



CENTRE FOR ORE DEPOSIT AND EARTH SCIENCES

2018 ANNUAL REPORT



UNIVERSITY of
TASMANIA



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 left) Au-Ag-As-rich orange flocculent on the edge of Champagne Pool, Waiotapu geothermal field, New Zealand, taken during the Master of Economic Geology short course on 'Volcanology and Mineralisation in Volcanic Terrains', which ran in March. (Top right) During 2018 Professor Vadim Kamenetsky and CODES PhD student Adam Abersteiner travelled to the Russian Far East visiting Central Siberia and Kamchatka. These Kamaz six-wheeled trucks – termed by Adam 'the finest examples of glorious Soviet engineering' – were the only practical way to travel around the rugged landscapes of Kamchatka, and are pictured at Mutnovsky volcano in the southern part of the Kamchatka Peninsula. (Bottom right) CODES PhD student Umer Habib using a spinning magnetometer at a University of Newcastle lab run by the Geological Survey of New South Wales.

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FRONT COVER: Master of Economic Geology student Victor Torres studying a tourmaline breccia pipe in the Soledad Cu-Au district, Cordillera Negra, Peru, during fieldwork in late 2018. BACK COVER: Master of Economic Geology students approaching acid sulfate crater lakes on Tongariro volcano, New Zealand, during the 2018 'Volcanology and Mineralisation in Volcanic Terrains' short course, which ran in March with 24 participants. RIGHT: Biotite shear bands disrupting porphyry-style quartz and chalcopyrite veins in diorite porphyry, Alpala porphyry Cu-Au deposit, Cascabel district, Ecuador.



Director's report 2018

► **2018 was a productive and successful year for CODES, with several new major research initiatives commencing, including AMIRA P1202, the Northwest Queensland exploration project, and Cerro Negro, Argentina.**

These new projects facilitated the recruitment of several new staff and students, and created new research partnerships with Goldcorp, Monash University, Universidad Austral de Chile and Mineral Mapping, among others. CODES continued to attract new research projects and partners with a substantial number of the new partners involved in the TMVC. Publication of a special issue of *Economic Geology* (January 2018) was a major highlight, with many articles written by CODES staff and students, and a

significant and sustained increase in download rates as the journal articles came online, demonstrating strong industry engagement with CODES research outcomes. 2018 also saw the reintroduction of CODES newsletters for the first time since 2014 as a way of providing our stakeholders with updates on current developments within CODES, including student and staff profiles.

A total of seven PhD studies were completed in 2018, and ten new PhD students joined our program. The Master of Economic Geology program saw the largest ever number of new recruits join the program in 2018: 19 new students plus one lapsed student who has recommenced their degree. As part of the Masters program, we presented three highly successful short courses, culminating in the very well-received three-day Garry Davidson Symposium (130 attendees), presented as part of the Ore Deposit Models and Exploration Strategies short course in 2018.

Our researchers in the Australian Research Council-funded Industrial Transformation Research Hub, Transforming the Mining Value Chain (TMVC), achieved several major

milestones in 2018. The TMVC's largest sub-project, AMIRA P1153, was brought to a successful conclusion in mid-2018, with a range of deliverables provided to the sponsor group via sponsors' research and field meetings in Australia and North America. The success of P1153 resulted in our industry partners supporting a new major AMIRA research initiative within the TMVC – AMIRA P1202 ('Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits'). P1202 follows on directly from AMIRA P1153 and is designed to bring together the major research themes of the first three years of the TMVC into the Hub's final, major endeavour that will deliver industry transformational workflows to our research partners that facilitate exploration, processing and geoenvironmental assessments. As such, it involves researchers from all three of the TMVC's research themes and our Underpinning Technologies group. P1202 is a collaboration with researchers from Lakehead University, Monash University and the Universidad Austral de Chile. It has provided the funding base to recruit several new PhD students and key TMVC postdoctoral researchers.



Some of the 130 participants of the highly successful Garry Davidson Symposium, which took place in October, gathered on the steps outside the CODES offices at UTAS, Hobart.

In December 2018, Dr Rebecca Carey (CODES) and Associate Professor Jo Whittaker (IMAS) led a two-week cruise on the *RV Investigator* to unravel the complex tectonic history of the Tasman Sea. Other CODES researchers onboard included Dr Karin Orth, Dr Martin Jutzeler, PhD student Tom Schaap, and four undergraduate Earth Science students. Sixteen sites were dredged, recovering approximately two tonnes of rock, and several new seamounts were mapped and named. We anticipate exciting new insights into this poorly understood part of Tasmania's local neighbourhood to arise in 2019, once the analytical program is completed.

► **Other highlights for the year included Professor Vadim (Dima) Kamenetsky and PhD student Adam Abersteiner's research trip to Kamchatka in the Russian Far East and Siberia.**

They established several collaborative projects relating to kimberlites and basaltic volcanism on this trip. Also, new collaborations continued to be made in the work done by CODES Analytical Laboratories, including a new working relationship with the University of Kiel looking at the application of nano-powder pressed pellets as reference materials for LA-ICP-MS. Program 6 researchers were involved in the development of new software for virtual reality and augmented reality analysis of geological data sets.

Awards and accolades

Following his award of the 2018 Haddon Forrester King Medal for life-long achievement and contribution to science, CODES/TMVC Director Professor David Cooke undertook a speaking tour of Australia in November, which included presentations in Melbourne, Canberra, Perth, Darwin, Townsville, Parkes and Brisbane.



