACRIM 2019, in New Zealand, completed his PhD in 2019 on ‘Machine-assisted modelling of lithology and metasomatism’ within the TMVC Underpinning Technologies theme.

against MLA and the micro-XRF (Bruker Tornado). The analyses show that although there are major benefits to the LA-ICP-MS rapid scan technique, full and accurate quantification remains difficult. Part of the issue that is currently being resolved is the cumbersome data processing routines. A new algorithm currently being commercialised with the LADR software platform will make data processing much more accurate and easier.

A spin-off from this work has been the method development by Associate Professor Shaun Barker and Dr Matthew Cracknell on the automatic identification and characterisation of inclusions from LA-ICP-MS data. This side project shows great promise and will be further developed in 2020.

The analysis of the data collected on Hot Chili’s La Productora Deposit in Chile was postponed due to staff availability issues but will be re-examined in 2020.

INTERPRETING STRUCTURAL AND GEOCHEMICAL PATTERNS USING MACHINE LEARNING

**Leaders:** Anya Reading, Matthew Cracknell

**Student:** Shawn Hood

**Collaborator:** Michael Gazley

In 2019 Shawn Hood submitted his PhD thesis titled ‘Machine-assisted modelling of lithology and metasomatism’. Shawn’s ground-breaking research culminated in the publication of two

peer-reviewed papers. A paper was published in *Chemical Geology* with the support of Gold Fields Australasia, which combined the use of geological domain expertise, machine learning and 3D visualisation to model fluid flow pathways in Orogenic gold systems by tracing element depletion and enrichment. A second paper, published in the new journal *Applied Computing and Geosciences*, provides a practical guide to getting the most out of geochemical, geophysical and remote sensing data for automated mapping of basement geology in difficult to access and challenging environments. In his approach, Shawn demonstrated the important role experienced geologists play in computer-assisted geological modelling. Shawn has achieved his goal to develop practical advice and reproducible workflows that fit seamlessly into existing industry methodology for targeting and defining ore bodies. Well done Shawn! In-between publishing research and submitting his thesis Shawn also presented at PACRIM 2019 and co-hosted two conference-based workshops aimed at introducing machine learning to geologists. These have been well received and will be instrumental in fostering the rapid uptake of data science and machine learning approaches in the field of economic geology.

GEOLOGICAL FEATURE DISCOVERY FROM QUANTITATIVE DATA INTEGRATION (ALGORITHM DEVELOPMENT)

**Leaders:** Anya Reading, Matthew Cracknell

**Students:** Stephen Kuhn, Peter Morse

**Collaborators:** Mike Christie, Tim Ireland, Christopher Lueg, Chris Wijins

This project continues to progress methods for the automated classification of lithology and alteration zonation from geological, geophysical and geochemical data and flexible approaches to visualising research results. Our focus continues to optimise the value of machine learning in practical workflows, given a resource project’s development stage (e.g., area selection, target prediction, resource evaluation, and resource development) and has progressed with the PhD research of Stephen Kuhn. In 2019, a paper was published detailing geochemical reconnaissance-stage research using machine learning to incorporate geochemical sampling and preliminary ground-based mapping. Currently in its final peer review stages, a new paper, again based on Steve’s research, details the application of machine learning prediction uncertainty to highlight the most likely areas for the occurrence of key lithologies. Steve is in the last stages of completing his PhD thesis, which has been generously supported by First Quantum Minerals, and is expected to submit early in 2020.

Visualisation development activities also took place with the development of a suite of interactive software for geoscientific visualisation. The software, developed by Peter Morse, incorporates understanding of human colour perception and perceptually uniform colour-space, enabling well-posed visualisation to enhance the confidence levels in visualised data and to characterise uncertainty. In 2019 a paper was published detailing application to 2D seismic contour maps, generating new insights for AuSREM seismic data. In 2020, a demonstration study is described in a new paper currently in peer review, extending this work to 3D global tomography in solid Earth geophysics. Peter is in the final stages of his PhD and will submit in early 2020. The software suite is available opensource on Github.

Professor Anya Reading, gave an invited talk and sat on a panel at the Stanford (Earth) Women in Data Sciences Workshop in November. This event highlighted the use of data science in various geoscience research areas.

METHOD DEVELOPMENT FOR LASER-ABLATION ICP-MS APPLIED TO COMPLEX MATRICES

**Leader:** Leonid Danyushevsky

**Team members:** Elena Lounejeva, Paul Olin, Terrie Sawyer, Jay Thompson

**Students:** Nanda Mrabawani, Xin Ni Seow

This project aims to develop quantitative methods, including full uncertainty budgets, for analysis of a range of mineral matrices, and covering a wide range of major and trace elements. The successful outcome of this project would allow performing quantitative LA-ICP-MS analyses without a requirement for data on mineral major element contents obtained by a different analytical technique.

Testing of the approach has been performed by comparing the results of measurements of 300 grains of plagioclase and 100 grains of apatite conducted at variable energies of the laser beam. This has demonstrated that variations in energy are capable of affecting the obtained concentrations of elements in these minerals, thus confirming the need for identifying optimal analytical conditions in addition to choosing optimal reference materials when developing fully-quantitative LA-ICP-MS methods. A new project has started aimed at developing a quantitative method for LA-ICP-MS analysis of alunite.

Two keynotes were delivered during the year describing the earlier outcomes of this project at the Goldschmidt Conference in Barcelona, Spain, and at the North American Workshop on Laser Ablation in Austin, Texas.

Knowledge transfer and training

Knowledge transfer and training are an integral part of the TMVC, encompassing all research themes and impacting all parts of the mining value chain.

During the year TMVC staff and students produced 18 refereed journal articles (including three in the Geometallurgy special issue of *Economic Geology*), provided 95 reports and 27 onsite presentations to industry, and delivered 34 conference presentations and eight workshops (both local and international). Several staff and students delivered a dedicated session on research highlights and the forward program at the annual CODES Annual Review (oral and poster presentations) in November.

Team members also participated in public outreach opportunities including Science in the Pub in February, and the UTAS Women in Technology Event held in September.

## Looking forward

Work on AMIRA project P1202, 'Far-field and near-mine footprints: finding and defining the next generation of Tier 1 ore deposits', will continue to be the focus of activity for many Theme 1 and 2 researchers. 2020 will see continued geochemical data acquisition and interpretation, commencement of work at Northparkes and sponsor review meetings in May and November.

The new one-year AMIRA project 'Identifying unique Resistate Indicator Mineral (RIM) chemistry as a guide in prospectivity for sediment-hosted copper mineralisation' will investigate mineral chemistry signatures associated with mineralisation proximity and aquifer fertility by acquiring new laser ablation ICP-MS data from approximately 150 samples from the Central African Copper Belt.

Theme 3 will see PhD students Annah Moyo and Sibebe Nascimento continue with their studies in Tasmania. Sibebe will commence flotation and bio-oxidation test work on collected sediment samples to determine the best methodology to extract cobalt and other metals, and Annah's bench-scale accelerated kinetic leach tests will continue throughout the year. Laura Jackson is expected to submit her PhD thesis on the mineralogical domaining of low grade and no grade zones using automated drill core logging at Cadia in Q2 2020.

Underpinning Technologies researchers will continue to investigate the development and application of Corescan-derived textural indices to diverse applications such as brownfields ore deposit exploration and geometallurgical process control. PhD candidate Nanda Mrabawani will commence LA-ICP-MS method development for alunite, and undertake completion of studies of apatite and bytownite plagioclase. In collaboration with Laurin Technic, the Underpinning Technologies team aims to develop quantitative methods for mineral analysis with the third prototype of the high-throughput laser cell.

Several PhD candidates are expected to submit their theses during the year including Laura Jackson, Steve Kuhn and Amos Garay.

Journal publications and, where possible with COVID-19-related travel restrictions, conference-related activities will remain key avenues for TMVC staff and students to present Hub research outcomes. Representation at the Goldschmidt conference is confirmed for 2020. A special publication in *Economic Geology* is scheduled for 2020, along with publications in *Applied Computing and Geosciences*, *Geochemistry: Exploration, Environment, Analysis*, and other journals.



*Sphalerite – galena – pyrite – calcite veins  
in quartz – muscovite – pyrite-altered  
feldspar crystal-rich volcaniclastic  
sandstone, Kelian Au-Ag deposit,  
Kalimantan, Indonesia.*

# Training and education

## Objectives

Provide an ongoing supply of world-class PhD, Masters and Honours geoscience graduates.

Deliver a range of professional development short courses and workshops tailored to meet the needs of the minerals industry in terms of re- and up-skilling its workforce.



**LEADERS** ROBERT SCOTT AND SHAUN BARKER



Master of Economic Geology 'Ores in Magmatic Arcs – South America' short course participants at the Atacocha polymetallic mine (Nexa Resources) in Huanuco, Peru. They were examining the Pasco Complex magmatic-hydrothermal district, which contains skarns and carbonate replacement deposits, intermediate sulfidation Ag-Pb-Zn veins and porphyry Cu-Mo mineralisation.



Senior Lecturer Dr Rebecca Carey (fourth from right with backpack) took two CODES Honours students – Acacia Clark (far right) and Imbi Simpson (in orange) – to New Zealand on a joint UTAS–University of Hawaii short course entitled 'Volcanic Processes and Products' in March 2019. This combined short course is held every two years, alternating with the CODES Masters volcanology short course to New Zealand.

## Introduction

The Centre has an international reputation for excellence in postgraduate education, which includes providing students with a comprehensive grounding in the Earth sciences. Students come from all over the world to study at CODES, with many graduates subsequently progressing to senior roles in the minerals industry, state and federal governments, and academia.

Training and education activities also play a vital role in the Centre's research program via the wide array of student theses, which are integral to research activities across our six research programs. Areas covered under Training and education include the Higher Degree by Research (HDR), Master of Economic Geology and Honours programs. CODES also runs a variety of one-off short courses and workshops, most of which are aimed at re- and up-skilling minerals industry professionals (see the Technology transfer section in this report for details about these short courses and workshops).

## Highlights

2019 has been a busy year for HDR enrolments and completions, with two Master of Science by Research students starting their courses, alongside six new PhD students. In 2019, we had eight PhD thesis submissions across research programs 1, 3, 4 and 6. In the Honours program we had 11 students completing in 2019, as well as a number of mid-year starters.

It was another busy year for the Master of Economic Geology program, with ten new students, and four short courses offered in a calendar year for only the second time. Six more students either graduated or completed the Master of Economic Geology degree in 2019. The major highlight of the MEconGeol teaching program in 2019 was the return to South America for the 'Ores in Magmatic Arcs' short course for the first time since 2015. 'Ores in Magmatic Arcs' was delivered twice in 2019. The first offering, delivered in Indonesia in March, had a record 29 participants. The second offering, in South America,

attended by 21 people, was timed to follow the mid-October Annual Meeting of the Society of Economic Geologists in Santiago, Chile. Despite civil unrest in Ecuador causing a last-minute relocation of the first week of the short course to Peru, the short course was very successful, and proved to be a social media hit. Short course leader David Cooke's 11 LinkedIn posts during the short course attracted over 116,000 views, over 2000 'likes' and more than 70 comments. This exceptional response highlights the widespread interest in the activities of the Master of Economic Geology program in the Earth sciences community.

Thirteen students were enrolled in the Honours program in 2019. This included two mid-year starters from 2018, and three who commenced mid-2019, and will complete their degrees in 2020.

## Postgraduate programs

CODES has a range of postgraduate programs aimed at providing the next generation of world-class geoscientists. The main programs are the Higher Degree by Research (HDR), Master of Economic Geology and Honours.

### HDR Program

Students enrolled in the UTAS HDR program make a major contribution to CODES' research activities. A total of 63% of the HDR projects involve collaborations with the minerals industry. CODES' success in attracting high-calibre international HDR students is underpinned by its reputation for excellence as a research training centre. The HDR program depends on UTAS funding in the form of highly competitive living allowance scholarships and tuition fee waivers, as well as industry funding of scholarships and research costs. Currently just under half of our HDR students are from overseas, from a total of 19 different countries.

There were 56 students enrolled in the HDR program during 2019 (53 PhD and 3 MSc), including seven new arrivals. The new enrolments were Australian students Alex Farrar and Zebedee Zivkovic, and international students Takeshy Coaquira (Peru), Nathaly Guerrero (Ecuador), Max Hohl (Germany), Hannah Moore (UK) and Xin Ni Seow (Malaysia). Ten HDR students graduated in 2019: Ayesha Ahmed, Jing Chen, Alex Cherry, Jodi Fox, Sam Holt, Shawn Hood, Brian McNulty, Josh Phillips, Naomi Potter and Daniele Vergani were all awarded PhDs. A further four students have PhD theses under examination, or were making final corrections following examinations in 2019. Three PhD candidates withdrew, with a fourth changing discipline, and several students had periods of suspension.

### Master of Economic Geology Program

The coursework-based Master of Economic Geology degree at CODES forms part of the national Minerals Geoscience Masters (MGM) program – a collaboration between UWA,



*Students undertaking the VIEPS Environmental Geology Field Techniques course during 2019 are pictured here measuring groundwater contamination in a tailings sediment bank on the lower King River, western Tasmania.*

UTAS and Curtin University. The MGM remains the course of choice for industry-based geoscientists, attracted by the opportunity of studying for an internationally recognised degree, while still being able to pursue full-time careers in the minerals industry.

It was another successful year for the Master of Economic Geology (MEconGeol) program, with ten new admissions taking the program to a new record of 57 active students in 2019. CODES also delivered four short courses in a calendar year for the first time since 2012, with 'Ores in Magmatic Arcs' being delivered twice, once in Indonesia (March) and once in South America (Peru and Chile in October). All up, 48 people participated in 'Ores in Magmatic Arcs' in 2019 (22 masters students, nine other students and 17 industry geologists and academics). The 'Ore Deposit Geochemistry, Hydrology and Geochronology' (also 48 participants) and 'Geometallurgy' (25 participants) short courses were also well attended. During the last short course for the year, CODES also celebrated 30 years of delivering the Master of Economic Geology program and we were very pleased to welcome back our first ever

graduate, Ken Morrison, as the guest of honour at a celebration to mark the event. Master of Economic Geology students Ken Bush, Jesse Clark, David Haddow, Juan Diego Rojas Lopez and Libas Ulaiwi all graduated during 2019, and Franco Ferreyra also completed his degree late in the year and will graduate in 2020.

The four UTAS-based short courses held during 2019 were:

### ORES IN MAGMATIC ARCS – INDONESIA 8–19 MARCH 2019

In early March 2019, the highly popular two-week 'Ores in Magmatic Arcs – Indonesia' short course began on Lombok island in Indonesia, led by CODES staff Lejun Zhang, David Cooke, Noel White and assisted by Indonesia-based colleagues Adi Maryono, Rachel Harrison (a former MEconGeol graduate and CODES PhD student) and Iryanto Rompo. The short course was attended by 16 Master of Economic Geology students and 13 other participants, the largest ever participation in this unit.

This course has a strong focus on field observations and hands-on practical skills, supported by an understanding

of theoretical aspects. Two days of lectures covered theories of geology, geochemistry and geometallurgy about the porphyry – epithermal deposits. The full spectrum of deposits was visited, including giant porphyry Cu-Au deposits (Batu Hijau, Elang), giant high-sulfidation – porphyry (Tujuh Bukit, open pit exposures and core from recent deep drilling into the upper high-grade zone), modern hydrothermal systems on an active volcano (Mt Ijen), and exploration projects on Lombok and Sumbawa. In addition to site visits, participants had the opportunity to spend a day learning and applying the Anaconda mapping method inside the Batu Hijau open pit.

There was great enthusiasm amongst the participants for learning about the amazing ore deposits of the Sunda-Banda Arc, and also for enjoying the wonderful hospitality and culture of Indonesia.

### ORE DEPOSIT GEOCHEMISTRY, HYDROLOGY AND GEOCHRONOLOGY 3–14 JUNE 2019

In June a large group, comprising 25 Masters students, nine industry participants and 14 other students (CODES PhD, MSc, and Honours students and two visiting higher degree students from Lakehead University) attended the 'Ore Deposit

Geochemistry, Hydrology and Geochronology' short course, led by Shaun Barker. This short course is designed to introduce participants to a wide range of geochemical, isotopic, hydrological, and geochronological techniques used to understand ore genesis and aid in the exploration for mineral deposits. During the short course participants are introduced to pioneering work on mineral chemistry vectoring and discrimination techniques for ore deposits developed by CODES researchers over the past decade. As usual, the unit was delivered by a mixture of CODES staff (Cooke, Baker, Barker, Berry, Danyushevsky, Meffre, Scott, Steadman and Zhang) and guest presenters with wide ranging expertise. Guest presenters included Ore Deposit Geochemistry regulars Phil Blevin (GSNSW), Stephen Cox (ANU), Scott Halley (Consultant), Nick Oliver (Consultant) and Leslie Wyborn (ANU), as well as Poul Emsbo from the USGS (Colorado, USA) and Peter McGoldrick (UTAS), who delivered a stimulating day of lectures detailing new geological, geochemical and fluid modelling constraints on the development of sedex deposits.

### ORES IN MAGMATIC ARCS – SOUTH AMERICA 11–26 OCTOBER 2019

In October, 11 Masters students and eight industry participants attended the 'Ores in Magmatic Arcs – South America' short course, led by David Cooke and Mike Baker, with significant logistical and translation support provided by CODES Masters students Victor Torres Pacheco and Carlos Diaz Castro. Originally scheduled to visit sites in Ecuador and Chile, the first week of the field trip was changed from Ecuador to Peru due to civil unrest in Ecuador that arose in early October days before the field trip was scheduled to begin. This last-minute change to the program was well received by all, as the deposits visited in Peru provided a greater and more varied array of mineralisation and deposit styles than was originally planned for the Ecuadorian leg of the trip.

The first week of the field trip saw the participants visit several deposits in Peru, including the Soledad Cu-Au-Ag tourmaline breccia-hosted prospect near Huaraz and associated core

facility in Lima (Chakana Copper), the Pasco Complex magmatic-hydrothermal district, which contains skarns and carbonate replacement deposits intermediate sulfidation Ag-Pb-Zn veins and porphyry Cu-Mo mineralisation at the Atacocha and El Porvenir mines and surrounds (Nexa Resources) and the Ayawilca Zn-Ag carbonate replacement deposit core facility in Huánuco (Tinka Resources). The second week of the field trip was held in northern Chile, with excursions to San Pedro de Atacama, Valle de la Luna and a transect along the Domeyko Fault zone north of Calama, along with a visit to El Abra porphyry Cu-Mo deposit north of Calama (Freeport McMoRan). Unfortunately, due to civil unrest that began in Chile in late October, additional visits to CODELCO and Anglo American sites in northern and central Chile were last-minute cancellations, so the field trip ended with two days of lectures on porphyry deposits in Santiago.

### GEOMETALLURGY 4–15 NOVEMBER 2019

During the first two weeks of November, the Master of Economic Geology short course in Geometallurgy was held for the fifth time at CODES and was led by Dr Julie Hunt and Dr Angela Escolme. The short course strives to cover key aspects of geometallurgy in order to equip participants with the knowledge and skills to run their own geometallurgy programs. Course content includes characterisation tools, sample selection and preparation, comminution, mineral processing, Grade Engineering®, statistical analysis and modelling, as well as environmental and social considerations.

In 2019 the short course was attended by 16 Masters students, two industry participants and seven other students, with attendees travelling from as far afield as the USA, Saudi Arabia and the Philippines. The course included an impressive line-up of invited experts, including Clint Bowker (Bureau Veritas), Sefton Darby (KPMG), Dr Luke Keeney (CRC ORE), Dr Toni Kojovic (SimSAGE), Dr Teresa McGrath (Curtin University), Joe Pease (Mineralis), Dr Kathy Ehrig (BHP), Karyn Gardner (Newcrest Mining) and Associate Professor Steinar Ellefmo (NTNU).

New to the 2019 program was expanded content on gold processing, social licence and industry case studies. The course also included an excursion to the ALS Metallurgy Lab, Burnie, and processing plants on Tasmania's West Coast at Hellyer (Hellyer Gold Mines) and Renison Bell (Bluestone Resources) where the group were treated to extensive tours by the company representatives – to whom we extend our gratitude. This short course will next be delivered in late 2021.

### The program for 2020

- 7–24 March: Volcanology and Mineralisation in Volcanic Terrains (KEA708)
- 1–12 June: Ore Deposit Models and Exploration Strategies (KEA712)
- 19–30 October: Exploration in Brownfields Terrains (KEA710)
- November: Geodata Analytics (KEA713) is planned, subject to approval by UTAS

### Honours Program

A total of 13 students were enrolled in the Honours Program in 2019. Of these students, two were mid-year starters from 2018, eight were February-starters in 2019, and three commenced mid-2019 and will complete their

degrees in mid-2020. The program was coordinated by Dr Martin Jutzeler, and the students were supervised by staff from CODES. Study areas for the Honours projects included Tasmania (4 projects), mainland Australia (7 projects) and New Zealand (2 projects).

Sponsoring companies and organisations in the Honours Program included the TMVC, ARC, AusIMM, (AusIMM Education Endowment and AusIMM, BHP and EIANZ Environment and Community Award), CMT, Dacian Gold, Evolution Mining, Kirkland Lake Gold, MMG Rosebery, Mineral Resources Tasmania, UTAS Foundation (CockerTwo Scholarship) and Vedanta. Mandalay Resources also provided in-kind support for one of the projects. In addition, some projects were supported by internal, university-based funding from the Discipline of Earth Sciences. CODES thanks all sponsors for their valued support. These sponsorships continue to be vital to both project success and student development at a crucial phase of their studies.

### Honours Coursework Program – VIEPS

In 2019, CODES offered four short courses as part of the Victorian Institute of Earth and Planetary Sciences (VIEPS) Honours coursework program:

### EXPLORATION FIELD SKILLS MAPPING CAMP

**Course leaders:** Robert Scott and David Selley

For most students, the Honours year begins with the Exploration Field Skills (EFS) Mapping Camp, which gives students the opportunity to develop or enhance skills in geological mapping, core logging and structural analysis, all within a mineral exploration context.

Twelve students attended the camp in 2019. The eight-day camp, held in February, began with a day at the Mineral Resources Tasmania core library in Hobart, where the students logged or examined core from three diamond drill holes from the mapping area, 20 km northwest of Queenstown. The following day, the students were driven to Queenstown to begin four days of mapping in the Cambrian Mount Read Volcanics. The 4–5 km<sup>2</sup> mapping area, centred on the Hall Rivulet Canal, is located 10 km along strike to the south of the world-class Rosebery VHMS, and only ~6 km south of the Hercules deposit. The students used data collected during the mapping and core logging exercises to unravel the stratigraphy and structure of the area, and interpret the nature and likely extent of any hydrothermal alteration

or mineralisation. Before returning to Hobart, each student produced their own fact and interpretation geological maps, a set of cross-sections showing the predicted subsurface extent of the prospective stratigraphy, and a report on the structure, stratigraphy and future exploration potential of the area.

### ORE DEPOSIT MODELS

**Course leader:** David Selley

**Course presenters:** Mike Baker, Stuart Bull, Jonathan Cloutier, Ross Large, Evan Orovan, Robert Scott, Lejun Zhang

From 13–17 May, nine students attended the five-day Ore Deposit Models short course, which provides an introduction to the key features of several major classes of economically important mineral deposits. Each deposit style was discussed in terms of geological and tectonic framework, mineralisation, alteration, genetic models and exploration criteria. The deposit types covered were:

- volcanic-hosted massive sulfide
- magmatic-hydrothermal: epithermal, porphyry and skarn
- IOCG
- sediment-hosted uranium, copper and lead-zinc
- Carlin-type and orogenic gold.

Each day of the short course involved a mixture of lectures and practical exercises. Lectures covered the general characteristics and setting of the abovementioned deposit types, as well as the various genetic models that have been proposed to explain their formation. In the practical exercises, students examined and interpreted samples from many of the premier mineral deposits and mineralised districts throughout the world.

### PRACTICAL IGNEOUS PETROLOGY

**Course leader:** Leonid Danyushevsky

In June, nine students attended the Practical Igneous Petrology course presented by Leonid Danyushevsky. The five-day program is a mixture of lectures and practical exercises, aimed at postgraduate students at Honours



*Current CODES Masters student Victor Torres Pacheco explaining the geological context of the Soledad Cu-Au-Ag tourmaline breccia-hosted prospect to participants of the 'Ores in Magmatic Arcs – South America' Masters short course at the Chakana Copper drill core facility in Lima, Peru, October 2019.*

level and above with an interest in the formation and evolution of basic and ultrabasic magmas and their relationship to magmatic ore deposits. Topics covered included:

- key theoretical aspects of petrology, including units of concentration, solid solution and mineral formulas, activities and equilibrium, the phase rule, mass balance, phase diagrams, and equilibrium/fractional crystallisation
- examination of a large layered intrusion (the Dovyren Magmatic Complex in Siberia), the effect of pressure and H<sub>2</sub>O on melting and crystallisation, and the causes of melting and crystallisation
- an introduction to the concept of distribution coefficients for trace elements
- trace elements in the main rock-forming minerals
- modelling of crystallisation and studies of melt inclusions
- examples from MORB, subduction-related lavas and komatiites.

### ENVIRONMENTAL GEOLOGY FIELD TECHNIQUES

**Course leader:** Matthew Cracknell

**Course presenters:** David Cooke, Yi Sun, Joseph Knight, Sibebe Nascimento

The Environmental Geology Field Techniques course ran in September and provided participants with the opportunity to develop skills in geoenvironmental sampling and in-field analyses, geophysical surveying with an environmental focus, and laboratory analysis (including mineralogical and static chemical methods).

The course ran for five days, starting with two days of lectures and practicals at CODES, followed by field site studies conducted in western Tasmania.

The eight participants joined KEA348 (Environmental Geology) students to learn about how mine waste is managed in western Tasmania with a visit to the Copper Mines of Tasmania mine in Queenstown. Students were



*Participants in the Master of Economic Geology 'Ores in Magmatic Arcs – South America' short course are seen here fossicking at Soledad, Peru, October 2019.*



then given the opportunity to examine mine waste associated with historic copper mining in Queenstown where, working in teams, they performed a hydrochemical survey along the Queen–King river system. At several locations students collected water samples and were taught how to take in-field chemical measurements. They were also taught how to correctly preserve the sample ahead of full chemical analysis back in the laboratory. In addition, they measured the river basin architecture and flow rates in order to allow for calculations of the mass-load of metals and metalloids moving through the system. Students then undertook their main exercise at the King River Bank D site, where, in teams, they dug a number of trenches, logged and sampled the tailings and associated trench waters and performed geophysical surveys.

Following the trip these data were collated and analysed in practical sessions and in the geochemical laboratory where students undertook net acid generation and paste pH tests. All collected data were shared between teams and this enabled the students to complete their site assessment. At the

end of the course, the students were assessed based on group assignments related to the three site visits. The most significant of these assessments was the King River Bank D report, which required the students to be able to both interpret and integrate the data in order to understand the site's geochemistry, identify potential geoenvironmental risks and recommend potential future management options.

### Other Honours Coursework

#### HONOURS SKILLS WORKSHOPS

**Workshops leader:**  
Martin Jutzeler

**Course presenters:** Mike Baker, Rebecca Carey, Matthew Cracknell, Leonid Danyushevsky, Angela Escolme, Elena Lounejeva, Evan Orovan, Jay Thompson, Lejun Zhang

From July to September, Honours and postgraduate students were invited to attend several day-long skills workshops, consisting of both lectures and practical sessions,

where students were encouraged to bring their own project data in order to get expert advice on how the data should be interrogated and presented. The workshops were organised by Martin Jutzeler, and led by various in-house presenters.

Skills and software covered during the sessions included:

- **Introduction to ioGAS** (Mike Baker) covered importing data, constructing and using diagrams, and interrogating geochemical data. These topics were followed by an interactive practical session.
- The basics of **Leapfrog** (Evan Orovan) provided students with an introduction to importing geochemical data from ioGAS and plotting this in a 3D context with case study examples given. Students were encouraged to bring their own data to work through a range of practical exercises.
- **ArcGIS for Geoscientists** (Matthew Cracknell) covered a number of GIS-related topics including ArcGIS software basics, data querying, and data analysis and

interrogation in the Earth sciences. Students were able to work with existing GIS data sets, as well as creating their own from freely available raster and tabular data.

- **Data Analytics with KNIME** (Matthew Cracknell) provided an introduction to the application of machine learning algorithms to data analysis and data inference. It covered the basic principles of supervised classification and unsupervised clustering, using the KNIME data analytics package. This software is open source and allows the user to build data mining and machine learning workflows. The course focussed heavily on the development of practical skills for classification and clustering of geochemical data, including the calculation and analysis of model uncertainty.
- Applications of **Adobe Illustrator** and **Indesign** software packages (Rebecca Carey) assisted students to draw figures and collate their final thesis. Students were taught the various features of these software packages through a series of
- hands-on practical exercises (using their own project data) and were given a template file to use in Indesign to bring together their thesis in a more professional format.
- **Laser software and geochronology** (Leonid Danyushevsky and Jay Thompson) introduced students to the fundamentals of the laser ablation analytical technique, its application to geochronology using U/Pb analysis of zircon, the principles of LA-ICP-MS data reduction and its implementation in data reduction software LADR.
- **Introduction to X-ray diffraction (XRD) for mineralogy** (Angela Escolme and Elena Lounejeva) provided an introduction to the XRD theory, the instruments available at CODES and how to acquire data, and how to process the data using Rietveld refinement software.
- **pXRF** (Jay Thompson) introduced students to the use of portable XRF instruments for the analysis of major and trace elements in geological samples.

*Mount Ijen, East Java, Indonesia: this spectacular crater lake was a high point of the itinerary for the Master of Economic Geology 'Ores in Magmatic Arcs – Indonesia' short course, which ran in March 2019.*

- **The Spectral Geologist workshop** (Lejun Zhang) covered a series of topics including the introduction of TerraSpec4, the basics of The Spectral Geologist (TSG) software, data acquiring, data interpreting and integrating with Ore Deposit Geology. Students were able to operate the TerraSpec4 to collect data from hand specimens and interpret the data using TSG software.

# Student projects

## IN AUSTRALIA

Project locations are shown in capitals. Unless marked otherwise, student projects shown here are PhDs. Projects related to the ARC TMVC Research Hub are marked with an asterisk.

**1. Behan, Joseph.**

VIC (Honours)

The petrophysical and geophysical characterisation of high-grade mineralisation at Fosterville Gold mine, Victoria: Implications for exploration.

**2. Burns-Nichols, Justin.**

NSW (Honours)

Volcanic architecture east of E41E, Cowal gold mine, NSW.

**3. Cavill, Chloe.**

VIC (Masters)

Geochemical classification of ore fluids, Costerfield Sb-Au deposit, Victoria.

**4. Chapman, Nathan.**

SA

Pb-isotopic insights into the crustal evolution and metallogensis of the Gawler Craton.

**5. Cherry, Alexander.**

SA

Geochronological constraints on the formation, setting and evolution of the Olympic Dam IOCG deposit and the Olympic IOCG Province, South Australia.

**6. Cowie, Hamish.**

WA (Honours)

Architecture of intrusion related mineralisation at Ora Banda, Eastern Goldfields, Western Australia.

**7. Denholm, Josh.**

TAS (Honours)

The trace element chemistry and U/Pb geochronology of Tasmanian cassiterite.

**8. Douth, David.**

WA

The geology and geological controls on gold mineralisation at the Invincible deposit, St Ives Gold Mine, Kambalda, WA.

**9. Enkhbold, Batbayar (Baggy).**

QLD (Masters)\*

Alteration sequence of Eastern Creek Volcanics of Mount Isa.

**10. Ferguson, Matt.**

SA

Late stage magmatic-hydrothermal evolution of A-type Hiltaba event rocks in the Gawler Craton.

**11. Foster, Cameron.**

WA (Honours)

Hydrothermal alteration and gold distribution in BIF-hosted gold deposits of the Westralia Mine area (Mount Morgans), WA.

**12. Fox, Jodi.**

TAS

Complex volcanic architecture produced by basaltic submarine and emergent volcanism in intraplate settings.

**13. Habib, Umer.**

VIC, NSW

Paleomagnetism and geochronology of Paleozoic rocks of Lachlan orogen in Victoria and New South Wales.

**14. Hardwick, Brendan.**

WA (Masters)

Ore mineral textures and their implication for gold genesis and deportment at the Tropicana Gold Mine, Western Australia.

**15. Hohl, Max.**

QLD

Defining the mineral chemistry footprints of IOCG deposits in northwest Queensland.

**16. Jackson, Laura.**

NSW\*

Mineralogical domaining of low grade and no grade zones using automated drill core logging.

**17. Jago, Corey.**

NSW (Masters)

Toward an understanding of the temporal, spatial and mineralogical characteristics of the Northparkes Alkaline Porphyry Deposits, New South Wales.

**18. James, Robert.**

NT (Honours)

Characterisation of gold mineralisation styles and vein types in the Lantern Gold Deposit, Northern Territory.

**19. Jenkins, Claudia.**

NSW (Honours)

Volcanic architecture east of GRE46, Cowal gold mine, NSW.

**20. Jones, Colin.**

TAS\*

Petrogenesis of northeast Tasmanian granites.

**21. Kameniar-Sandery, Verity.**

VIC (Honours)

Origin and significance of super-heavy pyrite in the Early Silurian Costerfield Siltstone, Costerfield Sb – Au Mine, Victoria.

**22. K’ng, Le Xi.**

TAS (Honours)\*

Geochemical and mineralogical characterisation of tailings: Evaluating the potential for reprocessing the Bobadil tailings, Rosebery.

**23. Kultaksayos, Sitthinon (Gun).**

TAS (Masters)

Provenance and mineralisation in latest Cambrian to Silurian sedimentary rocks in western Tasmania.

**24. Le’Gallais, Bridie.**

TAS

The tectonic significance of mafic/ultra mafic igneous rocks in western Tasmania.

**25. Leslie, Christopher.**

NSW

Porphyry and epithermal deposits of Cowal District, New South Wales.

**26. Nascimento, Sibeile Cristina do.**

TAS\*

Geoenvironmental characterisation of historic mine tailings: Evaluating opportunities for reprocessing.

**27. Ostensen, Thomas.**

TAS

Geoelectric structure of the Tasmanian lithosphere.

**28. Rivett, Hugh.**

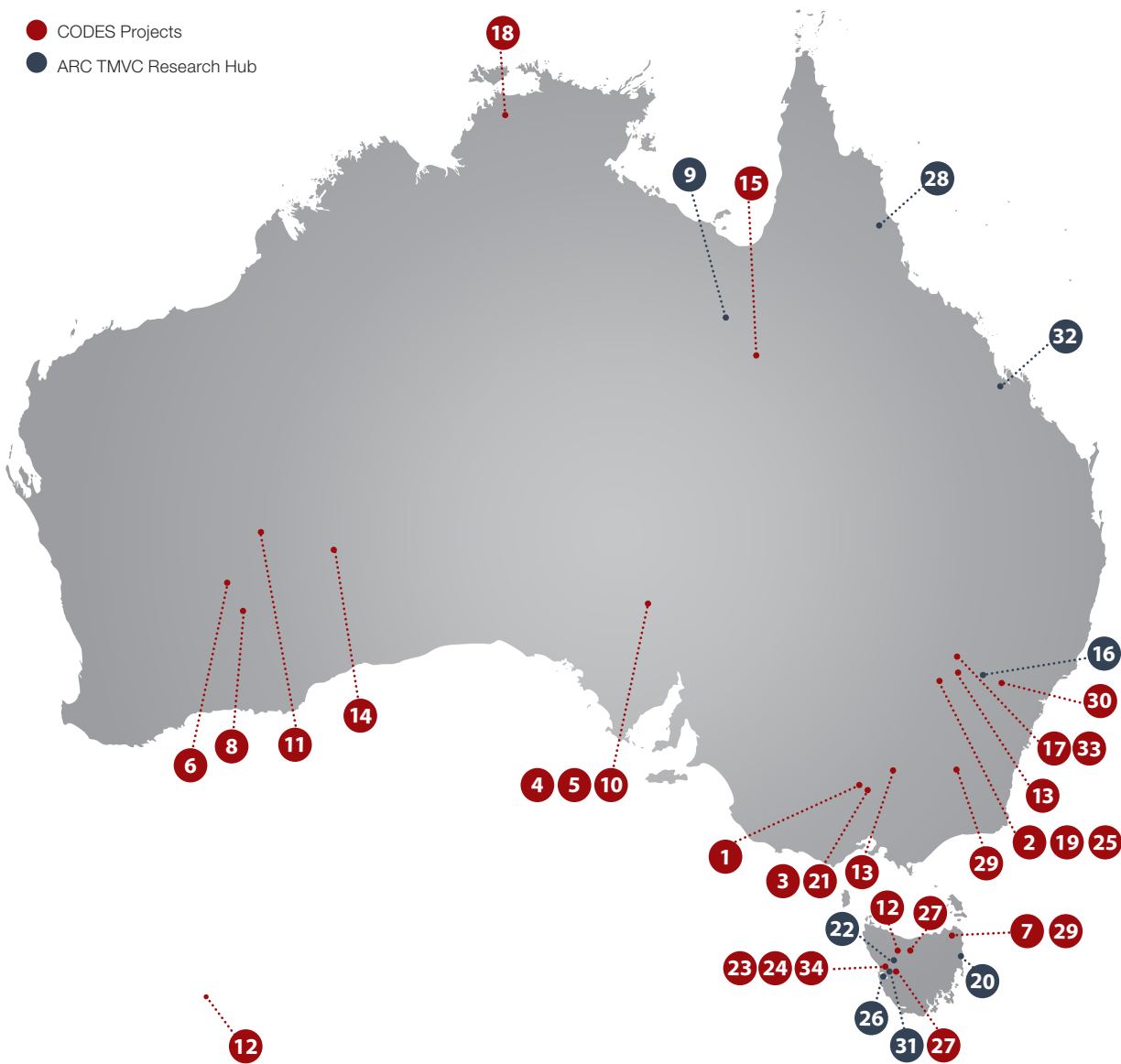
QLD (Honours)\*

Geochemical footprint and paragenesis of the Specimen Hill Au prospect, New England Orogen, Queensland.

**29. Schaap, Thomas.**

TAS, NSW, VIC

Plate tectonic modelling of the Palaeozoic Lachlan Orogen.



**30. Sritangsirikul, Peerapong.**

NSW (Masters)

Tectonic evolution and ore deposit prospectivity of the Rockley Volcanics, NSW Australia.

**31. van Balen, Johanna.**

TAS (Honours)\*

Determining the mineralogical and geochemical properties of tailings at Copper Mines of Tasmania: Opportunities for metal recovery.

**32. Vincent, Matthew.**

QLD (Honours)\*

The application of spectral analysis and mineral chemistry in exploration; a case study from the Mount Cassidy porphyry prospect, Rockhampton district, Queensland.

**33. Wells, Tristan.**

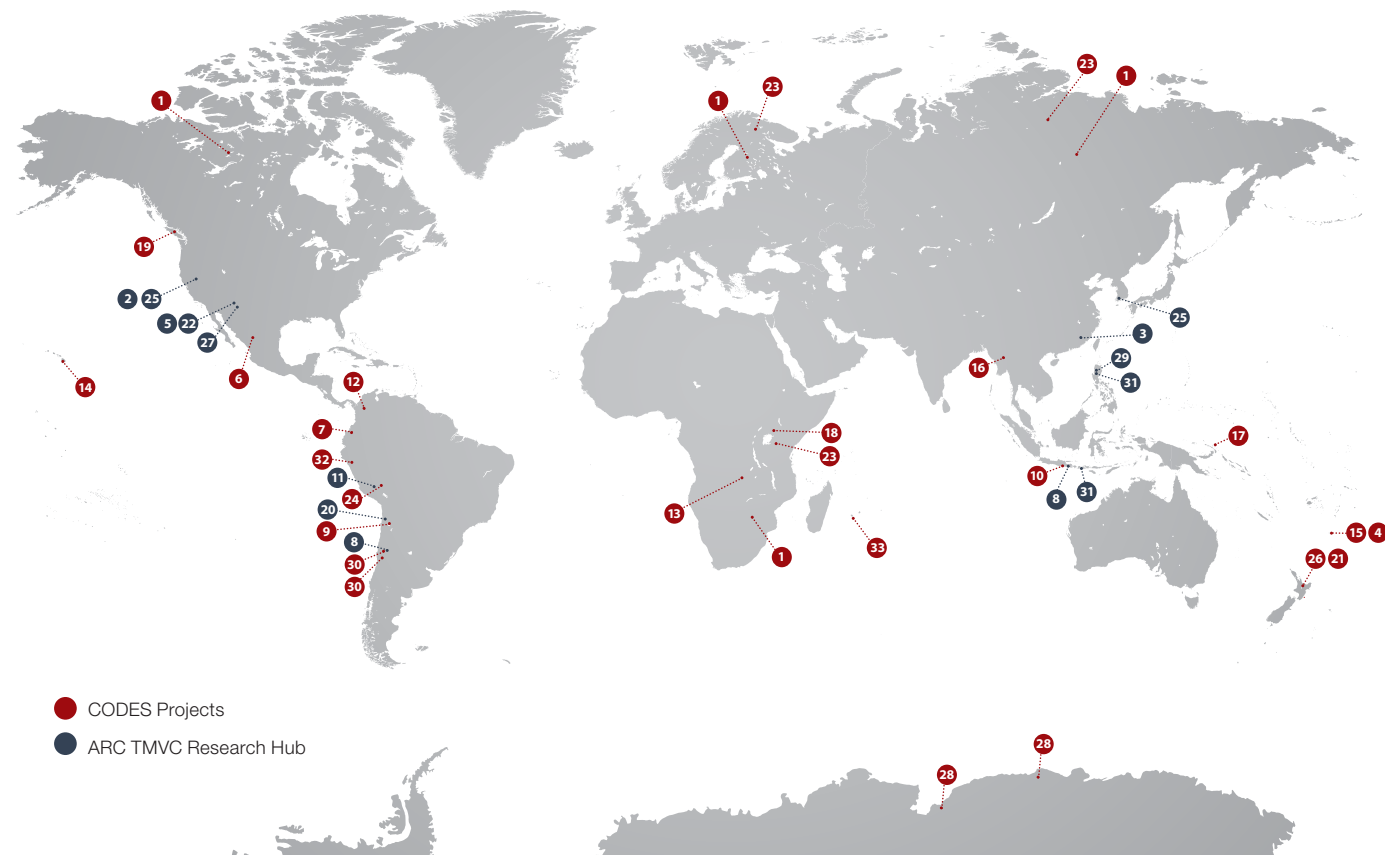
NSW

Magmatic fertility in the Macquarie Arc.