L–R: CODES/TMVC Director Professor David Cooke with Leonardo Aguilar, Santiago Vaca, Steve Garwin (all from SolGold) and new CODES Masters student Carlos Diaz during an exploratory field trip to the Alpala Creek discovery outcrop in the Cascabel district, Ecuador, in late 2018.

TMVC PhD candidate Jing Chen was awarded the best student talk on porphyry, skarn and epithermal deposits at the 14th National Conference on Mineral Resources of China, held in Shijiazhuang, Hebei Province, China, during October.

And in August Emeritus Professor Ross Large was presented with the Royal Society of Tasmania Medal 2018, which is awarded for substantial original research in any subject within the Society's purview. He also delivered the Royal Society of Tasmania Lecture as part of the medal winner's role.

Staff changes

There were several significant changes to our senior staff profile and administrative roles in 2018. Associate Professor Shaun Barker joined our academic profile staff in mid-2018, and immediately made significant

impacts to our research, teaching and industry engagement. Professor Leonid Danyushevsky relinquished his role as Head of Discipline of Earth Sciences in mid-2018 and was replaced by Associate Professor Sebastien Meffre. Leonid was confirmed as Deputy Director of CODES and Director of CODES Analytical Laboratories in late 2018. Professor Anya Reading transferred from the Discipline of Earth Sciences to the Discipline of Mathematics and Physics but has continued in her role as a Chief Investigator in the TMVC Research Hub. Several of our postdoctoral research fellows and professional staff gave notice in late 2018 and will depart CODES in early 2019. We wish Drs Irina Zhukova, Sasha Stepanov, Anita Parbhakar-Fox and Nathan Fox all the best in the next phases of their careers.



CODES staff and students took part in a range of conferences around the world during 2018; here PhD student Erin Lawlis and Dr Evan Orovan are pictured at the much-visited CODES booth at Roundup 2018, which took place in Vancouver, Canada, during January.

Conferences and short courses

CODES staff and students played pivotal roles in the 2018 Gordon Research Conference and associated Gordon Research Seminar on the Geochemistry of Mineral Deposits. These meetings were held in early August in Waterville Valley, New Hampshire, USA. PhD student Ayesha Ahmed and Dr Angela Escolme co-chaired the inaugural Gordon Research Seminar, which was for early career researchers and graduate students, and included Dr Indrani Mukherjee as a speaker. Professor David Cooke co-chaired the Gordon Research Conference, where Emeritus Professor Ross Large was a Discussion Leader of one of the conference sessions. Both the conference and seminar were highly successful, achieving their aims of stimulating discussion regarding future research directions, and providing extensive networking opportunities between academics, students, government and industry that will lead to future research collaborations.

In October 2018, the biennial two-week Master of Economic Geology short course Ore Deposit Models and Exploration Strategies began with a very special event to commemorate the career of our much loved and highly respected colleague, Dr Garry

Davidson, who passed away in April 2017. Garry was remembered as a dedicated teacher and an innovative, insightful researcher who had an insatiable curiosity and infectious passion for the Earth Sciences. In keeping with the objectives of the Masters short course, the Garry Davidson Symposium addressed the genesis of, and exploration for, the ore deposit types that Garry had devoted so much of his working life to characterising and understanding; namely IOCG, uranium, sediment-hosted Pb-Zn and copper, Broken Hill-type, volcanic-hosted massive sulfide and orogenic gold deposits. A total of 28 speakers, including many of Garry's friends, colleagues, former students and collaborators, presented talks at the symposium. It was a great success, and very well received by all 130 people who attended. Following the symposium, the regular short course included guest speakers Zhaoshan Chang (skarns) and Noel White (porphyry and epithermal deposits), along with contributions by CODES staff and students.

Another important event hosted by CODES and the Discipline of Earth Sciences was the very successful second GESS Symposium (known as GESS-TAS) which took place on 16 November. More than 80 people registered for the symposium, which featured keynotes from Dr Mark Curran (ACE CRC), Dr Jacqueline

STATISTICS AT A GLANCE 2018

Academic Research Staff	59
Postgraduate Students	133
Major Research Projects	71
Countries Involved	27
Publications in Refereed Journals	82
Research Reports to Industry	194
WORKSHOPS AND SHORT COURSES	
Number	21
Countries	4
Attendees	737
FUNDING	
Industry	\$1.34 million
UTAS	\$1.92 million
TMVC	\$1.97 million
WORLDWIDE COLLABORATIONS	
Industry	64
Institutes and Universities	128

Halpin (IMAS) and Dr Peter McGoldrick (CODES). Several CODES students also presented findings from their research projects.

Publications

Important publications and forthcoming publications that CODES staff/ collaborators contributed to in 2018 included the following:

- Special issue of *Economic Geology* published in January 2018, co-edited by Dr Mike Baker, Dr Evan Orovan and Dr Pete Hollings (Lakehead University).
- Associate Professor Ron Berry and Dr Julie Hunt (MDRU) continued work as guest editors on an *Economic Geology* special issue on Geometallurgy to be published in 2019.
- Dr Pete Hollings, Dr Mike Baker and Dr Evan Orovan commenced editorial work on a new special issue of *Economic Geology* focussed on geochemical exploration in green rocks around porphyry deposits, to be published in 2019.

CODES Annual Review

The second Annual Review was held in November and showcased a broad selection of the research being conducted at CODES. Various staff and students gave talks on their topic of choice, with a student poster session included to encourage lunchtime discussion among attendees.