**34. Zivkovic, Zebedee.**

TAS (Masters)

Lithogeochemical and mineral analysis of the Mt Read Volcanics – western Tasmania: Implications on mineralisation and exploration.



## Student projects

### OUTSIDE AUSTRALIA

Project locations are shown in capitals. Unless marked otherwise, student projects shown here are PhDs. Projects related to the ARC TMVC Research Hub are marked with an asterisk.

- 1. Abersteiner, Adam.** CANADA, FINLAND, RUSSIA, SOUTH AFRICA  
Kimberlites and diamonds: Understanding their petrogenesis and uncovering the identity of their source composition.
- 2. Ahmed, Ayesha.** USA\*  
Epidote and chlorite mineral chemistry from the Yerington porphyry copper district, USA: genetic and exploration implications.
- 3. Chen, Jing.** CHINA\*  
The geology, mineralisation, alteration and structural evolution of Zijinshan ore field, Fujian Province, China.
- 4. Clark, Acacia.** NZ (Honours)  
Transitions in eruptive style during the 2012 deep submarine silicic eruption of Havre Volcano, Kermadec Arc, New Zealand.

- 5. Coaquira, Takeshy.** USA\*  
Resolving multiple generations of white mica and clay alteration at the Resolution porphyry Cu-Mo deposit, Arizona.
- 6. Davidson, Rob.** MEXICO  
Geology and genesis of the San Sebastian vein system, Durango, Mexico.
- 7. Diaz Castro, Jamie Carlos.** ECUADOR (Masters)  
The Cascabel Cu-Au porphyry cluster in northern Ecuador.
- 8. Eastman, Kyle.** INDONESIA, ARGENTINA\*  
Geological and geometallurgical characterization of porphyry deposit alteration overprints.
- 9. Farrar, Alex.** CHILE  
Geodynamic and tectonic influence on giant porphyry copper deposit architectural controls.
- 10. Firmansyah, Arga.** INDONESIA (Masters)  
Geology and mineralisation of the Trenggalek district, East Java, Indonesia.
- 11. Garay, Amos.** PERU\*  
Magnetite and epidote chemistry and textures at Las Bambas Cu-Au-Fe

- skarn, Peru: Assessing district and deposit-scale fertility – implications for ore genesis and exploration.
- 12. Guerrero Ramirez, Nathaly.** COLOMBIA (Masters)  
Geometallurgical controls on grade by size at Gramalote Au deposit, Colombia.
- 13. Heathcote, Jacob.** ZAMBIA  
Gold distribution and association at the Kansanshi copper-gold deposit Zambia: Processes responsible for gold precipitation and implications for ore zone delineation and recovery.
- 14. Holt, Sam.** USA  
Understanding of basaltic eruption dynamics and mechanisms: Effusive and explosive eruptions in Hawaii.
- 15. Ikegami, Fumihiko.** NEW ZEALAND  
2012 submarine silicic eruption of Havre volcano and implications for ancient submarine successions in Australia.
- 16. Knight, Joseph.** MYANMAR  
The geodynamic and metallogenic setting of base- and precious-metal mineralisation in Myanmar: Implications for Cu and Au exploration.

- 17. Lawlis, Erin.** PNG  
Au-bearing pyritic ore of Lihir, Papua New Guinea: Its physiochemical character and nature of the causative fluids.
- 18. Maroa, George.** KENYA (Masters)  
Characterization of the geology, mineralization and genesis of the Bumbo polymetallic sulphide deposit within the Busia-Kakamega Greenstone Belt, Western Kenya.
- 19. McNulty, Brian.** CANADA  
Geology of the West Block Area of the late Devonian Myra Falls VHMS District, British Columbia, Canada.
- 20. Merrill, Javier.** CHILE\*  
Evaluating applications of hyperspectral data for predicting mineral processing attributes and waste characteristics of slurries.
- 21. Moore, Hannah.** NEW ZEALAND  
Investigation of the shallow conduit processes involved in the 1886 basaltic Plinian eruption at Tarawera Volcano, New Zealand.
- 22. Phillips, Joshua.** USA\*  
Geologic and geochemical vectors to mineralisation at the Resolution porphyry Cu-Mo deposit, Arizona.
- 23. Potter, Naomi.** TANZANIA, RUSSIA  
An investigation into the genesis of intrusive and extrusive carbonatitic melts.
- 24. Rojas Lopez, Juan Diego.** PERU (Masters)  
Origin, characteristics and age of mineralisation of the Ollachea orogenic gold deposit, Puno Region, southeastern Peru: Implications for exploration.
- 25. Seow, Xin Ni.** SOUTH KOREA, USA\*  
Geochemistry, mechanism of formation and exploration implications of alunite supergroup minerals.
- 26. Simpson, Imbi.** NEW ZEALAND (Honours)  
Transition in eruption dynamics between two major phases of the 1.8 ka eruption of Taupo Volcano, New Zealand.

- 27. Smyk, Emily.** USA\*  
A characterisation of the intrusive rocks and magmatic minerals and their related propylitic and skarn alteration at the Christmas porphyry Cu deposit, Arizona, USA: assessing the potential for mineral chemistry vectoring to mineralisation.
- 28. Staal, Tobias.** ANTARCTICA  
Lithospheric structure of Antarctica.
- 29. Sun, Yi.** PHILIPPINES\*  
Mineralogical, textural, geochemical characterisation and geometallurgical models of Lepanto Quartz – Pyrite – Gold vein and breccia system, Philippines.
- 30. Testa, Francisco.** ARGENTINA, CHILE  
Tourmaline breccia pipes: San Francisco de los Andes, Argentina and Rio Blanco-Los Bronces, Chile.
- 31. Thompson, Jennifer.** INDONESIA, PHILIPPINES\*  
Carbonate mineral chemistry in epithermal and porphyry hydrothermal systems.
- 32. Torres Pachecho, Victor.** PERU (Masters)  
Geology, genesis and exploration implications of Cu-Au mineralised tourmaline breccia pipes at Soledad, central Peru.
- 33. Vergani, Daniele.** REUNION  
The 2007 explosive activity at Piton de la Fournaise volcano (La Reunion Island): constraints on the eruptive processes by the volcanological study of the erupted deposits.

## Lab-based projects

- Berger, Peter.**  
Understanding and predicting hypogene and supergene footprints of Carlin-type gold deposits using a hydrochemical modelling approach.
- Hood, Shawn.\***  
Machine learning and automated geoscientific analyses for the spatial characterisation of metalliferous ore deposits.
- Jackson, Stewart.**  
Integrating passive and active methods of seismic imaging for structural stability of tailings dams.
- James, Darcy.** (Honours)  
Petrophysical, computational, and temporal determinations of rocks underlying the Tasmania Basin.
- Kuhn, Stephen.\***  
Lithological mapping for mineral exploration using machine learning.
- Lounejeva, Elena.**  
Geochemical signature of syngenetic and diagenetic pyrite from marine sediments as a paleo-environmental tool.
- Morse, Peter.**  
Interactive visualisation for data inference in the geosciences.
- Moyo, Annah.\***  
Controlling acid and metalliferous drainage at legacy sites in Tasmania using industrial wastes.
- Mrabawani, Nanda Yusentri.\***  
Laser Ablation applied to mineral characterisation.
- Thompson, Jay.**  
Understanding the specifics of H<sub>2</sub>O-free aerosol behaviour in the inductively-coupled plasma in geochemical LA-ICPMS applications involving U/Pb dating and accurate trace element analysis in silicate minerals and glasses.



Several SEG Student Chapter members took part in the 'Ores in Magmatic Arcs – Indonesia' Masters short course in early March. Here they are enjoying a swift trip on the ferry between Lombok and Sumbawa on their way to visit Batu Hijau.

## Society of Economic Geologists (SEG) Student Chapter

The CODES SEG Student Chapter at the University of Tasmania is a branch of the Society of Economic Geologists; we are dedicated to fostering an inclusive and collaborative social fabric within the geosciences research community. We pride ourselves in making significant contributions to the social and professional lives of students from a diverse range of backgrounds and cultures. During 2019 a new executive committee was elected for 2020; this includes Kyle Eastman (President), Emily Smyk (Vice-President), Xin Ni Seow (Treasurer), Nathaly Guerrero (Secretary) and Zebedee Zivkovic (Quartermaster). This new committee will be ready to hit the ground running in 2020 with social events, field trips, and more!

### Lectures and meetings

In February 2019, Dr Larry Meinert was invited to lead a short course on skarns which covered skarn formation, mineralisation styles and exploration. This course was well-attended by Honours and postgraduate students as well as research faculty members and industry professionals. The associated field trips also proved popular; attendees investigated

tourmaline orbicules in granite at Trial Harbour, visited the Renison and Mt Bischoff tin mining areas, and observed magmatic-hydrothermal transition textures in the Devonian granites of eastern Tasmania.

August 2019 saw the formation of a new SEG discussion group, the Ore Gangue. Ore Gangue is an opportunity for students of all levels to discuss technical papers in a non-intimidating environment, toss back a cold beverage, and chat about related hand samples with local experts. So far, we have hosted Dr Evan Orovan to discuss the formation of pegmatites and magmatic-hydrothermal transition textures, and Dr Lejun Zhang has provided an enlightening glimpse into the world of lithocaps. Attendees get a free raffle ticket for a mineral specimen—so keep an eye out for Ore Gangue meetings in 2020!

### Conferences, exhibitions and publications

In September, the annual SEG conference was held in Santiago, Chile, and SEG student member Yi Sun, who is doing a PhD, presented work on the Lepanto quartz-pyrite-gold system, Philippines. Also in September, the University of Tasmania held the first annual STEM State Future Forum; this all-day session at the iconic Elizabeth Street Pier featured talks and posters from throughout the natural sciences and engineering fields. This was a fantastic opportunity for SEG Student Chapter members to showcase their work in

a high-profile setting with members of the broader academic community, industry, and the general public in attendance. Participation in this event also allowed students eligibility for up to \$2,000 in travel funding through the CoSE Travel Scheme.

### Annual field trip

There was no annual field trip in 2019 but plans are afoot for one in 2020.

### Social events

In March 2019, several members participated in the Master of Economic Geology 'Ores in Magmatic Arcs' short course in Indonesia. This was an excellent opportunity to meet with the SEG Student Chapter in Yogyakarta. The Yogyakarta chapter is very well organised and we had a productive time chatting about the teaching samples out on display during the short course. The UTAS SEG Student Chapter is willing to help facilitate visits by other student chapters who may be interested in seeing the stunning geology of Tasmania.

The SEG Student Chapter served beverages and snacks during social events held as part of the Masters short courses which ran at CODES throughout 2019; we helped out with both the 'Ore Deposit Geochemistry, Hydrology and Geochronology' short course in June and the 'Geometallurgy' short course in November. The TANG<sup>3</sup>O (Thermochronology and Noble Gas Geochronology and Geochemistry Organisation) meeting was held in

Hobart on 6–7 November, and the SEG Student Chapter provided a social event for that meeting.

Frothy Fridays continue to be held as an opportunity to relax and enjoy a cold beverage at the end of the week, with ice cream also available on hot summer days!

Professor Ross Large hosted a wine-tasting night for the SEG Student Chapter on 6 December; this was well attended and everyone learned a bit more about Australian wine. The McLaren Vale shiraz was a decisive favourite!

### Fundraising

The SEG Student Chapter received \$2,165 of Stewart R. Wallace Funding from the Society of Economic Geologists in 2017. This money was not spent and has been rolled over for use towards a field trip in 2020. Our quartermaster, Zebedee Zivkovic, keeps our geological equipment store up to date; available items include mineral ID kits, hammers, hand lenses (with LEDs!), notebooks and more. Pricing is designed so that fieldwork necessities are provided nearly at cost; this service keeps students in possession of key equipment and introduces undergraduates to the SEG Student Chapter.

Funds raised from social events and beverage sales in 2019 have helped rebuild the Student Chapter finances, and we will enter 2020 with a strong position that will enable us to travel, educate and foster continued responsible growth.

### Awards and grants

SEG Student Chapter members were successful in gaining awards and grants in 2019; these include:

- Yi Sun received an SEG student research grant for his work on the Lepanto quartz-pyrite-gold system, Philippines;
- Kyle Eastman received an SEG student research grant for geochronological investigations of the Rincones de Araya porphyry prospect, Argentina; and
- Adam Abersteiner received the Central Science Laboratory Peter W. Smith Postgraduate Award.



TMVC PhD student Kyle Eastman carries out fieldwork in Rincones de Araya porphyry prospect, Argentina, during February 2019; he used an SEG student research grant to help him complete this research trip.

## Looking forward

The healthy level of HDR enrolments should be maintained in 2020, with the number of graduations again being balanced by the intake of new students, from both Australia and overseas. A major initiative for 2020 is the proposed expansion of the Master of Economic Geology Program. To address the current reduced unit offering in the national Minerals Geoscience Masters program following James Cook University's departure in 2018, and to ensure that all MEconGeol students can complete the degree entirely at UTAS if they wish, CODES is seeking UTAS approval to double our current unit offering over the next few years. The proposed new units are: Geodata Analytics; Advanced Field Skills in Economic Geology; Economic Geology Fundamentals; Geophysics for Geologists; Social, Environmental and Economic Responsibility in the Minerals Industry; and Special Topics in Economic Geology. If the Masters program expansion is approved, CODES plans to offer the first of the new units, Geodata Analytics, in November 2020. Other Master of Economic Geology short courses to be offered in 2020 are the field-based unit, Volcanology and Mineralisation in Volcanic Terrains, to be led by Martin Jutzeler and David Cooke in March; Ore Deposit Models and Exploration Strategies led by Shaun Barker in June, and Exploration in Brownfield Terrains led by Jonathan Cloutier in October.

Based on the large number of enquiries from prospective students, and increasing optimism in the Australian minerals industry, CODES expects to see the healthy influx of new students into the Master of Economic Geology program experienced in 2018–19 continued in 2020. In contrast, Honours enrolments are expected to be a bit lower for the next few years, due to a decrease in undergraduate student numbers following the mining boom. However, if career opportunities in the minerals industry keep improving as they have over the past few years, undergraduate student numbers should improve in future years. The series of Honours workshops introduced in 2016 will continue, as will the successful courses run in conjunction with the Victorian Institute of Earth and Planetary Sciences (VIEPS).

# Outreach

Activities that promote the geosciences to the wider community, and encourage young people to consider taking up a career in one of the many exciting topics it covers, were again a priority for the Earth Sciences and CODES staff in 2019. Some of the main events are listed below:

## International Day of Women and Girls in Science

This event was held on 8 March 2019, and several UTAS disciplines participated. The Discipline of Earth Sciences ran six sessions of a 'microscope tour of Tasmania' led by CODES/TMVC PhD student Emily Smyk and CODES/TMVC researcher Dr Angela Escolme. Participants got to see Tasmanian rocks (dolerite, sandstone and schist), discuss the formation of rocks and do some mineral identification. Around 120 girls from both private and public schools – including Princes Street, Collegiate and Mount Carmel – attended.

## Girls Dig Dinosaurs

On 23 March the Girls Dig Dinosaurs event was held at the Tasmanian Museum and Art Gallery (TMAG) to celebrate International Women's Day and to highlight the work done by female palaeontologists and Earth scientists. The aim of the event was also to encourage primary school girls to consider STEM subjects. CODES PhD student Jodi Fox gave a talk about volcanology while others spoke about palaeontology and the nineteenth-century female fossil hunter Mary Anning.

The talks were followed by hands-on activities such as fossil stations, touch objects, digital microscopes and opportunities to speak to the experts about dinosaurs, fossils, geology, volcanology and all things Earth sciences.

## Eat the Problem

In March the book titled *Eat the Problem* was launched in conjunction

with the exhibition of the same name by American artist Kirsha Kaechele from MONA. The *Eat the Problem* cookbook gathered together information and recipes around the theme of invasive species and how to deal with them. Dr Anita Parbhakar-Fox, who left CODES in February, was involved along with her TMVC research team which looked at problems connected to the environment, and part of her team's research was featured in the book.

## All Hazards Disaster Symposium

Researchers from Earth Sciences, Geography, Journalism and Media, IMAS and the Centre for Rural Health at UTAS hosted a research symposium on 'All Hazards' on 12 April 2019. The aim of this symposium was to encourage academics and the Tasmanian Community of Practice in disaster resilience, emergency management and response to share their current place-based research, projects, programs and initiatives.

OPPOSITE PAGE: (TOP LEFT) UTAS Vice-Chancellor Professor Rufus Black (with hammer) tries out the seismic signal display with Dr Michael Roach and Dr Robert Scott from Earth Sciences at the UTAS Open Day on the Sandy Bay campus. (TOP RIGHT) CODES PhD student Umer Habib lends a hand at the Cuboree Weekend in October when around 300 Cubs and Scouts descended upon the Discipline of Earth Sciences to learn about geology. (CENTRE LEFT) Earth Sciences Senior Lecturer Dr Rebecca Carey (right) with Dr Vanessa Lucieer (IMAS) pictured during one of several 2019 ABC radio interviews. (CENTRE RIGHT) Dr Indrani Mukherjee from CODES speaks to a packed audience at the highly successful Beaker Street Pop Up Science Bar in mid-October held at the TMAG. (BOTTOM) CODES PhD student Tristan Wells leads a group of students as they examine rocks under the microscope during the ConocoPhillips Science Experience, which took place in December 2019.



L-R: CODES PhD student Jodi Fox with Dr Caitlin Syme (UQ and Office of Queensland Chief Scientist) and Tessa Smith (research assistant (Palaeontology) in the ARC Centre of Excellence for Biodiversity and Heritage at UTAS) at the Girls Dig Dinosaurs event, March 2019, which celebrated the achievements of female palaeontologists and Earth scientists.





CODES PhD student Joe Knight (right) explains the intricacies of augmented reality rock photogrammetry to young enthusiasts at the 2019 Agfest event in May (with Anna Flittner from Plant Science assisting).

Current research in the 'All Hazards' space was showcased by UTAS researchers and during the afternoon a panel discussion was held with practitioners and the UTAS Vice-Chancellor to address the question: How can a Tasmanian Community of Practice work together to develop place-based excellence in All Hazards research?

In Tasmania, landslides, tsunamis and earthquakes are geohazards that have the potential to impact our state and this symposium offered the opportunity for ongoing studies in those areas to be discussed with a broad audience across government, academia and industry. In the geohazards area, Mineral Resources Tasmania geologists

Claire Kain, Colin Mazengarb and Nick Roberts presented research on tsunami inundation modelling in Tasmania, landslides as a result of the 2018 May floods, and the potential of InSAR for characterising Tasmania's slope and karst geohazards.

Earth Sciences and CODES are seeking opportunities for students to work within the geohazards space in these areas of research with collaborators from MRT, State Emergency Services and government.

### Festival of Bright Ideas

This popular science festival showcases the Tasmanian science community. In 2019 it again took place (14 and 15 August) on the waterfront

in Hobart where the Princes Wharf 1 shed was transformed into a thriving interactive science and technology hub for people of all ages. The first day was reserved for school students and the second was open to everyone. In 2019 a total of around 8,500 people attended across both days.