Vale Pat Quilty

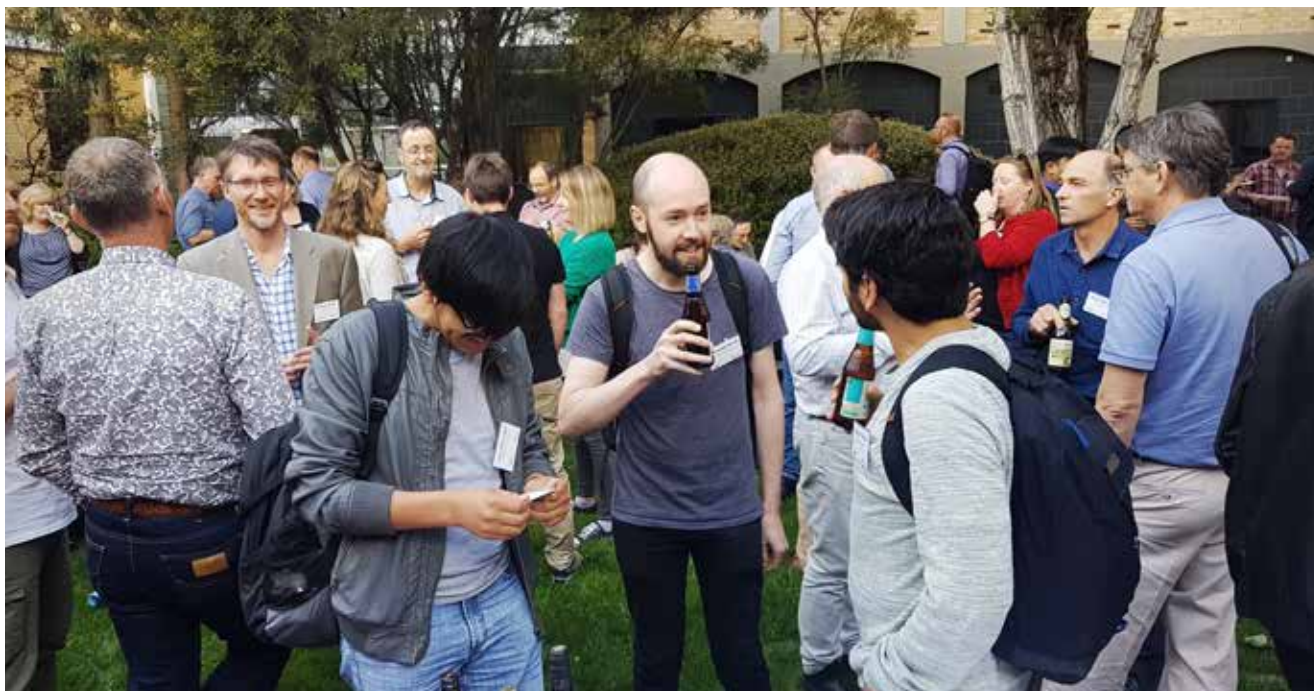
Professor Pat Quilty, a longtime stalwart of the CODES community, lost his battle with cancer in late August 2018. Pat was globally renowned as a pioneer of Antarctic scientific research, working for many years in the Australian Antarctic Division, where he was a former chief scientist. He won many awards during his illustrious career, including the United States Antarctic Services Medal in 1974, the Royal Society of Tasmania Medal in 1996 and the Phillip Law Medal in 2016. He was made a member of the Order of Australia in 1997. He is sorely missed by all who knew him at CODES.



Professor David Cooke (second from left) after receiving the Haddon Forrester King Medal at a ceremony held at the Academy of Science in Canberra during September. He and his wife Helen Cooke are pictured with Academy Secretary Physical Sciences, Emeritus Professor Jim Williams, and Paul Agnew from Rio Tinto.



Emeritus Professor Ross Large with Her Excellency Kate Warner, the Governor of Tasmania; Ross had just been presented with the Royal Society Medal for 2018 at a ceremony at Government House in Hobart.



Participants of the Garry Davidson Symposium enjoy some relaxation time at a BBQ hosted by the CODES SEG Student Chapter. The principal organiser, Robert Scott, is at left (wearing checked shirt under jacket).

The year ahead: 2019

We are looking forward to the appointment of two new profile staff members in Earth Sciences and CODES in 2019. One appointment will be in the fields of geoenvironment/geometallurgy, and the other will be in sedimentology, basin analysis, structural geology, metamorphic petrology, or tectonics. These new appointments will be female-only, to help us address a strong gender imbalance in our academic staff profile. Our new staff members will provide new research growth and student supervision opportunities for CODES and help to provide sustainability in teaching and administration in Earth Sciences.

In 2019 the CODES Master of Economic Geology course will celebrate 30 years of providing world-class teaching in the field of economic geology to students and industry professionals alike. The course has seen a resurgence in popularity in recent years, and in 2019 will be running four short courses instead of the usual three.

With regards to major research initiatives, 2019 will see the commencement of a major new project investigating the 4D architecture of the Cowal district in NSW, supported by Evolution Mining. We will distribute a new AMIRA research proposal in collaboration with iCrag, focussed on resistate minerals in sediment-hosted mineral systems. 2019 is the penultimate

year of our Australian Research Council's Industrial Transformation Research Hub, and we look forward to the TMVC staff and students working towards the finalisation of research sub-projects and increasing their emphasis on transferring research outcomes to our industry partners. A new research initiative focussed on pyrite geochemistry from the joint perspectives of exploration significance and evolution of the Early Earth is seeking funding support in 2019, as are initiatives into submarine volcanism and VHMS deposits. 2019 is likely to bring a series of new research and supervision opportunities and our team will embrace those opportunities while continuing to deliver major new findings in our ongoing research programs.



ABOVE: (Left) Professor David Cooke in full flight at the Evolution Chile Explore Congress 2018, Santiago, Chile, October. (Right) Participants in the 2018 Annual Review take a break from proceedings and view the many posters produced for the occasion, which took place at CODES in late November.

Profile and research structure

An overview

CODES was formed in 1989, and was known as the Australian Research Council (ARC) Centre of Excellence in Ore Deposits between 2005 and 2016. It is now known as CODES, the Centre for Ore Deposit and Earth Sciences. Based at the University of Tasmania, the Centre has grown substantially over the years and is now widely regarded as a global leader in ore deposit research and postgraduate training. It is home to 59 highly qualified research staff and 133 postgraduate students, further cementing its position as the largest university-based team of ore deposit researchers in the world.

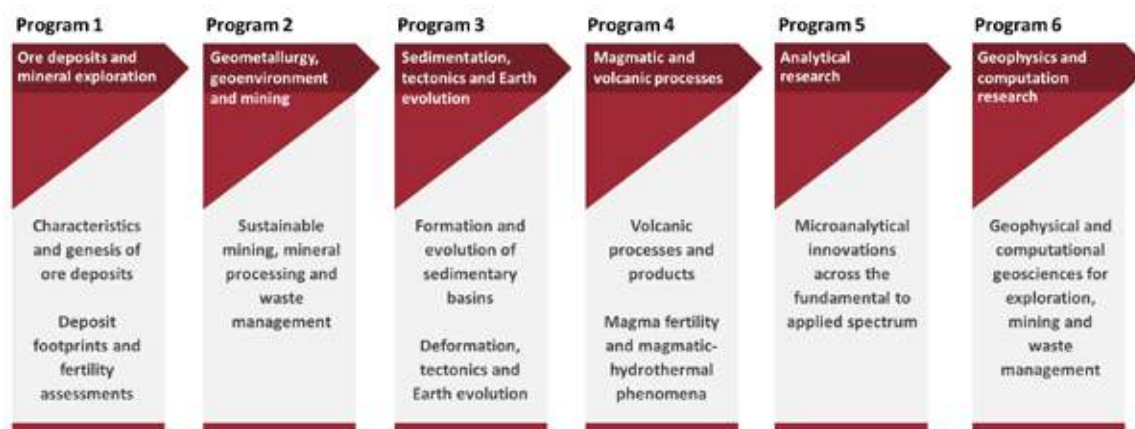
Highly productive worldwide collaborations have been developed with over 64 industry companies, plus a host of joint research initiatives with 128 institutions and universities – 27 in Australia and 101 overseas. It currently has 71 major research projects spanning 27 countries, and all seven continents. 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 194 reports to industry and conducting 21 short courses, workshops, conferences and field trips in four countries across the world as well as here in Australia.

Industry-focussed research and training

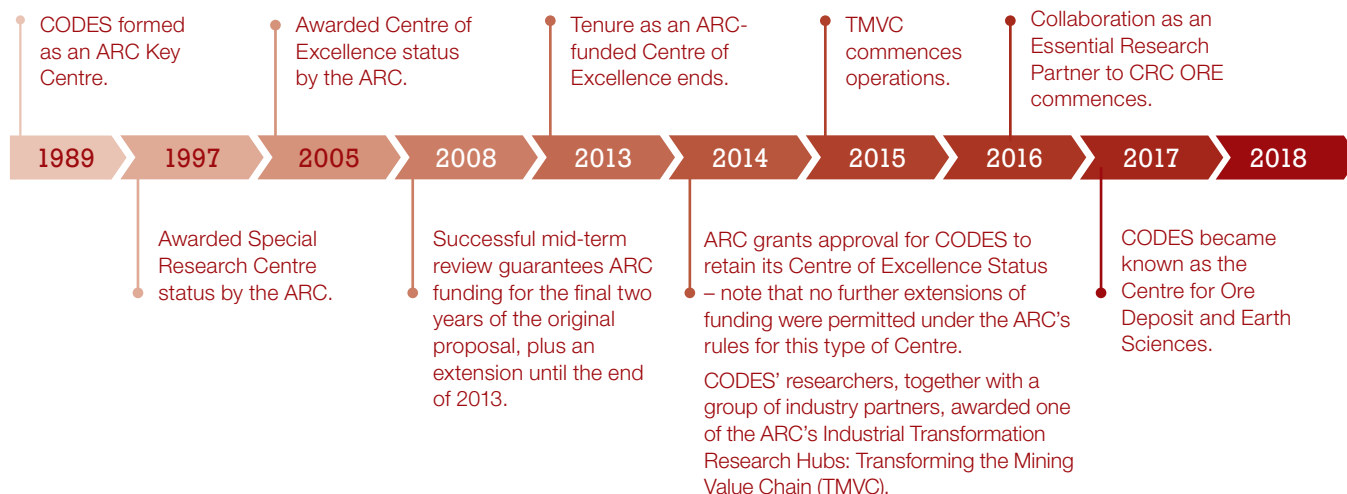
The transition in 2017 to our current six-program model, which now accurately reflects the breadth of CODES' present research activities, has been very successful. It provides a logical framework for CODES' role in developing exploration techniques for metal discovery, new practices for sustainable mining and a steady supply of world-class geoscience graduates, as well as creating a platform to meet the training and upskilling needs of the minerals industry.