The Discipline of Earth Sciences held two important displays:

- 'Sourcing metals for future technology from waste'. This explored how we may be able to recover metals for future technology from mining and industrial waste.
- 'Rock around Australia: Explore the 3D Virtual Library of Australia's Geology'. Here attendees were able to explore Australia's iconic rocks, cliffs and fossils using the virtual geology system developed by Dr Michael Roach in the Discipline of Earth Sciences.

### Agfest

The huge Tasmanian agricultural and machinery event that is Agfest takes place every year near Carrick in northern Tasmania, and has expanded to include a diverse range of educational stands. In 2019 nearly 64,000 people attended over the three days of the event (2–4 May).

The Discipline of Earth Sciences was capably represented at Agfest by CODES PhD student Joe Knight in the UTAS tent. He guided young and old through several geology displays, which included gemstones from around the world, fossils of trilobites from the Palaeozoic (supplied by CODES Rock Curator Izzy von Lichtan), and augmented reality highlighting rock photogrammetry (supplied by Dr Michael Roach).

### UTAS Open Days

As in previous years, UTAS held Open Days on all three of its main campuses in Tasmania during early August. And again, the Earth Sciences activities proved highly popular, particularly the roving CODES dinosaurs and the fossil dig. At the Sandy Bay campus Dr Michael Roach and Dr Robert Scott from Earth Sciences/CODES played host to Vice-Chancellor Professor Rufus Black at the Discipline of Earth Sciences stand, and explained to him the concepts behind a seismic signal display.

### Science in the Pub

CODES and Earth Sciences staff took part in two Science in the Pub events during 2019. These are informal gatherings for anyone curious about science, and with a taste for a beer or two. The goal is to promote understanding and enthusiasm for science in the general public.

On 7 February CODES/TMVC researcher Dr Angela Escolme joined a panel discussion on the topic of 'From Tasmania to Space: Rocks and future mineral resources' at the Republic bar in North Hobart. The event was very popular with more than 80 members of the public attending and standing room only available for latecomers. Dr Escolme was the first speaker and discussed the importance of copper as a future resource, particularly in the green energy sector.

And on 7 November the panellists for Science in the Pub's 'Volcanology: Venting scientific knowledge into the pub!' event at the Republic bar were Dr Karin Orth, Dr Martin Jutzeler (both from Earth Sciences/CODES) and Dr Jo Whittaker (IMAS). All of them wore Hawaiian-themed shirts, which fitted with the volcanic island topic for the evening.

Dr Karin Orth talked about seamounts as volcanoes underwater; exciting videos showcased underwater eruptions as well as those that are more typical when the volcanoes emerge from the sea and become islands. She also brought along some dredge samples from seamounts to demonstrate some of the major processes that form rocks that build the seamounts.

Dr Martin Jutzeler presented his recent research on the pumice raft that erupted from an underwater edifice in Tonga on 7 August 2019. Using satellite imagery, Martin was able to track the dispersal of the pumice raft westwards across the Lau Basin to the island of Lakemba and then onwards to Fiji, where much of the pumice collected against the northeastern shore of the elongated islands of Yasawa. Martin described how combining ocean current models, wind models and the effects of these on the pumice rafts could be used to model hazards for shipping. His pumice hazard maps for the Fiji area are the first pumice raft hazard maps ever made.



Dr Karin Orth from the Discipline of Earth Sciences speaking at a Science in the Pub event held during November at the Republic bar in North Hobart; the topic was 'Venting scientific knowledge into the pub!' in which Dr Orth and other UTAS scientists spoke about volcanic islands.

### Beaker Street

Beaker Street is a scientist-run social enterprise based in Tasmania and has received critical acclaim from scientists and commentators around the country.

In March, Beaker Street teamed up with the TMAG to present a Triassic Night, which was billed as 'an evening of dinosaur delights for adults' and included talks, live music, prehistoric cocktails, and more. The evening's events were linked to the 'Dinosaur rEvolution: Secrets of Survival' exhibition, which CODES' Professor Ross Large was instrumental in organising (see next page). Dr Karin Orth from the Discipline of Earth Sciences gave a presentation entitled: 'Did the Earth move for you too? What we know about dinosaur sex and reproduction'.

The third highly successful annual Beaker Street Pop-up Science Bar took place at the TMAG on 16–17 August. CODES postdoctoral researcher Dr Indrani Mukherjee gave an extremely well-received and entertaining talk entitled 'The evolution of life on Earth: Rethinking the "Boring Billion"'. It took several billion years to transition from a microbe-dominated planet to the tremendous diversity of life we see today. What shaped this course of evolution has always fascinated geologists. Indrani's talk focussed on some of the key biological events between 1800 and 800 mya, infamously known as the 'Boring Billion', and provided a geological explanation for the cause of these events.

### Cuboree Weekend

Over 300 cub scouts aged between eight and 14 visited the Discipline of Earth Sciences over a weekend in mid-October to participate in learning about geology! They looked at gemstones, found out about earthquakes and fossils, peered down microscopes and learnt about the geological time series, and more. Earth Sciences staff were on hand to share their enthusiasm for their subjects with this large group of curious young people.

### Inspiring Tasmania

CODES PhD student Erin Lawlis promoted geology at an 'Inspiring Tasmania' event hosted by Taroona High School on 23 October 2019:

The "STEM next" event at Taroona High School was all about introducing the next generation to the many facets of science, engineering and technology. About 50 booths ranged from virtual reality and solar car demonstrations to stick insect exhibits and math puzzles. The geology booth was set up in the school's science wing and consisted of a rock cycle display, Tasmanian ore deposit samples, some beautiful fossils and trilobite casts, and a "gemnasium". Erin also set up a collection of her own samples from around the world including sapphires, zircons and spinels from Weld River; visible gold specimens from Lihir gold mine in PNG; and a gneiss with Cu-Au porphyry mineralisation from Aitik in Sweden. Around 150 people visited the geology displays, including a large

number of very excitable primary school children. They LOVED the semi-precious gemstones and were excited that they got to keep one! The older kids were really interested and had a lot of questions about the rocks and minerals in Erin's collection and about the places that geology could take you. Erin got to teach many people how to use a hand lens, so they could observe the tiny specks of free gold.

### The Rock Library

Once again CODES Rock Library Curator Izzy von Lichten was called upon to supply Earth science-related material for a number of events during 2019.

### 'Art of the Body: health, beauty and desire'

This exhibition was held in Launceston at the Academy Gallery as part of the MONA FOMA festival (16 January–8 February), and then toured to Hobart. It investigated the physical, psychological and emotional aspects of the body and their significance in art and science. Samples, together with a geological background/context of minerals and rocks that have been used for pigments, were provided for the exhibition by Izzy from the Discipline of Earth Sciences' extensive rock collection.

### Children's Festival, Tasmanian Museum and Art Gallery

Rock curator Izzy von Lichten was the volunteer geologist answering questions as part of the Children's Festival at TMAG in mid-April.

### Blooming Tasmania Flower and Garden Exhibition

'Birth, death and everything in between' was the title of a Blooming Tasmania exhibition held at the Academy Gallery in Launceston (21 September–25 October). Several samples of Tasmanian fossil flora and petrified wood pieces from the UTAS Earth Sciences collection were included; artists were invited to respond to the idea that flowers are one of the central concerns in art. Izzy was also asked to be an exhibitor with two pieces of her own, one of which was from a scientific illustration course she had recently completed.

### 'Dinosaur rEvolution: Secrets of Survival' and the Dinosaur Symposium

The 'Dinosaur rEvolution: Secrets of Survival' exhibition, which Professor Ross Large was instrumental in organising, continued until May 2019. It opened in 2018 and was produced by Tasmanian company Gondwana Studios and held jointly with the Royal Society of Tasmania and the TMAG. The exhibition featured many recent fossil discoveries, especially from China and Mongolia, which demonstrate the evolution of one particular lineage of dinosaurs to birds. In March 2019 a two-day Dinosaur Symposium open to all was held in conjunction with the exhibition. CODES and Earth Sciences staff had input to this event.

### The ConocoPhillips Science Experience

This three-day program of science activities for Grade 9 and 10 students sponsored by ConocoPhillips took place on 10–12 December; the Earth sciences were showcased on 12 December with the assistance of Dr Sebastien Meffre, Dr Indrani Mukherjee and CODES PhD student Tristan Wells.

Around 30 students from a range of schools gathered in the Earth Sciences building and undertook a variety of geology-related activities including examining rocks under microscopes, learning about the evolution of life on Earth, and finding out about mining in Tasmania. Following this event UTAS received some very positive feedback from the participants as well as enquiries about study opportunities in STEM at the university.

### School visits and trips

It was another busy year for Earth Sciences/CODES outreach visits to schools and colleges around the state, and a selection of these are listed below:

In June there were four days of visits by Earth Sciences staff to Taroon High School Grade 8 student groups.

In September CODES PhD students Emily Smyk and Erin Lawlis visited New Norfolk High School to talk about geology to around 80 students from Grade 7.

Also in September CODES/TMVC Research Fellow in Earth Informatics Dr Matthew Cracknell visited Queenstown High School and spoke to Grade 8, 9 and 10 students.

And Research Fellow in Geochemistry Dr Jeff Steadman visited Huonville Primary School in September to talk to Grade 2 students.

Over three days in November Dr Michael Roach and CODES PhD student Joseph Knight ran six separate outreach demonstrations at Friends School for Grade 8 students. This included a field trip to the Waterworks area in Hobart to look at Tasmanian geology.

### Media

Once again CODES and Earth Sciences staff were in demand across various media platforms to give expert opinions on topics of geological interest or to talk about geology in general; a selection of the activities is included below:

- In January, CODES Rock Curator Izzy von Lichten was interviewed by Paul MacIntyre for the ABC Radio Hobart *Drive* program; she talked about fossil material held in the CODES Rock Library on loan to the Tasmanian Museum and Art Gallery.
- In March, Research Fellow Dr Karin Orth did a radio interview about the Dinosaur Symposium in Hobart on Joel Rheinberger's ABC Saturday morning show.
- And in April, Dr Orth spoke about kunyoni/Mt Wellington with Paul McIntyre for a program on ABC Radio Hobart.
- In April Senior Lecturer Dr Rebecca Carey was interviewed on ABC Radio's *Late Night Live* by Phillip Adams talking about seafloor mapping, submarine volcanoes and seafloor mining.
- In late May, Dr Rebecca Carey spoke on the topic of monitoring volcanoes on *Overnights* with Rod Quinn, ABC Radio.
- On 27 July, Dr Rebecca Carey did an ABC Radio interview with Robyn Williams on *The Science Show*, (<https://www.abc.net.au/radionational/programs/scienceshow/rebecca-carey/11351570>) on 'Submersibles



CODES Rock Curator Izzy von Lichten with curious young students during the 2019 Children's Festival at the TMAG.

take scientists to deep sea volcanic sites'; Rebecca describes what she saw while 1000 m beneath the surface at the Loihi Seamount in Hawaii).

- In early October, Dr Karin Orth again spoke about Tasmanian dinosaurs in a Sunday morning interview with the ABC's Joel Rheinberger.
- On 29 October Dr Karin Orth and Dr Martin Jutzeler were interviewed by Edge Radio (UTAS) on volcanology and the dispersal of the Tonga pumice raft; and in November, they did an ABC Radio interview on the same topic.
- On 6 November Professor David Cooke did a radio interview for *Drive* on ABC Northern Tasmania with Pia Wirsu about the recent Masters course trip to South America (<https://www.abc.net.au/radio/northtas/programs/drive/drive/11656702>).
- On 9 December Dr Rebecca Carey did radio interviews with ABC Hobart and ABC Sydney following the White

Island volcano eruption in early December.

- On 10 December, UTAS Honorary Professor Ray Cas gave TV interviews following the White Island volcano eruption in early December: SBS news, and 7.30 on ABC TV. (7.30 segment: 'White Island volcano eruption a "disaster waiting to happen", Australian expert says', [12-10/white-island-volcano-disaster-waiting-to-happen-expert-says/11785060\). Professor Cas was also quoted in \*The Guardian\* and other news outlets after commenting on the White Island volcano eruption \(comments to the Australian Science Media Centre\).](https://mobile.abc.net.au/news/2019-</a></li></ul></div><div data-bbox=)

## Social Media at CODES

CODES/Earth Sciences has an active presence on social media:

 CODES Facebook page: <https://www.facebook.com/CODES.UTAS/>

 Earth Sciences Facebook page: <https://www.facebook.com/EarthSciUTAS/>

 TMVC Facebook page: <https://www.facebook.com/tmvc.utas>

 CODES LinkedIn: [linkedin.com/company/codes-utas](https://www.linkedin.com/company/codes-utas)

# Industry links



## Objectives

To be a research focus for the national and international minerals industry.

Strategically collaborate with other top-level national and international research groups in the field of ore deposits, mineral exploration technologies and mineral processing.

(Top)(L–R:) Professor Ray Cas, Dr Martin Jutzeler, Dr Rebecca Carey, and Honours students Claudia Jenkins and Justin Burns-Nichols at Evolution Mining's core yard at Cowal, pictured while Claudia and Justin were undertaking fieldwork there.

CODES is recognised as a world leader in industry-linked, collaborative ore deposit research. Strong relationships have been developed with a range of industry partners and researchers who invest in, support and contribute to research projects. Fostering and growing these national and international collaborations is a key strategic focus.

## Industry links and synergies

CODES has strong, enduring and mutually beneficial links with a group of major Australian and international mining companies. These links have been critical for funding CODES' research, and for technology transfer to the mining and mineral exploration community. In 2019, the group of CODES' industry partners comprised of eight Australian and international

mining companies: Anglo American, Barrick, Evolution, First Quantum Minerals, Mount Isa Mines (Glencore), Newcrest Mining, Rio Tinto and Teck.

Partner companies have been providing support of up to \$60,000 in cash per year to the core research budget of the Centre. Representatives of these companies are invited to the CODES Annual Review, along with other government and university researchers. The Annual Review showcases the breadth of research undertaken at the Centre through a day of oral and poster presentations for our stakeholders, and offers the opportunity to influence future research directions. Gold and Platinum Partners are also offered a seat on the CODES Advisory Board, which meets at least annually to discuss the strategic direction of the Centre.



Professor David Cooke, Director of CODES (left), hands over a copy of TMVC PhD student Josh Phillips' thesis to Hamish Martin at the Resolution porphyry Cu-Mo deposit, Arizona, USA, in August 2019. Josh's work has provided important insights into the origin, timing and significance of distal alteration around the Resolution deposit with considerable significance for exploration in the region.



AMIRA P1202 team members and sponsors gathered outside the CODES offices in November 2019.

## Industry partnership opportunities

CODES offers partnership opportunities aligned to the evolving needs of mining companies. The minerals industry is cyclical by nature, and operating conditions can vary greatly from one year to the next, often through unforeseen circumstances. For this reason, our partnership opportunities are offered on an annual basis, giving partners the flexibility to adjust their involvement in line with their current operating conditions and research requirements. Funding levels are tailored to suit all levels of operation, from junior explorers through to the large multinationals. Companies may sign up at the Silver (\$20K), Gold (\$40K) or Platinum (\$60K) level, depending on their planned level of involvement with the Centre. In 2019 it was decided to introduce a

new Copper level Industry Partnership, available only to Tasmanian-based companies from 2020 onwards and involving a commitment of a minimum of \$10K.

Benefits of a partnership agreement vary depending on the level of investment, but include enhanced prospects of discoveries, optimisation of existing reserves, first call on geoscience graduates, and access to a world-class research team and state-of-the-art facilities. Further details can be found at: <http://www.utas.edu.au/codes/about-us/industry-partnership-program>

## Role of AMIRA International

AMIRA plays a vital role in facilitating the funding of collaborative research involving university research groups and the minerals industry. AMIRA has agreed to fund projects within the

Centre, which will run over a period of one to four years. In 2019 it funded AMIRA P1202 'Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits', as well as AMIRA P1206 'Identifying unique Resistate Indicator Mineral (RIM) chemistry as a guide in prospectivity for sediment-hosted copper mineralisation', both of which sit within the ARC TMVC Research Hub.

## Research collaborations

In 2019, CODES further cemented its reputation for cultivating research collaborations with other Australian and international research organisations. Throughout the year, collaborative research was conducted with 113 international and 23 national organisations.

## CODES Industry Partners 2019



# Technology transfer

## Objectives

Involve end-users (exploration and mining companies) in research planning, research evaluation and research adoption.

Promote technology transfer so that innovative research outcomes are accessible to end-users.

Comply with the national principles of intellectual property management for publicly funded research.

## Technology transfer activities

CODES undertakes strategic and applied research into ore deposits (characterisation and context) and geometallurgy, and the development of innovative enabling technologies to support these research endeavours.

(LEFT) Participants of the Latin American Metallogeny (CLAM) short course for which CODES Director Professor David Cooke was one of the main presenters. The course was held in Lima, Peru, during May 2019 and attracted around 70 geologists.

(RIGHT) AMIRA P1202 researchers Evan Orovan and Lejun Zhang present an overview of project goals to Fortescue Argentina geologists during February 2019 fieldwork at the Rincones de Araya porphyry Cu-Mo prospect, San Juan province, Argentina.

These initiatives create knowledge, processes, methods and solutions for the minerals industry and ore deposit researchers – locally, nationally and internationally. Research results and technical developments in the applied research programs are transferred to end-users via regular research meetings, research reports, monographs, books, digital presentations and software packages, where appropriate. In 2019, 208 research reports were presented to industry clients. Meetings were also held to present and discuss progress and adoption of research results.

## Publications targeted at end-users

CODES also delivers knowledge and applications to end-users and the wider scientific community through a selection of special publications that represent the culmination of major research efforts by the Centre's staff. The following publications were sold during 2019.

- ▶ *Altered volcanic rocks: A guide to description and interpretation* (2005). Authors: C. Giffkins, W. Herrmann and R. Large (22 copies).

- ▶ *Basins, fluids and Zn-Pb ores. CODES Special Publication 2* (1999). Editors: O. Holm, J. Pongratz and P. McGoldrick (2 copies).

- ▶ *Geophysical signatures of coppergold porphyry and epithermal gold deposits, and implications for exploration* (2011). Author: T. Hoschke (17 copies).

- ▶ *Giant ore deposits: Characteristics, genesis and exploration. CODES Special Publication 4* (2002). Editors: D. Cooke and J. Pongratz (1 copy).

- ▶ *New developments in Broken Hill type deposits. CODES Special Publication 1* (1976). Editors: G. Davidson and J. Pongratz (2 copies).

- ▶ *24ct Au workshop. CODES Special Publication 5* (2004). Editors: D. Cooke, C. Deyell and J. Pongratz (1 copy).

- ▶ *Volcanic environments and massive sulfide deposits* (2000). Editors: J.B. Gemmell and J. Pongratz (1 copy).

- ▶ *Volcanic textures: A guide to the interpretation of textures in volcanic rocks* (1993). Authors: J. McPhie, M. Doyle and R. Allen (28 copies).

## CODES-led short courses, workshops, conferences and field trips for end-users

Short courses, workshops, conferences and field trips continued to play a key role in the Centre's technology transfer activities. Throughout the year, a total of 24 events in these categories were held at various locations around the world, including China, New Zealand, Indonesia, the UK, South America and the USA.

Total attendance by industry geologists, academic researchers and postgraduate students was 643, with 27 different presenters from CODES involved in delivering the lectures or leading the conferences or field trips.