CODES PROGRAM STRUCTURE

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



TIMELINE





CODES on top of the world: L-R: Ingemar Arellano (Freeport-McMoRan), Andrew Jedemann (Lakehead University), Lejun Zhang (CODES) and Patrick Hamilton (Lakehead University) during fieldwork for the AMIRA P1202 project, pictured at Pemberton Hills prospect, Vancouver Island, Canada.

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. Typical courses include Geophysics for Geologists and Engineers, and Advances in Geo-logging. 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. Or students can undertake a full Masters degree, which is available in coursework only and coursework/thesis (25%) options. The degree is part of the national Minerals Geoscience Masters (MGM) program.

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' state-of-the-art analytical facilities cover a wide range of applications, 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' leading edge is based on the development of a number of unique analytical techniques 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

CODES is home to an Australian Research Council Industrial Transformation Research Hub called Transforming the Mining Value Chain (TMVC). The Hub encompasses a wide array of activities from exploration, discovery, ore deposit characterisation, and environmental assessment, through to mining, ore processing and waste rock disposal. The main objective 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 2018

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, the Program Leaders, the TMVC Research Hub Manager, and the leaders of the training program. 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 a representative from all partner companies. The Annual Review is designed to provide industry with an opportunity to see the breadth of the research conducted at CODES and to influence future research directions.

Staff movements 2018

Appointments

Academic staff

Dr Shaun Barker joined CODES in July 2018 as Associate Professor of Economic Geology and leader of Program 3: Sedimentation, tectonics and Earth evolution. He was previously Senior Lecturer at the University of Waikato in Hamilton, New Zealand.

Dr Indrani Mukherjee completed her PhD during the year, and was appointed as a Postdoctoral Research Fellow working within Program 1.

Mr Francisco Testa returned to CODES in 2018 and was appointed as Postdoctoral Research Fellow in epithermal ore deposits.

Dr James Tolley was appointed as a Research Fellow in LA-ICP-MS in April 2018 working in Program 5: Analytical research.

Departures

Academic staff

Postdoctoral researcher in computational geophysics Dr Martin Gal left CODES in November to work with the Institute of Mine Seismology based in Kingston, Tasmania.

Dr Karin Orth is now focussing on teaching only and no longer has a research role.

Professor Pat Quilty sadly passed away in August 2018, and is fondly remembered by all those he worked with over many years at CODES and Earth Sciences.

Professor Anya Reading stepped down from her role as the leader of the Computational Geophysics and Earth Informatics research group in mid-2018 and moved to the Discipline of Mathematics and Physics within UTAS. She retains an adjunct role with CODES and Earth Sciences.



The Annual Review, held each year in November at CODES, gives staff, students, partner companies and representatives from geoscience organisations a chance to catch up on CODES' latest findings and to plan research and strategies for the coming year. Here Associate Professor Shaun Barker and Professor David Cooke give an overview of proceedings at the 2018 meeting.

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 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)	Geomaterials, geochemistry, mineralogy	100	*
Dr Trevor Falloon, BSc Hons (Canterbury), BTeaching, PhD (UTAS)	Marine geoscience, petrology	Hon	
Dr Nathan Fox, MSc Hons (Imperial), PhD (UTAS)	Ore deposit geology, environmental mineralogy and geomaterials	100	
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 Martin Jutzeler, MSc (U Lausanne), PhD (UTAS)	Volcanology and clastic sedimentology	50	
Dr Maya Kamenetsky, PhD (UTAS)	MLA-SEM, geomaterials, 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	25	
Dr Evan Orovan, BSc Hons (Carleton), PhD (UTAS)	Porphyry environment, mineral chemistry and hydrothermal geochemistry	100	*
Dr Anita Parbhakar-Fox, MSc Hons (London), PhD (UTAS)	Environmental geology, mineralogy, geochemistry	100	*
Professor Anya Reading, BSc Hons (Edinburgh), PhD (Leeds)	Geophysics, seismology, computational methods	50	*
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	
Dr Aleksandr (Sasha) Stepanov, MSc (Novosibirsk), PhD (ANU)	Geochemistry of rare metals	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	*

*Research percentage † TMVC affiliated



CODES staff and graduate students, including Master of Economic Geology students, pictured in October 2018 in the CODES Rock Garden at UTAS.

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	*
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 Julie Hunt	Mineral Deposit Research Unit (MDRU)	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
Adele Seymon	AMIRA International	*
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

Note: Research staff at CODES/TMVC were current as at 31 December 2018.

TECHNICAL/ADMINISTRATIVE STAFF

NAME		%*	TMVC†
Dr Ivan Belousov, BSc, MSc (Moscow), PhD (Vernadsky)	Research Associate – ARC TMVC Research Hub	100	*
Mrs Michele Chapple-Smith, Grad Dip App Sc (UTAS)	Lapidary Technician	60	
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	
Dr Jane Higgins, BIS, BAntSt Hons, PhD (UTAS)	Personal Assistant to the Director	100	
Dr Wei Hong, BSc (CUG), PhD (UTAS)	Research Assistant	30	
Ms Karen Huizing	Administrative Assistant	100	
Ms Elena Lounejeva, MSc (UNAM)	Laboratory Analyst	100	
Dr Charles Makoundi, MSc, PhD (UTAS)	Research Assistant and Laboratory Assistant	25	
Mrs Michelle Makoundi, B Acc (U Marien Ngouabi)	Laboratory Assistant	35	
Ms Caroline Mordaunt, BA Hons (King's London)	Administrative Assistant	60	
Dr Paul Olin, BA (SOU), MSc, PhD (WSU)	Laser Ablation Technician – ARC TMVC Research Hub	100	*
Mrs Claire Rutherford BBus (Acc) (RMIT)	Administrative Assistant – ARC TMVC Research Hub	60	*
Ms Helen Scott, BSc Hons (UTAS), BEd (QUT)	Hub Manager – ARC TMVC Research Hub	100	*
Mr Jay Thompson, BSc Hons, MSc (U Iowa)	Laboratory Analyst	100	
Ms Isabella von Lichtan, BSc Hons (UTAS)	Curator	25	
Dr Irina Zhukova, MSc (Novosibirsk), PhD (ANU)	Research Assistant and Laboratory Analyst	40	

ADVISORY BOARD

Chair: Paul Heithersay	Department for Energy and Mining, South Australia	Ned Howard	Evolution Mining (via phone)
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Rebecca Carey	Fundamental Research	Helen Scott	Administration
		Robert Scott	Education

Panorama of Mount Owen and Queenstown, western Tasmania, from Owen Spur.



ANNUAL REVIEW

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

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Andrew McNeill	Mineral Resources Tasmania
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Tim Rawlings	University of Melbourne
Anya Reading	Physics, UTAS
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Angela Rodriguez	Monash University
Adele Seymon	AMIRA International
Penny Sinclair	Vimy Resources
Roger Smart	Blue Minerals Consultancy
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Noel White	Consultant
Guo Xianzheng	(student) China University of Geosciences (Wuhan)
Mingyu Zhang	(student) Institute of Mineral Resources, CAGS
Zhiyuan Zhang	(student) Institute of Mineral Resources, CAGS



Top to bottom: Dr Matthew Cracknell, Dr Indrani Mukherjee and Dr Michael Roach all make their point during presentations at the CODES 2018 Annual Review.

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 nine 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 and its prior iterations within CODES have consistently retained a critical mass of projects, spread across a diverse range of geological fields, deposit types and locations. That trend has continued in 2018 with the carry-over of several major projects from previous years. 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 that commenced in late 2017 on the Lepanto quartz-pyrite-gold (QPG) veins in the Mankayan district, Philippines. In 2018 Yi completed his first major field campaign to collect samples from these newly discovered epithermal vein systems, located underneath and beside the Lepanto high sulfidation orebody. His ongoing work will look at gold deportment and alteration mineral chemistry within the vein systems. (See the TMVC section of this report for further details about Yi Sun's research.)

SE Asia

From 2017 to 2018, a 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 will be linked with the ARC Linkage project '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

PhD student Brian McNulty continued his research on the Myra Falls VHMS district on Vancouver Island, Canada. In 2018, Brian published a paper in the *Journal of Geochemical Exploration* titled 'Lithological discrimination of altered volcanic rocks based on systematic portable X-ray fluorescence analysis of drill core at the Myra Falls VHMS deposit, Canada'. PhD student Rob Davidson has also continued his research on the San Sebastian intermediate sulfidation epithermal vein system in Durango, Mexico, with the aims of understanding the structural, host rock, geochemical and hydrothermal controls on the deposit.

South America

In 2018 Juan Diego Rojas Lopez submitted his Master of Economic Geology project on the Ollachea deposit, situated in north Region Puno, southeast Peru. The results of Juan's research project indicated that three main paragenetic stages of gold-bearing veins and breccias occur at Ollachea, with the first stage being the principle stage for gold mineralisation.

Two Master of Economic Geology students commenced research projects in 2018: Carlos Diaz is working on the Cascabel porphyry deposit cluster in Ecuador, and Victor Torres is investigating the Soledad tourmaline breccia complex in the Cordillera Negra of central Peru.

Australia

David Douth has continued his PhD study on the geology and genesis of the Invincible Au deposit in the St Ives Goldfield, Kambalda, Western Australia, and expects to submit his thesis in 2019. Major highlights of David's research in 2018 include unravelling the structural history and vein and alteration mineral paragenesis at Invincible, as well as the development of a new structural model for the deposit.

The 'Power of pyrite' project operated across a series of sub-projects in 2018, including the use of laser ablation analysis of sulfides to ascertain new targets for exploration in sediment-hosted environments, such as the Stuart Shelf, and several PhD research projects. Former CODES PhD student Dan Gregory has also drafted a manuscript for publication in *Economic Geology* on the chemical characterisation of pyrites from a range of deposit types that have been analysed at the CODES LA-ICP-MS laboratory. This manuscript is scheduled for publication in mid-2019.

Two publications stemming from the PhD project by Wei Hong on Tasmanian tin granites were drafted during 2018, including one that details Heemskirk granite unidirectional solidification textures, and one that presents the results of boron and oxygen isotope geochemistry of tourmaline and quartz in tin granites. Both manuscripts will be published in 2019.

OPPOSITE PAGE: (TOP) Tourmaline breccia pipe, Breccia West, Soledad, Cordillera Negra, Peru. (BOTTOM) TMVC PhD student Yi Sun (left) and supervisor Dr Lejun Zhang examine the advanced argillic alteration overprint on the Buaki porphyry stockwork, Mankayan district, Philippines, as part of Yi's PhD research project.