### 2019 SHORT COURSES, WORKSHOPS, CONFERENCES AND FIELD TRIPS LED BY CODES

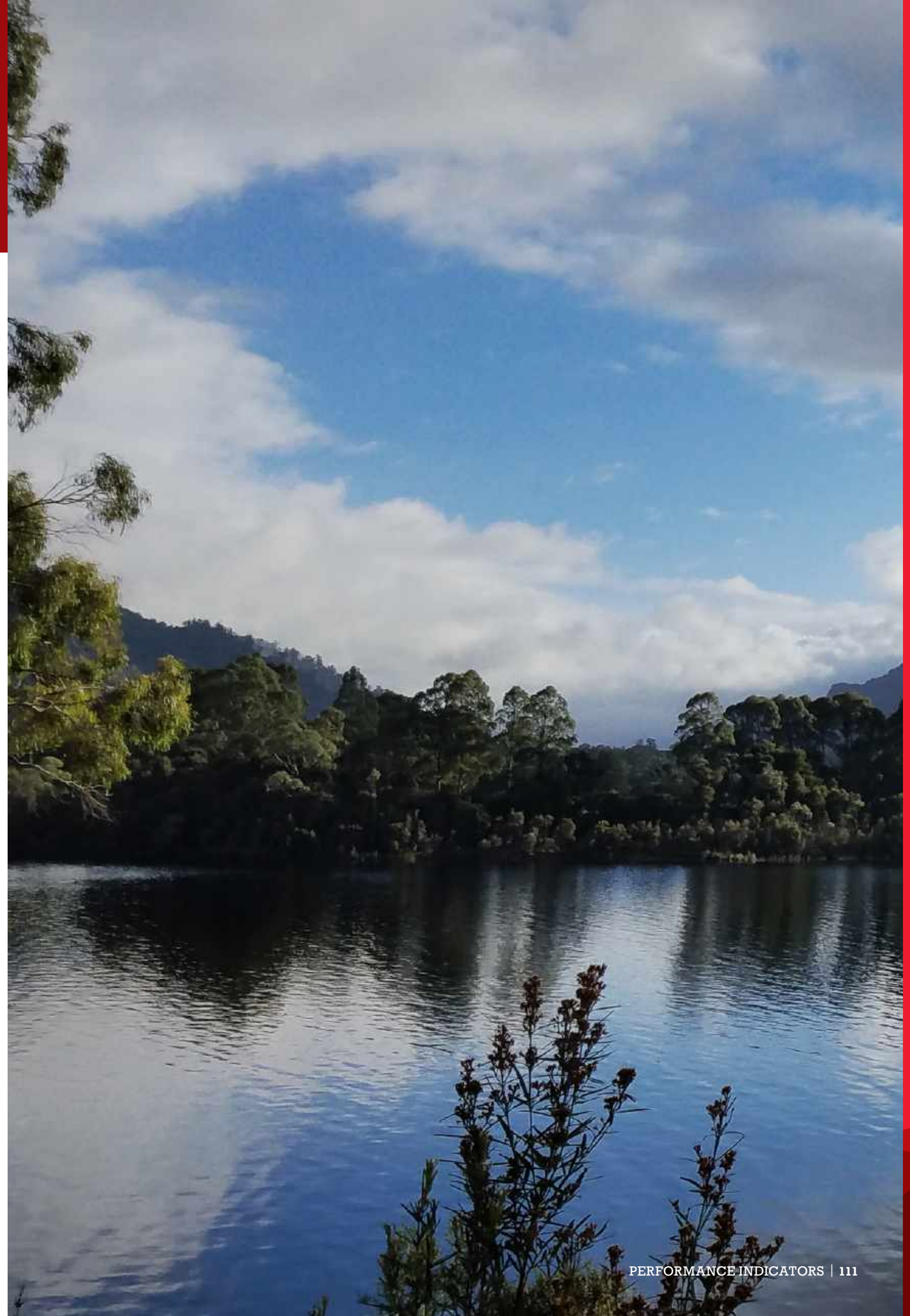
| TITLE                                                                                                                                                              | PRESENTERS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | NO. | LOCATION                    | DATE          |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|-----------------------------|---------------|
| Skarn short course (SEG)                                                                                                                                           | Larry Meinert                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 25  | Western Tasmania            | Early Feb     |
| Exploration Field Skills Mapping Camp (VIEPS)                                                                                                                      | <b>Robert Scott, David Selley</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 12  | Hobart/western Tasmania     | February      |
| Ores in Magmatic Arcs Workshop at Universitas Gadjah Mada                                                                                                          | <b>David Cooke</b> , Rachel Harrison, Terry Hoschke, Adi Maryono, Lucas Donny Setijadji, Noel White, <b>Lejun Zhang</b>                                                                                                                                                                                                                                                                                                                                                                                 | 78  | Yogyakarta, Indonesia       | 4–6 March     |
| Ores in Magmatic Arcs – Indonesia (MEconGeol short course)                                                                                                         | <b>David Cooke, Angela Escolme</b> , Rachel Harrison, Adi Maryono, Noel White, Iryanto Rompo, <b>Lejun Zhang</b>                                                                                                                                                                                                                                                                                                                                                                                        | 29  | Indonesia                   | 8–19 March    |
| Introduction to Machine Learning (PACRIM 2019)                                                                                                                     | <b>Matthew Cracknell, Shawn Hood</b> , Michael Gazley, Juan Carlos Ordóñez Calderón                                                                                                                                                                                                                                                                                                                                                                                                                     | ~10 | Auckland, NZ                | 6 April       |
| All Hazards Disaster Symposium                                                                                                                                     | <b>Rebecca Carey</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 40  | Hobart, Tasmania            | 12 April      |
| Ore Deposit Models (VIEPS)                                                                                                                                         | <b>Mike Baker, Stuart Bull, Jonathan Cloutier, Ross Large, Evan Orovan, Robert Scott, David Selley, Lejun Zhang</b>                                                                                                                                                                                                                                                                                                                                                                                     | 9   | CODES, Hobart               | 13–17 May     |
| Laser Ablation Inductively Coupled Plasma Mass-spectrometry (LA-ICP-MS): Principles and Applications short course at the North American Workshop on Laser Ablation | <b>Leonid Danyushevsky</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 25  | Austin, Texas, USA          | 16 May        |
| Breccia Workshop (Chakana Core Facility)                                                                                                                           | <b>David Cooke</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 20  | Lima, Peru                  | 17 May        |
| Porphyry and Epithermal Deposits short course (ProExplo pre-conference short course)                                                                               | <b>David Cooke</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 25  | Lima, Peru                  | 18–19 May     |
| Latin American Metallogeny Course (CLAM) short course                                                                                                              | <b>David Cooke</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 70  | Lima, Peru                  | 23–25 May     |
| Practical Igneous Petrology (VIEPS)                                                                                                                                | <b>Leonid Danyushevsky</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 9   | CODES, Hobart               | Early June    |
| Ore Deposit Geochemistry, Hydrology and Geochronology (MEconGeol short course)                                                                                     | <b>Mike Baker, Shaun Barker, Ron Berry</b> , Phil Blevin, <b>David Cooke, Leonid Danyushevsky</b> , Poul Emsbo, Scott Halley, <b>Sebastien Meffre, Paul Olin</b> , Nick Oliver, <b>Robert Scott, Jeff Steadman</b> , Lesley Wyborn, <b>Lejun Zhang</b>                                                                                                                                                                                                                                                  | 48  | CODES, Hobart               | 3–14 June     |
| Mineralising Processes in Basins short course (SGA)                                                                                                                | <b>Jonathan Cloutier</b> , Dan Gregory, Simon Jones, Murray Hitzman, Tony Prave, Koen Torremans, John Walsh                                                                                                                                                                                                                                                                                                                                                                                             | 22  | Glasgow, UK                 | 24–25 August  |
| Environmental Geology Field Techniques (VIEPS)                                                                                                                     | <b>Matthew Cracknell, David Cooke, Yi Sun</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 8   | Hobart/Queenstown, Tasmania | 2–6 September |
| AMIRA P1202 Santiago field trip                                                                                                                                    | <b>David Cooke</b> , José Piquer                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 15  | Rio Maipo, Chile            | 5 October     |
| Porphyry Deposits – Characteristics, Origins and Exploration Strategies (SEG pre-conference workshop)                                                              | <b>David Cooke</b> , Peter Hollings, <b>Michael Roach</b>                                                                                                                                                                                                                                                                                                                                                                                                                                               | 17  | Santiago, Chile             | 7 October     |
| Ores in Magmatic Arcs – South America (MEconGeol short course)                                                                                                     | <b>Mike Baker, David Cooke</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 24  | Peru/Chile                  | 11–26 October |
| Trace Elements in Past Ocean (TEPO) Research                                                                                                                       | <b>Ross Large, Indrani Mukherjee</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | ~30 | Beijing, China              | 23–28 October |
| Geometallurgy (MEconGeol short course)                                                                                                                             | <b>Ron Berry, Matthew Cracknell, Angela Escolme, Julie Hunt, Javier Merrill</b>                                                                                                                                                                                                                                                                                                                                                                                                                         | 25  | CODES, western Tasmania     | 4–15 November |
| LADR Laser Ablation Short Course (pre-conference course for TANG <sup>3</sup> O)                                                                                   | <b>Leonid Danyushevsky</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 10  | CODES, Hobart               | 5 November    |
| TANG <sup>3</sup> O meeting (Thermochronology and Noble Gas Geochronology and Geochemistry Organisation)                                                           | Yuri Amelin, Scarlett Blewett, Ling Chung, Ryan Dwyer, Geoff Fraser, Fred Fryer, Sarah Gilbert, Stijn Glory, Allan Gomes, Doug Hamilton, <b>Margaret Hawke</b> , Fred Jourdan, <b>Sebastien Meffre</b> , Brent McInnes, Angus Nixon, Ashley Norris, <b>Khin Zaw</b> , Fabian Kohlmann, Barry Kohn, Ruby Marsden, Erin Matchan, Wayne Mozer, David Phillips, Alex Prent, Phillipe Saliot, <b>Jeff Steadman</b> , Damien Tootell, Sian Tooze, Paulo Vasconcelos, Michael Ventura, Bryant Ware, Qing Zhang | 62  | CODES, Hobart               | 6–7 November  |
| Introduction to Machine Learning (Mining Geology 2019 AusIMM)                                                                                                      | <b>Matthew Cracknell</b> , Michael Gazley, Shawn Hood                                                                                                                                                                                                                                                                                                                                                                                                                                                   | ~10 | Perth, WA                   | 24 November   |
| Volcanic Processes, Products, Successions and Resources short course                                                                                               | Ray Cas, Patrick Hayman, <b>Martin Jutzeler</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 20  | Merimbula, NSW              | 2–6 December  |

# Performance indicators

## PERFORMANCE MEASURES

|                                                                   | TARGET        | 2019          |
|-------------------------------------------------------------------|---------------|---------------|
| <b>Research Findings (CODES and Earth Sciences)</b>               |               |               |
| Publications in international journals                            | 50pa          | 68            |
| Percentage of publications in high-quality international journals | 70%           | 78%           |
| Reports to industry collaborators                                 | 80pa          | 208           |
| Special issues and/or research monographs                         | 1 per 2 years | 1             |
| Invitations to give keynote conference presentations              | 10pa          | 10            |
| Papers at national/international meetings                         | 70pa          | 72            |
| <b>Research Training and Professional Education</b>               |               |               |
| Percentage of HDR students attracted from interstate              | 25%           | 19%           |
| Percentage of HDR students attracted from overseas                | 65%           | 42%           |
| Number of Honours students in CODES' programs                     | 15            | 15            |
| Number of HDR students in CODES' programs                         | 50            | 57            |
| Percentage of students in projects linking with industry          | 80%           | 71%           |
| Professional short courses workshops for industry                 | 4pa           | 24            |
| <b>International, National and Regional Links and Networks</b>    |               |               |
| CODES' national or international conferences/workshops            | 1 per 2 years | 1             |
| Registrants at CODES' conferences/workshops                       | 600pa         | 643           |
| <b>End-user Links</b>                                             |               |               |
| Frequency of meetings with industry representatives               | 15pa          | 25+           |
| <b>National Benefit</b>                                           |               |               |
| CODES' research has input into a major mineral discovery          | 1 per 5 years | 9 in 30 years |

OPPOSITE PAGE: Early morning light over Lake Rosebery, Tullah, Tasmania, taken by TMVC PhD student Kyle Eastman during the 2019 Master of Economic Geology 'Geometallurgy' short course.



# Finances

## 2019 income

Total CODES income was \$6.1 million (see Table 1). This was derived principally from UTAS (31%), the combined income sources of the ARC TMVC Research Hub (22%), and Contracts/Consultancies/Revenue Raising (22%) (see Figure 1). The main income streams over time are compared in Figure 2, showing a decrease in overall income to CODES in 2019 when compared to 2018, due in part to the winding down of the ARC TMVC Research Hub (all ARC funding has now been received). This decrease occurred in all categories apart from Contracts/Consultancies/Revenue Raising which showed a strong increase, in part due to Short Course income as well as increased external use of the CODES Analytical Laboratories.

Summary of the main income streams to CODES in 2019:

- **Host institution support:** Funding from UTAS in 2019 was \$1.9 million, comparable to the figure for 2018, mostly due to sustained research salaries and PhD scholarship funding (living and tuition fee) from central sources. UTAS funding relates primarily to research salaries, PhD scholarships and income earned by the Centre from research output.
- **ARC TMVC Research Hub:** The combined income sources for the TMVC amounted to \$1.4 million in 2019, comprising of funding from industry Partner Organisations (\$1.1 million), Host Institution (\$131k), and other sources including Additional Funder Projects (\$106k).

- **Contracts/Consultancies/Revenue Raising:** Combined funding of \$1.4 million comprises funding related to Short Courses/Symposiums (\$290k), Analytical Services (\$1.1 million) and Book Sales (\$8k).

## 2020 income estimates

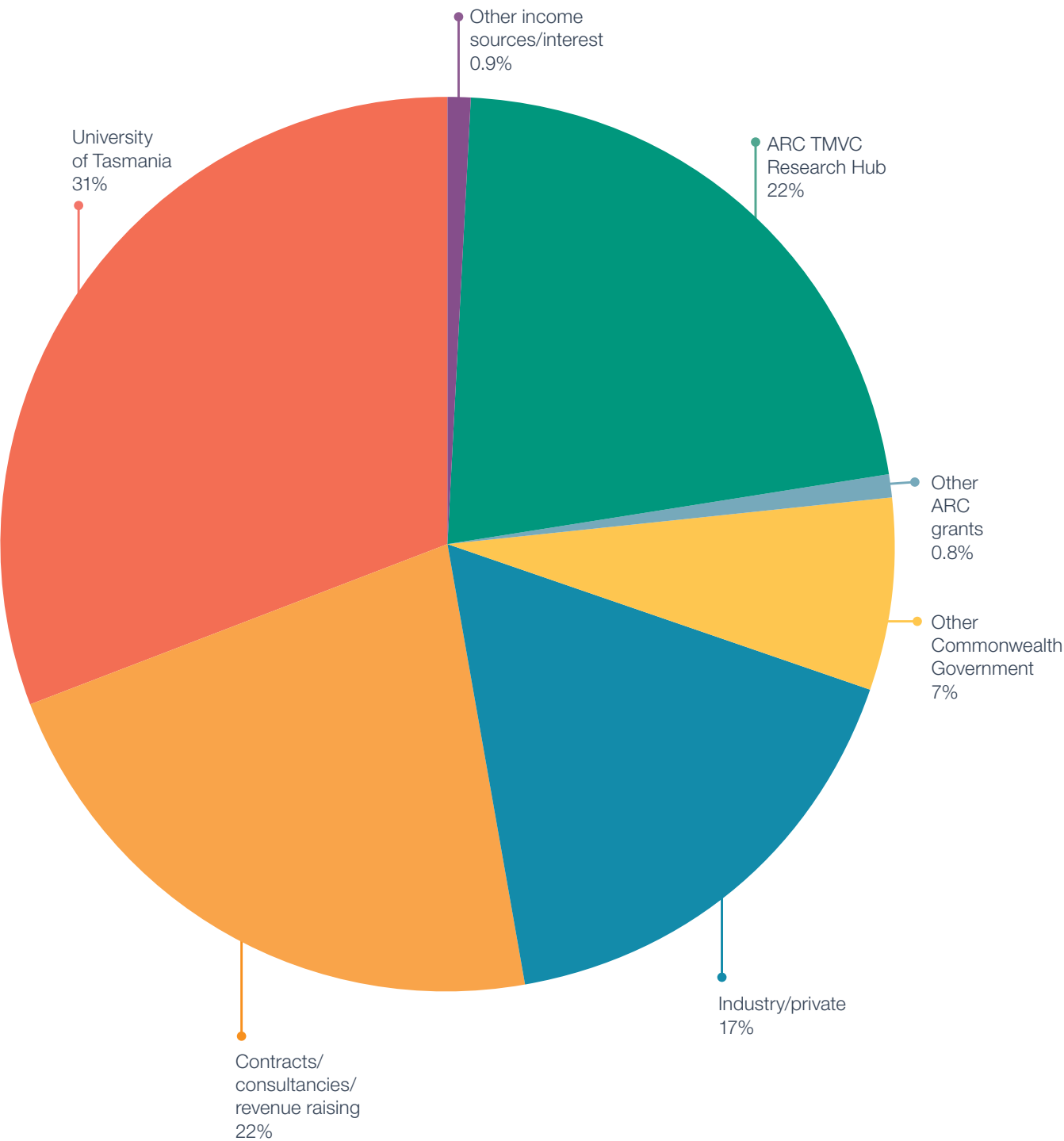
There is expected to be a similar level of funding to CODES in 2020 when compared to 2019, with most of the remaining Partner Organisation and UTAS funding to the TMVC having been received in 2019. ARC funding is expected to increase with the commencement of a Linkage project early in the year, with Industry, UTAS and Other funding to CODES expected to remain steady into 2020.

**TABLE 1: CASH INCOME FINANCIAL STATEMENT 2019**

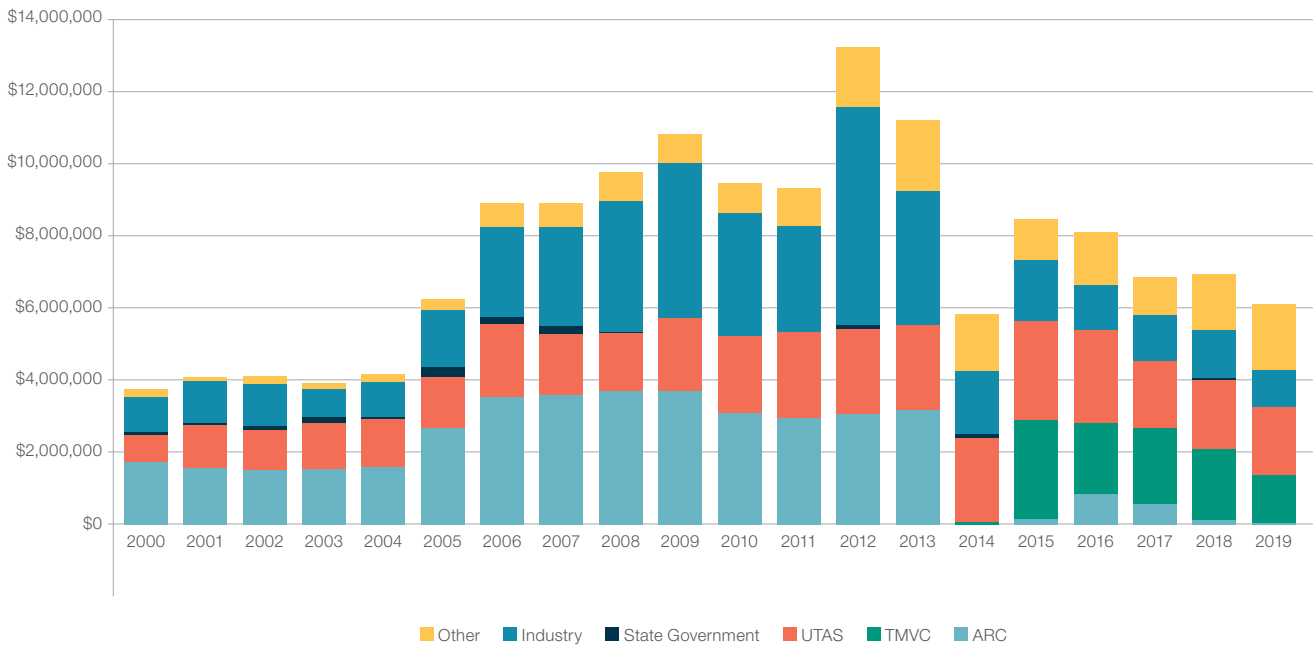
|                                                             |                  |
|-------------------------------------------------------------|------------------|
| <b>ARC Transforming the Mining Value Chain Research Hub</b> |                  |
| ARC Industrial Transformation Research Project              | 0                |
| Partner Organisations                                       | 1,114,789        |
| - AMIRA International                                       | 799,589          |
| - BHP Billiton Olympic Dam                                  | 150,000          |
| - Newcrest Mining                                           | 165,200          |
| Host Institution                                            | 130,738          |
| Additional Funder Projects                                  | 105,834          |
| Miscellaneous                                               | 482              |
|                                                             | <b>1,351,843</b> |
| <b>ARC Grants</b>                                           |                  |
| Discovery Grants                                            | (19)             |
| Linkage Grants                                              | 48,044           |
|                                                             | <b>48,025</b>    |
| <b>Other Commonwealth Government</b>                        |                  |
| Specific Projects                                           | 407,863          |
|                                                             | <b>407,863</b>   |
| <b>Industry/private</b>                                     |                  |
| CODES Industry Partners                                     | 270,000          |
| Cooperative Research Centre Projects                        | 253,518          |
| Directly Funded Research Projects                           | 384,500          |
| Directly Funded Student Projects                            | 101,730          |
| Miscellaneous                                               | 7,436            |
|                                                             | <b>1,017,184</b> |
| <b>Contracts/consultancies/revenue raising</b>              |                  |
| Short Courses                                               | 280,010          |
| Symposiums                                                  | 9,682            |
| Book Sales                                                  | 7,888            |
| Miscellaneous (incl. Analytical Services)                   | 1,055,948        |
|                                                             | <b>1,353,527</b> |
| <b>University of Tasmania – host institution support</b>    |                  |
| Operating Grant                                             | 874,154          |
| Scholarships and Tuition Fee Waivers                        | 882,876          |
| Strategic Projects                                          | 119,661          |
|                                                             | <b>1,876,691</b> |
| <b>Other income sources/interest</b>                        |                  |
| Student Support                                             | 36,382           |
| Miscellaneous                                               | 16,669           |
|                                                             | <b>53,051</b>    |
| <b>Total annual income</b>                                  |                  |
|                                                             | <b>6,108,184</b> |



**FIGURE 1**  
**Total Cash Income 2019**



**FIGURE 2**  
**Comparison of CODES main income streams 2000–2019**



**Notes to, and forming part of, the financial statements for 2019**

The financial pages of this Annual Report were prepared by Helen Scott (ARC TMVC Research Hub Manager). Data for the financial statements was extracted from UTAS systems, particularly its Finance System.