The program team

LEADER MIKE BAKER

DEPUTY LEADER LEJUN ZHANG



TEAM MEMBERS:

Shaun Barker, Ron Berry, David Cooke, Matthew Cracknell, Leonid Danyushevsky, Angela Escolme, Nathan Fox, Bruce Gemmell, 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, Rob Davidson, David Douch, Peter Duerden, Amos Garay, Rachel Harrison, Jacob Heathcote, Joseph Knight, Erin Lawlis, Christopher Leslie, Claire McMahon, Brian McNulty, Indrani Mukherjee, Joshua Phillips, Subira Sharma, Emily Smyk, Nathan Steeves, Yi Sun, Francisco Testa, Jennifer Thompson, Tristan Wells

MASTERS STUDENTS:

Chloe Cavill, Carlos Diaz, Arga Firmansyah, Brendan Hardwick, Kyle Hughes, Corey Jago, Juan Diego Rojas Lopez, Victor Torres

HONOURS STUDENTS:

Hamish Cowie, Colin Jones, Ben Kowaluk, Fatin Amni Mohamed Amin, Emmet O'Keefe, Ben Ridgers, Riquan Ropli, Xin Ni Seow, Matthew Vincent

COLLABORATORS:

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Akira Imai

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David Busch, Todd McGilvray

AUSTRALIAN MUSEUM

Lin Sutherland

BRITISH GEOLOGICAL SURVEY, UK

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MANDALAY UNIVERSITY, MYANMAR

Tin Aung Myint

MANITOBA GEOLOGICAL SURVEY, CANADA

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MINERAL RESOURCES TASMANIA

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Ray Cas

NANYANG TECHNOLOGY UNIVERSITY, SINGAPORE

Grahame Oliver

NEW BOLIDEN

Rodney Allen, Georgian Manuc, Roger Nordin

NEWCREST MINING

Karyn Gardner, Anthony Harris

NYRSTAR

Rick Sawyer, Armond Stansell

PIONEER RESOURCES

David Crook

QPX

Nic Jansen

ROYAL HOLLOWAY UNIVERSITY OF LONDON, UK

Tony Barber, Ian Watkinson

SANDFIRE RESOURCES

Bruce Hooper

SOLGOLD

Steve Garwin, Santiago Vaca

TINTINA RESOURCES

Jerry Zieg

UNIVERSITAS PADJADJARAN, INDONESIA

Mega Rosana

UNIVERSITI BRUNEI DARRUSALAM, BRUNEI

Kit Chun Lai

UNIVERSITI KEBANGSAAN, MALAYSIA

Mohd Basril Iswadi Bin Basori, Mohd Shafeea Leman

UNIVERSITY OF CALIFORNIA RIVERSIDE, USA

Dan Gregory

UNIVERSITY OF GENEVA, SWITZERLAND

Robert Moritz

UNIVERSITY OF MALAYA, MALAYSIA

Azman Ghandi

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 SYDNEY

Dietmar Müller, Sabin Zahirovic

UNIVERSITY OF TASMANIA

Clive Burrett



Master of Economic Geology student Juan Diego Rojas Lopez preparing to take a sample of a mafic dyke for zircon U-Pb geochronology at the Ollachea deposit, Peru, January 2018, as part of his Masters research project.



View from the Soledad tourmaline breccia to the Hercules epithermal deposit, Cordillera Negra, Peru, visited by Masters student Victor Torres and CODES Director David Cooke during fieldwork in late 2018.

Projects

Geology and genesis of the Invincible gold deposit, St Ives

Geology and genesis of the mineral deposits of the Myra Falls VHMS district, Canada

Origin, characteristics and age of mineralisation of the Ollachea orogenic gold deposit, Region Puno, southeastern Peru: Implications for exploration

The power of pyrite

Tectonic and mineral resources of Sumatra and 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 Douch

Collaborator: Ray Cas

David Douch's PhD study, funded by Gold Fields, is investigating the geology and genesis of the >1 Moz Au Invincible deposit in the St Ives Goldfield, Kambalda, WA. This deposit differs from most in the >12 Moz Au St Ives Goldfield, as it 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), which host the vast majority of the known deposits. This project seeks to better understand stratigraphic and structural controls on gold mineralisation at Invincible, unravel the deposit paragenesis, characterise the geochemical footprint of the deposit, and develop criteria to guide future exploration.

David's initial work focussed on refining the internal stratigraphy of, and stratigraphic relationships in, the upper Black Flag Group (BFG) and overlying lower Merougil Formation. A laterally discontinuous black shale unit at the top of the BFG is the primary host to ore at Invincible.

In 2018, David Douch completed all remaining fieldwork and analytical studies for his PhD study. He continued work commenced in 2017 which led to the recognition of two distinct stages of gold mineralisation at the deposit. Work in 2018 was aimed at further characterisation of the vein and alteration mineral assemblages, and likely ore fluid chemistries, associated with each. In particular, David's detailed paragenetic and mass-balance studies, which investigated both growth sequence and composition of minerals at the deposit, and geochemical changes in the wall rocks as a result of alteration, provide important new constraints on the timing and origin of previously identified geochemical dispersion haloes around the Invincible deposit. Further work on the mineralised veins also led to the development of a new structural model for the deposit.