**Income statement explanations**

The income figures in Table 1 represent actual income recorded in the University's finance system, transferred internally from UTAS to CODES during 2019, or centrally administered for CODES RHD students (as in the case of scholarships and tuition fee waivers).



# 2019 publications

*Outputs related to the TMVC Research Hub are marked with an asterisk.*

## Refereed journal articles (68)

**Abersteiner, A., Kamenetsky, V.S.,** Goemann, K., Golovin, A.V., Sharygin, I.S., Giuliani, A., Rodemann, T., Spetsius, Z.V., and **Kamenetsky, M.**, 2019, Djerfisherite in kimberlites and their xenoliths: implications for kimberlite melt evolution: Contributions to Mineralogy and Petrology, v. 174, article 8.

**Abersteiner, A., Kamenetsky, V.S.,** Goemann, K., Golovin, A.V., Sharygin, I.S., Pearson, D.G., **Kamenetsky, M.**, and Gornova, M.A., 2019, Polyminerale inclusions in kimberlite-hosted megacrysts: Implications for kimberlite melt evolution: Lithos, v. 336–337, p. 310–325.

**\*Ahmed, A., Crawford, A.J., Leslie, C., Phillips, J., Wells, T., Garay, A., Hood, S.B., and Cooke, D.R.**, 2019, Assessing copper fertility of intrusive rocks using field portable X-Ray fluorescence (pXRF) data: Geochemistry: Exploration, Environment, Analysis, <https://doi.org/10.1144/geochem2018-077>

Astill, S., Corney, S., **Carey, R.**, Auckland, S., and Cross, M., 2019, Reconceptualising ‘community’ to identify place-based disaster management needs in Tasmania: The Australian Journal of Emergency Management, v. 34(1), p. 48–51.

**\*Barker, S.L.L., Hood, S.**, Hughes, R.M., and Richards, S., 2019, The lithogeochemical signatures of hydrothermal alteration in the Waihi epithermal district, New Zealand: New Zealand Journal of Geology and Geophysics, v. 62(4), p. 513–530.

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New olivine reference material for in situ microanalysis: Geostandards and Geoanalytical Research, v. 43(3), p. 453–473.

Beinlich, A., **Barker, S.L.L.**, Dipple, G.M., Hansen, L.D., and Megaw, P.K.M., 2019, Large-scale stable isotope alteration around the hydrothermal carbonate-replacement Cinco de Mayo Zn-Ag Deposit, Mexico: Economic Geology, v. 114(2), p. 375–396.

**Berkenbosch, H.A.**, de Ronde, C.E.J., Ryan, C.G., McNeill, A.W., Howard, D.L., **Gemmell, J.B.**, and **Danyushevsky, L.V.**, 2019, Trace element mapping of copper- and zinc-rich black smoker chimneys from Brothers Volcano, Kermadec Arc, using synchrotron radiation XFM and LA-ICP-MS: Economic Geology, v. 114(1), p. 67–92.

**Berry, R.F.**, Goemann, K., **Thompson, J.**, **Meffre, S.**, and Bottrill, R., 2019, Geochemistry and provenance of the Turquoise Bluff Slate, NE Tasmania: tectonic significance: Australian Journal of Earth Sciences, v. 66(2), p. 227–246.

**\*Cao, M.**, Evans, N.J., Reddy, S.M., Fougereuse, D., Hollings, P., Saxey, D.W., McInnes, B.I.A., **Cooke, D.R.**,

McDonald, B.J., and Qin, K., 2019, Micro- and nano-scale textural and compositional zonation in plagioclase at the Black Mountain porphyry Cu deposit: Implications for magmatic processes: American Mineralogist, v. 104(3), p. 391–402.

**\*Chen, J., Cooke, D.R.**, Piquer, J., **Selley, D., Zhang, L.J.**, and **White, N.C.**, 2019, Hydrothermal alteration, mineralization and structural geology of the Zijinshan high sulfidation Au-Cu deposit, Fujian Province, South East China: Economic Geology, v. 114, p. 639–666.

Dimabayao, J.J.T., Rowe, M.C., and **Barker, S.L.**, 2019, Stable isotope systematics of fluids and epidote in the Bacon-Manito Geothermal Field, Philippines: Indicators of fluid origin and evolution: Geothermics, v. 80, p. 31–43.

Dmitrijeva, M., Ciobanu, C.L., Ehrig, K.J., Cook, N.J., Metcalfe, A.V., Verdugo-Ihl, M.R., and **McPhie, J.**, 2019, Mineralization-alteration footprints in the Olympic Dam IOCG district, South Australia: The Acropolis prospect: Journal of Geochemical Exploration, v. 2015, Article 106333.

Duraiswami, R.A., **Jutzeler, M.**, Karve, A.V., Gadpallu, P., and Kale, M.G., 2019, Subaqueous effusive and explosive phases of late Deccan volcanism: Evidence from Mumbai Islands, India: Arabian Journal of Geosciences, v. 12, Article 703.

**\*Escolme, A., Berry, R.F., Hunt, J.**, Halley, S., and Potma, W., 2019, Predictive models of mineralogy from whole-rock assay data: Case study from the Productora Cu-Au-Mo Deposit, Chile: Economic Geology, v. 114(8), p. 1513–1542.

Golovin, A.V., Sharygin, I.S., Korsakov, A.V., **Kamenetsky, V.S.**, and **Abersteiner, A.**, 2019, Can primitive kimberlite melts be alkali-carbonate liquids: Composition of the melt snapshots preserved in deepest mantle xenoliths: Journal of Raman Spectroscopy, <https://doi.org/10.1002/jrs.5701>

**\*Gregory, D.D., Cracknell, M.J., Large, R.R., McGoldrick, P., Kuhn, S.**, Maslennikov, V.V., **Baker, M.J., Fox, N., Belousov, I.**, Figueroa, M.C., **Steadman, J.A.**, Fabris, A.J., and Lyons, T.W., 2019, Distinguishing ore deposit type and barren sedimentary pyrite using laser ablation-inductively coupled plasma-mass spectrometry trace element data and statistical analysis of large data sets: Economic Geology, v. 114(4), p. 771–786.

**\*Gregory, D., Mukherjee, I.**, Olson, S.L., **Large, R.R., Danyushevsky, L.V.**, Stepanov, A.S., Avila, J.N., Cliff, J., Ireland, T.R., Raiswell, R., **Olin, P.H.**, Maslennikov, V.V., and Lyons, T.W., 2019, The formation mechanisms of sedimentary pyrite nodules determined by trace element and sulfur isotope microanalysis: Geochimica et Cosmochimica Acta, v. 259, p. 53–68.

Hamilton, A.R., Campbell, K.A., Rowland, J.V., **Barker, S.**, and Guido, D.M., 2019, Fossilised geothermal surface features of the Whitianga Volcanic Centre (Miocene), Coromandel Volcanic Zone, New Zealand: controls and characteristics: Journal of Volcanology and Geothermal Research, v. 381, p. 209–226.

**\*Harraden, C.L., Cracknell, M.J.**, Lett, J., **Berry, R.F.**, Carey, R., and Harris, A.C., 2019, Automated core logging technology for geotechnical assessment: A study on core from the

Cadia East porphyry deposit: Economic Geology, v. 114(8), p. 1495–1511.

Hayman, P.C., Cas, R.A.F., Squire, R.J., Campbell, I.A., Chen, M., and **Doutch, D.**, 2019, Emplacement origins of coarsely-crystalline mafic rocks hosted in greenstone belts: Examples from the 2.7 Ga Yilgarn Craton, Western Australia: Precambrian Research, v. 324, p. 236–252.

Heap, M.J., Gravley, D.M., Kennedy, B.M., Gilg, H.A., Bertolett, E., and **Barker, S.L.L.**, 2019, Quantifying the role of hydrothermal alteration in creating geothermal and epithermal mineral resources: The Ohakuri ignimbrite (Taupō Volcanic Zone, New Zealand): Journal of Volcanology and Geothermal Research, <https://doi.org/10.1016/j.jvolgeores.2019.106703>

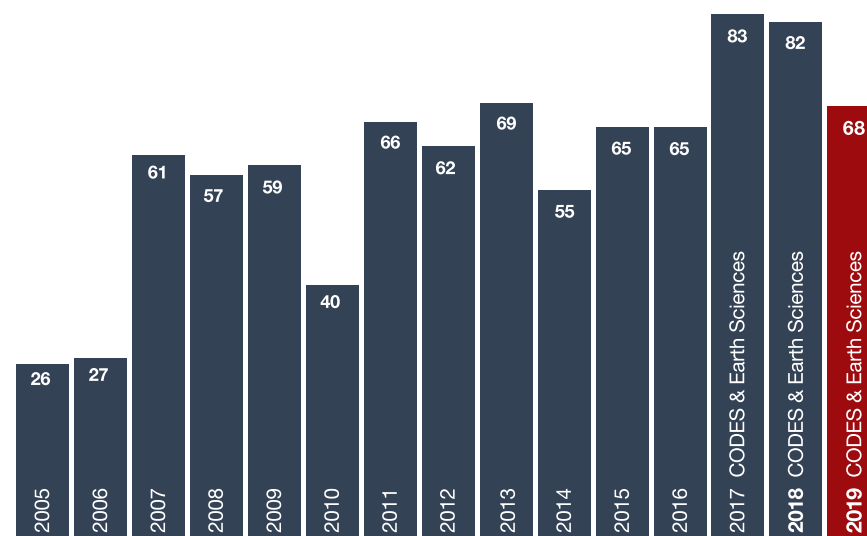
**Holt, S.J., Carey, R.J.**, Houghton, B.F., Orr, T., **McPhie, J.**, and Feig, S., 2019, Eruption and fountaining dynamics of selected 1985–1986 high fountaining episodes at Kilauea volcano, Hawaii, from quantitative vesicle microtexture

analysis: Journal of Volcanology and Geothermal Research, v.369, p. 21–34.

**\*Hong, W., Cooke, D.R., Zhang, L., Fox, N.**, and **Thompson, J.**, 2019, Cathodoluminescence features, trace elements, and oxygen isotopes of quartz in unidirectional solidification textures from the Sn-mineralized Heemskirk Granite, western Tasmania: American Mineralogist, v. 104(1), p. 100–117.

**\*Hong, W., Fox, N., Cooke, D.R., Zhang, L.**, and Fayek, M., 2019, B- and O-isotopic compositions of tourmaline constrain late-stage magmatic volatile exsolution in Tasmanian tin-related granite systems: Mineralium Deposita, <https://doi.org/10.1007/s00126-019-00885-5>

**\*Hood, S.B., Cracknell, M.J.**, Gazley, M.F., and **Reading, A.R.**, 2019, Element mobility and spatial zonation associated with the Archean Hamlet orogenic Au deposit, Western Australia: Implications for fluid pathways in shear zones: Chemical Geology, v. 514, p. 10–26.



## REFEREED JOURNAL ARTICLES



*Professor David Cooke taking water samples at sunset in Macquarie Harbour, western Tasmania, during an Environmental Geology field trip, September 2019, photographed by Masters student Nathaly Guerrero. This photo won the Program 2 section of the CODES 2019 Photo Competition.*

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*View towards the town of Aija, northern Peru, within the Cordillera Negra near the Chakana Copper Soledad Project. This photo was taken by CODES Masters student Victor Torres while doing fieldwork in 2019, and pictured is Chakana junior geologist Hans Carhuaricra.*

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Olin, P., Belousov, I., Goemann, K., and Danyushevsky, L., 2019, P806: Iron contents in spodumene, albite, alkali feldspar and mica, and fluorine contents in mica: Report to ALS, 8 p.

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CODES postgraduate students 2019

BACHELOR OF SCIENCE (HONOURS) (15)

| STUDENT                 | SUPERVISORS                           | RESEARCH PROGRAM | PROJECT                                                                                                                                                            | SUPPORT                                             |
|-------------------------|---------------------------------------|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|
| Joseph Behan ^          | Roach                                 | 6                | The petrophysical and geophysical characterisation of high-grade mineralisation at Fosterville Gold mine, Victoria: Implications for exploration                   | Kirkland Lake Gold                                  |
| Justin Burns-Nichols    | Jutzeler, Carey                       | 4                | Volcanic architecture east of E41E, Cowal gold mine, NSW                                                                                                           | Evolution Mining                                    |
| Acacia Clark ^          | Carey, Jutzeler                       | 4                | Transitions in eruptive style during the 2012 deep submarine silicic eruption of Havre Volcano, Kermadec Arc, New Zealand                                          |                                                     |
| Hamish Cowie ^          | Scott, Steadman                       | 3                | Paragenetic and geochemical analysis of the Perimeter Gold prospect, Ora Banda, Western Australia                                                                  | Evolution Mining                                    |
| Josh Denholm ^          | Stepanov, Bottrill (MRT), Hong        | 5                | The trace element chemistry and U/Pb geochronology of Tasmanian cassiterite                                                                                        | MRT, UTAS Foundation, Venture Minerals, ARC Linkage |
| Cameron Foster ^        | Scott, Barker                         | 1                | Hydrothermal alteration and gold distribution in BIF-hosted gold deposits of the Westralia Mine area (Mount Morgans), WA                                           | Dacian Gold                                         |
| Darcy James ^           | Meffre, Bottrill (MRT), McNeill (MRT) | 3                | Petrophysical, computational, and temporal determinations of rocks underlying the Tasmania Basin                                                                   | MRT, ARC Linkage                                    |
| Robert James ^          | Scott, Baker                          | 1                | Characterisation of gold mineralisation styles and vein types in the Lantern Gold Deposit, Northern Territory                                                      | Kirkland Lake Gold                                  |
| Claudia Jenkins         | Jutzeler, Carey                       | 4                | Volcanic architecture east of GRE46, Cowal gold mine, NSW                                                                                                          | Evolution Mining                                    |
| Verity Kameniar-Sandery | Scott                                 | 3                | Origin and significance of super-heavy pyrite in the Early Silurian Costerfield Siltstone, Costerfield Sb – Au Mine, Victoria                                      | Mandalay Resources, CODES                           |
| Le Xi K'ng *^           | Meffre, Parbhakar-Fox (UQ)            | 2                | Geochemical and mineralogical characterisation of tailings: Evaluating the potential for reprocessing the Bobadil tailings, Rosebery                               | ARC TMVC, MMG, AusIMM, BHP, EIANZ, UTAS Foundation  |
| Hugh Rivett *^          | Zhang, Baker                          | 1                | Geochemical footprint and paragenesis of the Specimen Hill Au prospect, New England Orogen, Queensland                                                             | ARC TMVC, Signature Gold                            |
| Imbi Simpson ^          | Carey, Jutzeler                       | 4                | Transition in eruption dynamics between two major phases of the 1.8 ka eruption of Taupo Volcano, New Zealand                                                      |                                                     |
| Johanna van Balen*^     | Meffre, Parbhakar-Fox (UQ)            | 2                | Determining the mineralogical and geochemical properties of tailings at Copper Mines of Tasmania: Opportunities for metal recovery                                 | ARC TMVC, CMT, AusIMM, UTAS Foundation, Vedanta     |
| Matthew Vincent *^      | Zhang, Baker, Cooke                   | 1, 5             | The application of spectral analysis and mineral chemistry in exploration; a case study from the Mount Cassidy porphyry prospect, Rockhampton district, Queensland | Signature Gold, ARC TMVC                            |

\* Affiliated with the ARC TMVC Research Hub # Degree completed, not yet graduated ^ Graduated § Withdrawn

MASTER OF ECONOMIC GEOLOGY (57)

| STUDENT                       | SUPERVISORS                       | RESEARCH PROGRAM | PROJECT                                                                                                                  | SUPPORT                  |
|-------------------------------|-----------------------------------|------------------|--------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Robert Ayres                  |                                   |                  | coursework only                                                                                                          |                          |
| Stuart Badock                 |                                   |                  | coursework only                                                                                                          |                          |
| Emma Beattie                  |                                   |                  | coursework only                                                                                                          |                          |
| Mark Bolario                  | TBC                               |                  | TBC                                                                                                                      |                          |
| Christopher Booth             |                                   |                  | coursework only                                                                                                          |                          |
| Kim Boundy                    |                                   |                  | coursework only                                                                                                          |                          |
| James Bresnahan               |                                   |                  | coursework only                                                                                                          |                          |
| Kenneth Bush ^                |                                   |                  | coursework only                                                                                                          |                          |
| Jimmy Carranza Meza           |                                   |                  | coursework only                                                                                                          |                          |
| Glen Cathers                  |                                   |                  | coursework only                                                                                                          |                          |
| Chloe Cavill                  | Scott                             | 1, 3             | Geochemical classification of ore fluids, Costerfield Sb-Au deposit, Victoria                                            | Mandalay Resources       |
| Brianna Clark                 |                                   |                  | coursework only                                                                                                          |                          |
| Jesse Clark ^                 |                                   |                  | coursework only                                                                                                          |                          |
| Sarah Cochrane                |                                   |                  | coursework only                                                                                                          |                          |
| Jamin Cristall                |                                   |                  | coursework only                                                                                                          |                          |
| Roseanna Dale                 |                                   |                  | coursework only                                                                                                          |                          |
| Lieth de Selincourt           |                                   |                  | coursework only                                                                                                          |                          |
| Jamie Carlos Diaz Castro      | Cooke                             | 1                | The Cascabel Cu-Au porphyry cluster in northern Ecuador                                                                  | SolGold                  |
| Alison Dines                  |                                   |                  | coursework only                                                                                                          |                          |
| Laura Dowling                 |                                   |                  | coursework only                                                                                                          |                          |
| David Eddy                    |                                   |                  | coursework only                                                                                                          |                          |
| Paul Edmonds                  |                                   |                  | coursework only                                                                                                          |                          |
| Batbayar (Baggy) Enkhbold *   | Barker, Baker                     | 1, 3             | Alteration sequence of Eastern Creek Volcanics of Mount Isa                                                              | DFAT, AMIRA P1202        |
| Benjamin Ferguson             |                                   |                  | coursework only                                                                                                          |                          |
| Franco Ferreyra #             |                                   |                  | coursework only                                                                                                          |                          |
| Arga Firmansyah               | Cooke                             | 1                | Geology and mineralisation of the Trenggalek district, East Java, Indonesia                                              | PT Pamapersada Nusantara |
| Daniel Foulds                 |                                   |                  | coursework only                                                                                                          |                          |
| David Haddow ^                |                                   |                  | coursework only                                                                                                          |                          |
| Brendan Hardwick              | Meffre, Doyle (AngloGold Ashanti) | 1, 3             | Ore mineral textures and their implication for gold genesis and deportment at the Tropicana Gold Mine, Western Australia | AngloGold Ashanti        |
| Michael Harris                |                                   |                  | coursework only                                                                                                          |                          |
| Jonathan Higgins              |                                   |                  | coursework only                                                                                                          |                          |
| Kyle Hodges                   |                                   |                  | coursework only                                                                                                          |                          |
| Corey Jago #                  | Meffre, Cooke                     | 1, 3             | Spectral characterisation of the E26 and E48 porphyry Cu-Au deposits, Northparkes, New South Wales                       | ARC Linkage              |
| Ashleigh Job                  | TBC                               |                  | TBC                                                                                                                      |                          |
| Benjamin Johnson              |                                   |                  | coursework only                                                                                                          |                          |
| Lucy Jones                    |                                   |                  | coursework only                                                                                                          |                          |
| Pascal Kabilo #               |                                   |                  | coursework only                                                                                                          |                          |
| Sitthinon (Gun) Kultaksayos # | Meffre                            | 3                | Provenance and mineralisation in latest Cambrian to Silurian sedimentary rocks in western Tasmania                       | ARC Linkage              |
| Greer Lane                    |                                   |                  | coursework only                                                                                                          |                          |
| Esther Little                 |                                   |                  | coursework only                                                                                                          |                          |
| David Mallon                  |                                   |                  | coursework only                                                                                                          |                          |

\* Affiliated with the ARC TMVC Research Hub # Degree completed, not yet graduated ^ Graduated § Withdrawn

MASTER OF ECONOMIC GEOLOGY (57) cont.

| STUDENT                  | SUPERVISORS | RESEARCH PROGRAM | PROJECT                                                                                                                                                         | SUPPORT              |
|--------------------------|-------------|------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| George Maroa             | Scott       | 1, 3             | Characterization of the geology, mineralization and genesis of the Bumbo polymetallic sulphide deposit within the Busia-Kakamega Greenstone Belt, Western Kenya | DFAT, Acacia Mining  |
| Todd McGilvray           |             |                  | coursework only                                                                                                                                                 |                      |
| Paul Merriner            |             |                  | coursework only                                                                                                                                                 |                      |
| Dominic Murphy           |             |                  | coursework only                                                                                                                                                 |                      |
| Menford Ngara            |             |                  | coursework only                                                                                                                                                 |                      |
| Alister Orton            |             |                  | coursework only                                                                                                                                                 |                      |
| Bailey Payten            |             |                  | coursework only                                                                                                                                                 |                      |
| Nicholas Poznik          |             |                  | coursework only                                                                                                                                                 |                      |
| Hugo Rios Mansilla       | TBC         |                  | TBC                                                                                                                                                             |                      |
| Juan Diego Rojas Lopez ^ | Escolme     | 1                | Origin, characteristics and age of mineralization of the Ollachea orogenic gold deposit, Puno Region, southeastern Peru: implications for exploration           | PRONABEC, Minera IRL |
| Torrin Rowe              |             |                  | coursework only                                                                                                                                                 |                      |
| Markus Staubmann         |             |                  | coursework only                                                                                                                                                 |                      |
| James Taylor             |             |                  | coursework only                                                                                                                                                 |                      |
| Luke Timmermans          |             |                  | coursework only                                                                                                                                                 |                      |
| Victor Torres Pachecho   | Cooke       | 1                | Geology, genesis and exploration implications of Cu-Au mineralised tourmaline breccia pipes at Soledad, central Peru                                            | Chakana Copper       |
| Libas Ulaiwi ^           |             |                  | coursework only                                                                                                                                                 |                      |

MASTER OF SCIENCE (3)

| STUDENT                  | SUPERVISORS              | RESEARCH PROGRAM | PROJECT                                                                                                                           | SUPPORT                                     |
|--------------------------|--------------------------|------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|
| Nathaly Guerrero Ramirez | Cracknell, Hunt, Escolme | 2                | Geometallurgical controls on grade by size at Gramalote Au deposit, Colombia                                                      | CRC ORE, UTAS                               |
| Peerapong Sritangsirikul | Meffre                   | 3                | Tectonic evolution and ore deposit prospectivity of the Rockley Volcanics, NSW Australia                                          | Thai Royal Government Scholarship           |
| Zebedee Zivkovic         | Barker                   | 1, 4             | Lithogeochemical and mineral analysis of the Mt Read Volcanics - western Tasmania: Implications on mineralisation and exploration | Mineral Resources Tasmania, Mineral Mapping |

DOCTOR OF PHILOSOPHY (53)

| STUDENT            | SUPERVISORS                               | RESEARCH PROGRAM | PROJECT                                                                                                                              | SUPPORT                                                            |
|--------------------|-------------------------------------------|------------------|--------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|
| Adam Abersteiner # | V.Kamenetsky, M.Kamenetsky, Goemann (CSL) | 4                | Kimberlites and diamonds: Understanding their petrogenesis and uncovering the identity of their source composition                   | UTAS, ARC Discovery, Institute of Seismology and Volcanology – RAS |
| Ayesha Ahmed *^    | Cooke, Baker, Orovan                      | 1                | Epidote and chlorite mineral chemistry from the Yerington porphyry copper district, USA: genetic and exploration implications        | AMIRA P1153, ARC TMVC, UTAS, AusIMM                                |
| Peter Berger       | Barker, Cooke                             | 1                | Understanding and predicting hypogene and supergene footprints of Carlin-type gold deposits using a hydrochemical modelling approach | UTAS                                                               |
| Nathan Chapman     | Meffre, V.Kamenetsky                      | 4                | Pb-isotopic insights into the crustal evolution and metallogenesis of the Gawler Craton                                              | ARC Linkage, BHP                                                   |
| Jing Chen *^       | Cooke, Zhang                              | 1                | The geology, mineralisation, alteration and structural evolution of Zijinshan ore field, Fujian Province, China                      | UTAS, China Scholarship Council, ARC TMVC, SEG, Zijin Mining       |

\* Affiliated with the ARC TMVC Research Hub # Degree completed, not yet graduated ^ Graduated § Withdrawn

DOCTOR OF PHILOSOPHY (53) cont.

| STUDENT               | SUPERVISORS                       | RESEARCH PROGRAM | PROJECT                                                                                                                                                                            | SUPPORT                                                                             |
|-----------------------|-----------------------------------|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Alexander Cherry ^    | V.Kamenetsky, McPhie, Ehrig (BHP) | 3, 4             | Geochronological constraints on the formation, setting and evolution of the Olympic Dam IOCG deposit and the Olympic IOCG Province, South Australia                                | UTAS, ARC Linkage, SEG, BHP                                                         |
| Takeshy Coaquira *    | Cooke, Zhang, Escolme             | 1, 2             | Resolving multiple generations of white mica and clay alteration at the Resolution porphyry Cu-Mo deposit, Arizona                                                                 | ARC TMVC, AMIRA P1202, UTAS                                                         |
| Rob Davidson          | Gemmell, Cooke                    | 1                | Geology and genesis of the San Sebastian vein system, Durango, Mexico                                                                                                              | Hecla Mining, UTAS                                                                  |
| Paulina Dobrowolska § | Roach, Walters, Berry             | 2                | Mineralogical and textural controls on grade-by-size fractionation in porphyry copper deposits                                                                                     | CRC ORE, UTAS                                                                       |
| David Douth #         | Scott, Cas                        | 1, 3, 4          | The geology and geological controls on gold mineralisation at the Invincible deposit, St Ives Gold Mine, Kambalda, WA                                                              | St Ives Gold                                                                        |
| Evan Draayers §       | Danyushevsky                      | 4                | The boninite magma genesis debate: Assessing the role of mantle sources associated with intra-plate magmatism in the generation of boninitic magmas above subduction zones         | UTAS                                                                                |
| Peter Duerden §       | Meffre, Cooke                     | 1, 3             | Geological framework and metallogenesis of the Northern Molong Volcanic Belt, Lachlan Orogen, New South Wales                                                                      | ARC Linkage, Alkane Resources                                                       |
| Kyle Eastman *        | Escolme, Zhang, Cooke             | 2                | Geological and geometallurgical characterization of porphyry deposit alteration overprints                                                                                         | AMIRA P1202, ARC TMVC, SEG, UTAS                                                    |
| Alex Farrar           | Cracknell, Cooke                  | 1, 3, 6          | Geodynamic and tectonic influence on giant porphyry copper deposit architectural controls                                                                                          | First Quantum Minerals                                                              |
| Matt Ferguson #       | V.Kamenetsky, Ehrig (BHP), Meffre | 4                | Late stage magmatic-hydrothermal evolution of A-type Hiltaba event rocks in the Gawler Craton                                                                                      | UTAS, ARC Linkage, BHP, SEG, GSA                                                    |
| Jodi Fox ^            | McPhie, Carey                     | 4                | Complex volcanic architecture produced by basaltic submarine and emergent volcanism in intraplate settings                                                                         | UTAS, CoE, ANZIS, Australian Antarctic Science Program, MRT, Linnean Society of NSW |
| Amos Garay *          | Cooke, Baker, Zhang               | 1                | Magnetite and epidote chemistry and textures at Las Bambas Cu-Au-Fe skarn, Peru: Assessing district and deposit-scale fertility – implications for ore genesis and exploration     | AMIRA P1153, ARC TMVC, UTAS Foundation, SEG                                         |
| Umer Habib            | Meffre, Roach, Musgrave (GSNSW)   | 3, 6             | Paleomagnetism and geochronology of Paleozoic rocks of Lachlan orogen in Victoria and New South Wales                                                                              | ARC Linkage, Geological Survey of NSW                                               |
| Jacob Heathcote       | Scott, Barker                     | 1, 3             | Gold distribution and association at the Kansanshi copper-gold deposit Zambia: Processes responsible for gold precipitation and implications for ore zone delineation and recovery | First Quantum Minerals                                                              |
| Max Hohl              | Barker, Cloutier, Steadman        | 3                | Defining the mineral chemistry footprints of IOCG deposits in northwest Queensland                                                                                                 | UTAS, GSQ                                                                           |
| Sam Holt ^            | Carey, McPhie                     | 4                | Understanding of basaltic eruption dynamics and mechanisms: Effusive and explosive eruptions in Hawaii                                                                             | UTAS, CoE, Hawaiian Volcano Observatory, USGS, CSL                                  |
| Shawn Hood *^         | Cracknell, Reading (Physics)      | 6                | Machine learning and automated geoscientific analyses for the spatial characterisation of metalliferous ore deposits                                                               | UTAS, ARC TMVC, Gold Fields Australia, Saracen Mineral Holdings, SEG                |
| Fumihiko Ikegami      | Carey, McPhie                     | 4                | 2012 submarine silicic eruption of Havre volcano and implications for ancient submarine successions in Australia                                                                   | UTAS, ARC, US National Science Foundation                                           |
| Laura Jackson *       | Parbhakar-Fox (UQ), Cooke, Fox    | 2                | Mineralogical domaining of low grade and no grade zones using automated drill core logging                                                                                         | ARC TMVC, UTAS, Newcrest Mining, Corescan                                           |
| Stewart Jackson       | Roach, Olivier (IMS)              | 6                | Integrating passive and active methods of seismic imaging for structural stability of tailings dams                                                                                | UTAS, GHD, IMS                                                                      |

\* Affiliated with the ARC TMVC Research Hub # Degree completed, not yet graduated ^ Graduated § Withdrawn

DOCTOR OF PHILOSOPHY (53) cont.

| STUDENT                         | SUPERVISORS                                  | RESEARCH PROGRAM | PROJECT                                                                                                                                                                                                                                         | SUPPORT                                                               |
|---------------------------------|----------------------------------------------|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Colin Jones *                   | Orovan, Cooke, Meffre                        | 4                | Petrogenesis of northeast Tasmanian granites                                                                                                                                                                                                    | MRT, ARC TMVC, UTAS                                                   |
| Joseph Knight                   | Orovan, Zhang, Cooke                         | 1                | The geodynamic and metallogenic setting of base- and precious-metal mineralisation in Myanmar: Implications for Cu and Au exploration                                                                                                           | Anglo American                                                        |
| Stephen Kuhn *                  | Reading (Physics), Cracknell                 | 6                | Lithological mapping for mineral exploration using machine learning                                                                                                                                                                             | UTAS, CODES, ARC TMVC, First Quantum Minerals, Gold Fields, ASEG, AIG |
| Erin Lawlis                     | Cooke                                        | 1                | Au-bearing pyritic ore of Lihir, Papua New Guinea: Its physiochemical character and nature of the causative fluids                                                                                                                              | Newcrest Mining, UTAS, SEG                                            |
| Bridie Le’Gallais               | Danyushevsky                                 | 4, 5             | The tectonic significance of mafic/ultra mafic igneous rocks in western Tasmania                                                                                                                                                                | UTAS, MRT                                                             |
| Christopher Leslie              | Meffre, Cooke, Steadman                      | 1, 3             | Porphyry and epithermal deposits of Cowal District, New South Wales                                                                                                                                                                             | ARC Linkage, UTAS, Evolution Mining                                   |
| Elena Lounejeva                 | Steadman, Large                              | 3                | Geochemical signature of syngenetic and diagenetic pyrite from marine sediments as a paleo-environmental tool                                                                                                                                   | ARC Discovery, CODES                                                  |
| Brian McNulty ^                 | Gemmell, Fox                                 | 1, 4             | Geology of the West Block Area of the late Devonian Myra Falls VHMS District, British Columbia, Canada                                                                                                                                          | Nyrstar, UTAS, SEG                                                    |
| Javier Merrill *                | Cracknell, Escolme                           | 2                | Evaluating applications of hyperspectral data for predicting mineral processing attributes and waste characteristics of slurries                                                                                                                | AMIRA P1202, Minerals Council of Australia, BECAS Chile, ARC TMVC     |
| Stephen Meyer §                 | Reading (Physics), Bassom (Mathematics)      | 6                | A model-based approach to the interpretation of seismicity associated with mass mining                                                                                                                                                          | Institute of Mine Seismology                                          |
| Hannah Moore                    | Carey, Jutzeler                              | 4                | Investigation of the shallow conduit processes involved in the 1886 basaltic Plinian eruption at Tarawera Volcano, New Zealand                                                                                                                  | UTAS                                                                  |
| Peter Morse                     | Reading (Physics), Lueg (Computing)          | 6                | Interactive visualisation for data inference in the geosciences                                                                                                                                                                                 | UTAS, CODES, ARC TMVC                                                 |
| Annah Moyo *                    | Cooke, Meffre, Parbhakar-Fox (UQ)            | 2                | Controlling acid and metalliferous drainage at legacy sites in Tasmania using industrial wastes                                                                                                                                                 | UTAS, Mineral Resources Tasmania, ARC TMVC                            |
| Nanda Yusentri Mrabawani *      | Danyushevsky, Meffre                         | 5                | Laser Ablation applied to mineral characterisation                                                                                                                                                                                              | ARC TMVC, UTAS                                                        |
| Sibele Cristina do Nascimento * | Cracknell, Cooke, Meffre, Parbhakar-Fox (UQ) | 2                | Geoenvironmental characterisation of historic mine tailings: Evaluating opportunities for reprocessing                                                                                                                                          | ARC TMVC, UTAS                                                        |
| Thomas Ostersen                 | Reading (Physics), Cracknell                 | 6                | Goelectric structure of the Tasmanian lithosphere                                                                                                                                                                                               | UTAS, CODES, MRT, U Adelaide, Geoscience Australia, GSSA              |
| Joshua Phillips *^              | Cooke, Scott, Baker                          | 1                | Geologic and geochemical vectors to mineralisation at the Resolution porphyry Cu-Mo deposit, Arizona                                                                                                                                            | ARC TMVC, AMIRA P1153, Rio Tinto, Resolution Copper Ltd               |
| Naomi Potter ^                  | V.Kamenetsky, Goemann (CSL), M.Kamenetsky    | 4                | An investigation into the genesis of intrusive and extrusive carbonatitic melts                                                                                                                                                                 | UTAS, ARC Discovery                                                   |
| Thomas Schaap                   | Meffre, Whittaker (IMAS), Cracknell, Roach   | 3, 6             | Plate tectonic modelling of the Palaeozoic Lachlan Orogen                                                                                                                                                                                       | ARC Linkage, UTAS                                                     |
| Xin Ni Seow *                   | Zhang, Orovan, Cooke, Danyushevsky           | 1, 5             | Geochemistry, mechanism of formation and exploration implications of alunite supergroup minerals                                                                                                                                                | ARC TMVC, UTAS, AMIRA P1202                                           |
| Emily Smyk *                    | Cooke, Baker, Barker, Meffre                 | 1                | A characterisation of the intrusive rocks and magmatic minerals and their related propylitic and skarn alteration at the Christmas porphyry Cu deposit, Arizona, USA: assessing the potential for mineral chemistry vectoring to mineralisation | AMIRA P1202, ARC TMVC, UTAS                                           |

DOCTOR OF PHILOSOPHY (53) cont.

| STUDENT             | SUPERVISORS                                        | RESEARCH PROGRAM | PROJECT                                                                                                                                                                                                                                   | SUPPORT                                                      |
|---------------------|----------------------------------------------------|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|
| Tobias Staal        | Reading (Physics), Halpin (IMAS), Whittaker (IMAS) | 6                | Lithospheric structure of Antarctica                                                                                                                                                                                                      | Antarctic Gateway Partnership, Australian Antarctic Division |
| Yi Sun *            | Zhang, Escolme, Cooke                              | 1, 2             | Mineralogical, textural, geochemical characterisation and geometallurgical models of Lepanto Quartz – Pyrite – Gold vein and breccia system, Philippines                                                                                  | ARC TMVC, AMIRA P1202, UTAS, SEG, Lepanto Consolidated       |
| Francisco Testa #   | Cooke, Baker                                       | 1                | Tourmaline breccia pipes: San Francisco de los Andes, Argentina and Rio Blanco-Los Bronces, Chile                                                                                                                                         | UTAS, AMIRA P1060                                            |
| Jay Thompson        | Danyushevsky, Meffre                               | 5                | Understanding the specifics of H <sub>2</sub> O-free aerosol behaviour in the inductively-coupled plasma in geochemical LA-ICPMS applications involving U/ Pb dating and accurate trace element analysis in silicate minerals and glasses |                                                              |
| Jennifer Thompson * | Cooke, Danyushevsky, Meffre                        | 1                | Carbonate mineral chemistry in epithermal and porphyry hydrothermal systems                                                                                                                                                               | UTAS, AMIRA P1153, ARC TMVC, SEG                             |
| Daniele Vergani ^   | Carey, McPhie                                      | 4                | The 2007 explosive activity at Piton de la Fournaise volcano (La Reunion Island) : constraints on the eruptive processes by the volcanological study of the erupted deposits                                                              | UTAS, CoE, Reunion Volcano Observatory                       |
| Tristan Wells       | Meffre, Cooke, Steadman                            | 1, 3             | Magmatic fertility in the Macquarie Arc                                                                                                                                                                                                   | ARC Linkage, UTAS, CODES, NorthParkes                        |

\* Affiliated with the ARC TMVC Research Hub # Degree completed, not yet graduated ^ Graduated § Withdrawn

Major externally funded research projects^

ARC INDUSTRIAL TRANSFORMATION RESEARCH HUB GRANTS 2019

| INVESTIGATORS                                                                                                                                                                  | PROJECT                             | FUNDING BODY                                         | PERIOD    | ARC FUNDING FOR 2019 | PARTNER FUNDING FOR 2019 | UTAS FUNDING FOR 2019 | MISC FUNDING FOR 2019 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|------------------------------------------------------|-----------|----------------------|--------------------------|-----------------------|-----------------------|
| Cooke, Danyushevsky, Jiang, Gemmell, Large, Meffre, Reading, Harris (Newcrest), Seymon (AMIRA), Ehrig (BHP), Goodey (Corescan), Lottermoser (Aachen), Shelley (Laurin Technic) | Transforming the mining value chain | ARC, AMIRA International, BHP, Newcrest Mining, UTAS | 2015–2020 | **                   | \$1,114,789              | \$130,738             | \$482                 |

ADDITIONAL FUNDER PROJECTS WITHIN THE ARC TMVC RESEARCH HUB 2019

| INVESTIGATORS                            | PROJECT                                                                                                                              | FUNDING BODY                         | PERIOD    | FUNDING FOR 2019 |
|------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|-----------|------------------|
| Zhang                                    | Alteration minerals chemistry at Yaojialing Zn-Au-W skarn deposit, China: implications for ore genesis and exploration               | Hefei University of Technology       | 2019–2021 | \$24,000         |
| Orovan, Cooke, Jones (student)           | Petrogenesis of northeast Tasmanian granites                                                                                         | Mineral Resources Tasmania           | 2018–2021 | \$24,000         |
| Meffre, van Balen (student)              | Determining the mineralogical and geochemical properties of tailings at Copper Mines of Tasmania: Opportunities for metal recovery   | Copper Mines of Tasmania             | 2019      | \$18,400         |
| Meffre, K’ng (student)                   | Geochemical and mineralogical characterisation of tailings: Evaluating the potential for reprocessing the Bobadil tailings, Rosebery | MMG                                  | 2019      | \$14,900         |
|                                          |                                                                                                                                      | AusIMM/EIANZ/ BHP C&E Research Award | 2019      | \$3,000          |
| Escolme, Zhang, Cooke, Eastman (student) | Geological and geometallurgical characterization of porphyry deposit alteration overprints                                           | Society of Economic Geologists       | 2019–2020 | \$7,093          |

ADDITIONAL FUNDER PROJECTS WITHIN THE ARC TMVC RESEARCH HUB 2019 cont.

|                                              |                                                                                                                                                                                |                                                     |           |         |
|----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|-----------|---------|
| Zhang, Baker, Rivett (student)               | Geochemical footprint and paragenesis of the Specimen Hill Au prospect, New England Orogen, Queensland                                                                         | UTAS Foundation                                     | 2019      | \$5,000 |
| Zhang, Escolme, Cooke, Sun (student)         | Mineralogical, textural, geochemical characterisation and geometallurgical models of Lepanto Quartz – Pyrite – Gold vein and breccia system, Philippines                       | Society of Economic Geologists                      | 2019–2020 | \$4,965 |
| Cooke, White, Zhang, Gemmell, Testa          | Geological and geochemical vectors to low sulfidation epithermal gold mineralization, Cerro Negro district, Deseado Massif, Argentina                                          | Oro Plata SA                                        | 2017–2020 | \$4,477 |
| Cooke, Meffre, Parbhakar-Fox, Moyo (student) | Controlling acid and metalliferous drainage at legacy sites in Tasmania using industrial waste materials                                                                       | Mineral Resources Tasmania                          | 2017–2022 | **      |
| Zhang                                        | Geochemical and mineralogical vectors to the ore at Bilihe-Hadamiao district, Inner Mongolia, China                                                                            | Peking University                                   | 2017–2020 | **      |
|                                              |                                                                                                                                                                                | Inner Mongolia Mining Technology Research Institute | 2017–2020 | **      |
| Cooke, Baker, Zhang, Garay (student)         | Magnetite and epidote chemistry and textures at Las Bambas Cu-Au-Fe skarn, Peru: Assessing district and deposit-scale fertility - implications for ore genesis and exploration | UTAS Foundation                                     | 2015–2020 | **      |

^ projects with greater than \$2,000 external funding per year \*\* all project funding received, project still active

ARC LINKAGE GRANTS 2019

| INVESTIGATORS                                                                                                              | PROJECT                                                                 | FUNDING BODY                                                                                                                                                                                                                                                                                    | PERIOD    | ARC FUNDING FOR 2019 | PARTNER FUNDING FOR 2019 |
|----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|----------------------|--------------------------|
| Meffre, Whittaker (IMAS), Norman (ANU), Cracknell, Belousova (Macquarie), Collins (UoN), Arundell (IMEx Consulting), Cooke | Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia | ARC, Rio Tinto, Alkane Exploration, Sandfire Resources, Evolution Mining, Geoscience Australia, Geological Survey of New South Wales, Heron Resources, Mineral Resources Tasmania, Northparkes Mines, New South Resources, AngloGold Ashanti, Geological Survey of Victoria, Emmerson Resources | 2016–2019 | \$48,044             | **                       |

ARC DISCOVERY EARLY CAREER RESEARCHER AWARDS 2019

| INVESTIGATORS | PROJECT                                                                    | PERIOD    | ARC FUNDING FOR 2019 | UTAS FUNDING FOR 2019 |
|---------------|----------------------------------------------------------------------------|-----------|----------------------|-----------------------|
| Carey         | The role of hydrostatic pressure in modulating submarine silicic eruptions | 2015–2020 | **                   | **                    |

CRC PROJECTS 2019

| INVESTIGATORS  | PROJECT                                                         | PERIOD    | CRC FUNDING FOR 2019 | UTAS FUNDING FOR 2019 |
|----------------|-----------------------------------------------------------------|-----------|----------------------|-----------------------|
| Cooke, Gemmell | CRC ORE II Participant funding                                  | 2015–2021 | \$0                  | \$100,000             |
| Hunt, Cooke    | CRC ORE II – Predictive geometallurgy controls on grade by size | 2016–2021 | \$253,518            | \$0                   |



The sun sets on another day of sampling and data collection at the Resolution porphyry deposit, Arizona.

INDUSTRY AND OTHER EXTERNALLY FUNDED RESEARCH GRANTS 2019

| INVESTIGATORS                      | PROJECT                                                                                                                                                         | FUNDING BODY                                                                                                                                                                | PERIOD    | FUNDING FOR 2019 |
|------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------------------|
| Barker, Steadman, Cooke            | Mineral geochemistry vectoring uncovering North West Queensland's hidden potential                                                                              | Geological Survey of Queensland                                                                                                                                             | 2018–2020 | \$393,000        |
| Cooke, Meffre, Jutzeler, Carey     | 4D geological modelling of the Cowal district, NSW                                                                                                              | Evolution Mining                                                                                                                                                            | 2018–2021 | \$200,000        |
| Mukherjee, Steadman, Large, Olin   | Application of pyrite chemistry to exploration and deep-time geology                                                                                            | Ian Potter Foundation                                                                                                                                                       | 2019      | \$125,000        |
|                                    |                                                                                                                                                                 | Teck, Rio Tinto, Anglo American, First Quantum Minerals, Mt Isa Mines, Red Metal, Geological Survey of Queensland, Geological Survey of South Australia, Sandfire Resources | 2019–2020 | \$0              |
| Gemmell, Cooke, Davidson (student) | Geology and genesis of the San Sebastian vein system, Durango, Mexico                                                                                           | Hecla Mining Company                                                                                                                                                        | 2017–2020 | \$48,000         |
| Cooke, Diaz (student)              | The Cascabel Cu-Au porphyry cluster in northern Ecuador                                                                                                         | SolGold                                                                                                                                                                     | 2019–2020 | \$32,240         |
| Meffre, Steadman, Cracknell, Cooke | Ore deposits and tectonics of SE Australia                                                                                                                      | Freeport McMoRan Exploration Australia                                                                                                                                      | 2019      | \$30,000         |
| Large, Hawke, Olin                 | Pyrite vectors for the Cobar Basin                                                                                                                              | Dept of Industry, Innovation and Science                                                                                                                                    | 2019–2020 | \$16,431         |
|                                    |                                                                                                                                                                 | Peel Mining                                                                                                                                                                 | 2019–2020 | \$0              |
| Steadman                           | Evaluating epidote and chlorite mineral chemistry in the Temora area, NSW                                                                                       | Argent Minerals                                                                                                                                                             | 2019–2020 | \$15,000         |
| Kamenetsky, Abersteiner (student)  | APR Internship – Sulfur isotopes in Olympic Dam                                                                                                                 | Australian Institute of Mathematics and Science                                                                                                                             | 2019–2020 | \$14,500         |
| Scott, Maroa (student)             | Characterization of the geology, mineralization and genesis of the Bumbo polymetallic sulphide deposit within the Busia-Kakamega Greenstone Belt, Western Kenya | Acacia Mining Kenya                                                                                                                                                         | 2019–2020 | \$13,990         |
| Cooke, Li (visiting student)       | The mechanism of lithocap and its relationship with copper, gold, iron metallogenic systems in Luzong Basin, Anhui Province, China                              | Hefei University of Technology                                                                                                                                              | 2018–2019 | \$13,550         |
| Jutzeler, Carey                    | Volcanic architecture and eruption behaviour at Site U1437 Izu-Bonin-Mariana rear-arc, IODP 350                                                                 | IODP (via Australian National University)                                                                                                                                   | 2019–2020 | \$10,000         |

INDUSTRY AND OTHER EXTERNALLY FUNDED RESEARCH GRANTS 2019 cont.

|                                        |                                                                                                                                                  |                                           |           |          |
|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|-----------|----------|
| Scott, Foster (student)                | Hydrothermal alteration and gold distribution in BIF-hosted gold deposits of the Westralia Mine area (Mount Morgans), WA                         | Mt Morgans WA Mining (Dacian Gold)        | 2019      | \$10,000 |
| Scott, R James (student)               | Characterisation of gold mineralisation styles and vein types in the Lantern Gold Deposit, Northern Territory                                    | NT Mining Operations                      | 2019      | \$10,000 |
| Cooke, Zhang, Nie (visiting student)   | The genesis of skarn tungsten deposits in the Middle-Lower Yangtze River Metallogenic Belt                                                       | Hefei University of Technology            | 2018–2019 | \$8,351  |
| Roach, Behan (student)                 | The petrophysical and geophysical characterisation of high-grade mineralisation at Fosterville Gold mine, Victoria: Implications for exploration | Fosterville Gold Mine                     | 2019      | \$5,000  |
| Jutzeler, Carey                        | Eruption styles and periodicity of the silicic Sumisu caldera, Izu-Bonin-Mariana Arc                                                             | IODP (via Australian National University) | 2018–2020 | **       |
| Orovan, Zhang, Cooke, Knight (student) | The geodynamic and metallogenic setting of base- and precious-metal mineralisation in Myanmar: Implications for Cu and Au exploration            | Anglo American                            | 2015–2020 | **       |
| Scott, Steadman, Cowie (student)       | Paragenetic and geochemical analysis of the Perimeter Gold prospect, Ora Banda, Western Australia                                                | Evolution Mining                          | 2018–2019 | **       |
| Cooke, Torres (student)                | Geology, genesis and exploration implications of Cu-Au mineralised tourmaline breccia pipes at Soledad, central Peru                             | Chakana Copper                            | 2017–2019 | **       |
| Danyushevsky, Tolley                   | Development of fundamental aspects of laser-ablation analysis applied to geological problems                                                     | Laurin Technic                            | 2015–2019 | **       |
| Gemmell, Fox, McNulty (student)        | Geology of the West Block Area of the late Devonian Myra Falls VHMS District, British Columbia, Canada                                           | Nyrstar Myra Falls                        | 2015–2019 | **       |
| Scott, Cas, Douth (student)            | The geology and geological controls on gold mineralisation at the Invincible deposit, St Ives Gold Mine, Kambalda, WA                            | St Ives Gold                              | 2015–2019 | **       |

^ projects with greater than \$2,000 external funding per year    \*\* all project funding received, project still active

OPPOSITE PAGE: The open pit at Batu Hijau, Sumbawa, Indonesia, photographed in 2019 by TMVC PhD student Kyle Eastman.



Visitors 2019

INDUSTRY VISITORS TO CODES IN 2019

| NAME                | COMPANY                                                                     |
|---------------------|-----------------------------------------------------------------------------|
| Paul Agnew          | Rio Tinto                                                                   |
| Ben Andrew          | Mt Isa Mines (Glencore)                                                     |
| Debora Araujo       | Rio Tinto                                                                   |
| John Barr           | Anglo American                                                              |
| Julian Bartlett     | Merdeka Copper-Gold                                                         |
| Jeff Bigelow        | Newmont                                                                     |
| Thomas Bissig       | Newmont Goldcorp                                                            |
| Dave Braxton        | Anglo American                                                              |
| Alex Brown          | Mt Isa Mines (Glencore)                                                     |
| David Close         | Santos                                                                      |
| Andrew Davies       | Teck                                                                        |
| John Doherty        | Watermark Numerical Computing                                               |
| David First         | Freeport McMoRan                                                            |
| Kim Frankcombe      | ExploreGeo                                                                  |
| Rizal Fraval        | Rio Tinto                                                                   |
| Mary Frey           | Australian Government Department of Industry, Science, Energy and Resources |
| Karyn Gardner       | Newcrest Mining                                                             |
| Steve Garwin        | Consultant                                                                  |
| Simon Gatehouse     | BHP                                                                         |
| Geoff Green         | Visitor                                                                     |
| Abhi Gupta          | Panalytical                                                                 |
| Scott Halley        | Mineral Mapping                                                             |
| Anthony Harris      | Newcrest Mining                                                             |
| Mary Harris         | Newcrest Mining                                                             |
| Jane Harvey         | Freeport McMoRan                                                            |
| Tony Hope           | Copper Gold Cambodia                                                        |
| Ned Howard          | Evolution Mining                                                            |
| Rob Hutchinson      | Elemental Scientific Inc.                                                   |
| Christian Ihlenfeld | Anglo American                                                              |
| Jake Jarvinen       | Olympus Innov-x                                                             |

| NAME               | COMPANY                        |
|--------------------|--------------------------------|
| Brian Kay          | Fortescue Metals Group         |
| Alan Koenig        | Applied Spectra                |
| Joshua Leigh       | First Quantum Minerals         |
| Neil Macalalad     | Anglo American                 |
| Peter Manchester   | Consultant                     |
| Larry Meinert      | Society of Economic Geologists |
| John Miller        | BHP                            |
| Ken Morrison       | Consultant                     |
| Erin Newman        | Newmont Goldcorp               |
| Ashley Norris      | Norris Scientific              |
| Dana Olafson       | Fortescue Metals Group         |
| Adam Pacey         | Rio Tinto                      |
| Cynthia Palfreyman | GHD, Hobart                    |
| Martin Patriat     | Ifremer                        |
| Josh Phillips      | Freeport McMoRan               |
| Cameron Quinn      | Fortescue Metals Group         |
| Anton Rada         | Unmanned Aerial Magnetics      |
| Peter Rea          | Mt Isa Mines (Glencore)        |
| Chris Reed         | Teck                           |
| Catherine Reynolds | Anglo American                 |
| Martin Scott       | Fortescue Metals Group         |
| Ivan Semenov       | Rio Tinto                      |
| Adele Seymon       | AMIRA International            |
| Trevor Shaw        | Mt Isa Mines (Glencore)        |
| Adam Simmons       | Anglo American                 |
| Tony Webster       | GeoDiscovery Group             |
| Matt Wetzel        | Freeport McMoRan               |
| Mike Whitbread     | Rio Tinto                      |
| Noel White         | Consultant                     |
| Greg Wilkie        | CRC ORE                        |

NATIONAL ACADEMIC AND GOVERNMENT VISITORS IN 2019

| NAME              | INSTITUTION                                       |
|-------------------|---------------------------------------------------|
| Laurent Ailleres  | Monash University                                 |
| Robin Armit       | Monash University                                 |
| Michael Asten     | Monash University                                 |
| Tui Aualiitia     | Environment Protection Agency, Tasmania           |
| Rufus Black       | Vice-Chancellor, UTAS                             |
| Ralph Bottrill    | Mineral Resources Tasmania                        |
| Marita Bradshaw   | Geoscience Australia                              |
| Ray Cas           | Monash University/UTAS                            |
| Richard Chopping  | Geological Survey of Western Australia            |
| Andrew Cole       | Physics, UTAS                                     |
| Tamara Coyte      | Mineral Resources Tasmania                        |
| Nathan Daczko     | Macquarie University                              |
| Mark Duffett      | Mineral Resources Tasmania                        |
| Simon Ellingsen   | Physics, UTAS                                     |
| Michael Gatell    | Environment Protection Agency, Tasmania           |
| David Green       | Mineral Resources Tasmania                        |
| Boris Gurevich    | Curtin University/CSIRO                           |
| Brett Harris      | College of Sciences and Engineering, UTAS         |
| Paul Heithersay   | Department for Energy and Mining, South Australia |
| Mark Hunt         | UTAS                                              |
| Anita Hansen      | Royal Society                                     |
| Brita Hansen      | Royal Society                                     |
| Lorraine Ingham   | College of Sciences and Engineering, UTAS         |
| Claire Kain       | Mineral Resources Tasmania                        |
| Anthony Koutoulis | Research, UTAS                                    |

| NAME                    | INSTITUTION                                                       |
|-------------------------|-------------------------------------------------------------------|
| Helen McFarlane         | Centre for Exploration Targeting, University of Western Australia |
| Teresa McGrath          | Curtin University                                                 |
| Matthew McDowell        | UTAS                                                              |
| Andrew McNeill          | Mineral Resources Tasmania                                        |
| Nicholas Mériaud        | Centre for Exploration Targeting, University of Western Australia |
| Stephen Meyer           | Institute of Mine Seismology                                      |
| Brenda Mooney (student) | ACROSS, UTAS                                                      |
| Gerrit Olivier          | Institute of Mine Seismology                                      |
| Brett Paull             | College of Sciences and Engineering, UTAS                         |
| Luke Roberts            | State Emergency Service, Tasmania                                 |
| Nick Roberts            | Mineral Resources Tasmania                                        |
| Kevin Robinson          | Mineral Resources Tasmania                                        |
| Angela Rodrigues        | Monash University                                                 |
| Bob Rutherford          | Department of State Growth, Tasmania                              |
| Phil Sansom             | Consultant                                                        |
| Kate Selway             | Macquarie University                                              |
| Clint Siggins           | Mineral Resources Tasmania                                        |
| Miles Smith             | School of Natural Sciences, UTAS                                  |
| Noel White              | Consultant                                                        |
| Greg Wilkie             | CRC ORE                                                           |
| Brian Yates             | College of Sciences and Engineering, UTAS                         |

INTERNATIONAL ACADEMIC AND GOVERNMENT VISITORS IN 2019

| NAME                    | INSTITUTION                                                             |
|-------------------------|-------------------------------------------------------------------------|
| Huayong Chen            | Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, China |
| Xianzheng Guo (student) | China University of Geosciences in Wuhan, China                         |
| Patrick Hamilton        | Lakehead University, Canada                                             |
| Mathilde Henri          | Institut de Physique du Globe de Paris, France                          |
| Bruce Houghton          | University of Hawaii, USA                                               |
| Osamu Ishizuka          | Geological Survey of Japan                                              |
| Andrew Jedemann         | Lakehead University, Canada                                             |
| Simon Jones             | University of St Andrews, Scotland, UK                                  |
| Xinghai Lang            | Chengdu University of Technology, China                                 |
| Xuanxuan Li (student)   | Hefei University of Technology, China                                   |
| Wenbo Li                | Peking University, China                                                |
| Robert Linnen           | Western University, Canada                                              |

| NAME                   | INSTITUTION                                                                               |
|------------------------|-------------------------------------------------------------------------------------------|
| Cui Minli              | China Geological Survey, China                                                            |
| John O'Donnell         | University of Leeds, UK                                                                   |
| Bernhard Pracejus      | Sultan Qaboos University, Oman                                                            |
| Hongying Qu            | Institute of Mineral Resources at the Chinese Academy of Geological Sciences, China       |
| Peter Sorjonen-Ward    | Geological Survey of Finland (GTK)                                                        |
| Shiqiang Su            | Institute of Geology and Geophysics, Chinese Academy of Sciences, China                   |
| J. Paul Winberry       | Central Washington University, USA                                                        |
| Tao Zhang (student)    | School of Earth Sciences and Resources, China University of Geosciences in Beijing, China |
| Shaorui Zhao (student) | China University of Geosciences in Wuhan, China                                           |



The 2019 CODES Annual Review in full swing.



(TOP) Students learning about multi-element geochemical analysis methods at the ALS metallurgy lab, Burnie, whilst on the 2019 'Geometallurgy' Masters short course field excursion. They are (L-R): Menford Ngara, George Maroa, Batbayar Enkhbold, Scott Jimmerson, Chris Booth and Markus Staubmann with an ALS lab technician. (ABOVE) An early start for AMIRA P1202 Module 4 research team members Dr Mike Baker and Javier Merrill with Alina Gaibor (BHP) at the Spence core facilities, Chile, where they spent ten days reviewing and sampling drill core from the Cu-Mo porphyry deposit during 2019. (LEFT) Dr Evan Orovan getting ready to take a chrysocolla-stained porphyry sample from a dusty outcrop during fieldwork at the Rincones de Araya prospect, San Juan Province, Argentina, during 2019.

## **CODES**

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## VISION

To be the premier international research centre in ore deposit geology.

## MISSION

Significantly advance collaborative and innovative ore deposit research for Australian and international researchers and the minerals industry.

## GOALS

- > Undertake and publish high-quality research.
- > Lead the global minerals industry in research on the exploration and recovery of new mineral resources.
- > Equip the Australian minerals industry with world-class graduates.
- > Communicate the Centre's research to the wider research, industry and general communities.



(TOP) L–R: Professor David Cooke, Dr Angela Escolme and Masters student Libas Ulaiwi inspecting drill core during the 'Ores in Magmatic Arcs – Indonesia' short course, which ran in March 2019. (MIDDLE) Dr Rachel Harrison, a CODES PhD graduate, provides students on the 'Ores in Magmatic Arcs – Indonesia' Master of Economic Geology short course with an overview of the Tanjung Jahe diatreme while on Candrian Beach, southeast of Tujuh Bukit district, Indonesia. (BOTTOM) Ankaramite lavas, Tenerife, Canary Islands, Spain, photographed by Professor Jocelyn McPhie. Very thin, very crystal-rich lava flow units, each with internal normal grading of coarse pyroxene crystals and red, oxidised tops. Three complete flow units, and part of a fourth flow unit, are visible.