GEOLOGY AND GENESIS OF THE MINERAL DEPOSITS OF THE MYRA FALLS VHMS DISTRICT, CANADA

Leaders: Nathan Fox, Bruce Gemmell

Student: Brian McNulty

Collaborators: Rick Sawyer, Armond Stansell

Brian McNulty neared the completion of 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 2018. 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 2018 Brian published a paper, co-authored with Nathan Fox, Ron Berry and Bruce Gemmell, entitled 'Lithological discrimination of altered volcanic rocks based on systematic portable X-ray fluorescence analysis of drill core at the Myra Falls VHMS deposit, Canada' in the *Journal of Geochemical Exploration*. His results indicate that both pXRF sampling methods reproduce the laboratory-based XRF results for Ti and Zr, and that there is no significant improvement in accuracy or precision between drill core powders and unprepared drill core samples. He proposed a calibration, estimation of total measurement uncertainty, and data reduction procedure for systematic three-spot pXRF analysis of drill core samples to improve lithological logging of altered volcanic rock types. Brian suggested that pXRF analysis become a routine part of lithology logging providing, for some key elements, robust and time-efficient chemical analyses with results that can be used to define important, often cryptic, lithological boundaries, and that portable XRF has the ability to improve geological and stratigraphic interpretations, which are vital for developing mineral exploration models, for VHMS deposits and other economic mineral systems.

ORIGIN, CHARACTERISTICS AND AGE OF MINERALISATION OF THE OLLACHEA OROGENIC GOLD DEPOSIT, REGION PUNO, SOUTHEASTERN PERU: IMPLICATIONS FOR EXPLORATION

Team members: Angela Escolme, Robert Scott

Student: Juan Diego Rojas Lopez

The Ollachea deposit, situated in north Region Puno, southeastern Peru, contains >2.4 Moz Au with an average grade of 3.5 g/t Au. Mineralisation is hosted within slates belonging to the Silurian-Devonian Ananea Formation, and locally within metamorphosed igneous dykes and sills. At a regional scale, the deposit is located in the western margin of an orogenic belt that extends along the northwest-trending Eastern Cordillera of the Andes.

This Master of Economic Geology project, funded by a PRONABEC Scholarship, was submitted for examination in late 2018. The project documented the characteristics of the Ollachea deposit, constrained the age of mineralisation and developed a new genetic model. During 2018, Juan completed a second field season and laboratory studies including LA-ICP-MS

and sulfur and lead isotope analysis on a range of sulfides. Juan's observations and data indicate that three main paragenetic stages of gold-bearing veins and breccias occur at Ollachea, and gold is predominantly associated with the first stage, with evidence for local remobilisation. Sulfide trace element data and sulfur isotopic compositions provide evidence of formation from sedimentary-sourced fluids and incorporation of biogenic sulfur.

THE POWER OF PYRITE

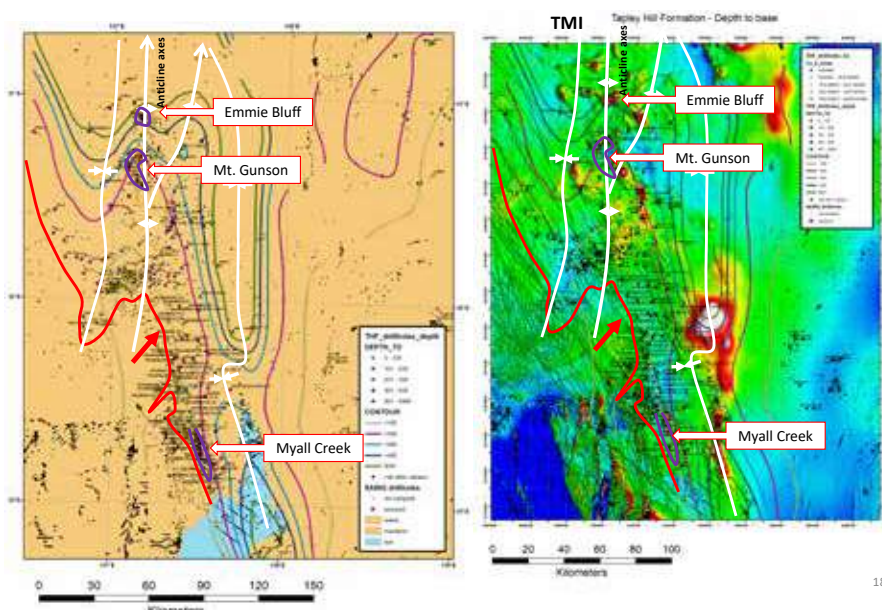
Leaders: Ross Large, Indrani Mukherjee, Jeff Steadman

Team members: Matthew Cracknell, Leonid Danyushevsky, Charles Makoundi, Sebastien Meffre

Collaborators: Rodney Allen, David Busch, David Crook, Frank Doedens, Adrian Fabris, Dan Gregory, Steve Hill, Bruce Hooper, Georgian Manuc, Todd McGilvray, Roger Nordin, Dermot Ryan, Tom Woolrych, Jerry Zieg

The research in 'The power of pyrite' project is split into the following sub-projects:

- Using pyrite as a vector to stratiform copper on the Stuart Shelf.



Maps showing the area of Stuart Shelf, South Australia, where the 'Power of pyrite' project evaluated sedimentary pyrite as a vector to copper mineralisation in the base of the Tapley Hill Formation. The left-hand map shows positions of major sedimentary copper deposits, drill holes and structure contours on the base of the Tapley Hill Formation. The right-hand map is the same data superimposed on a total magnetic intensity image.



Professor Khin Zaw (left) and geologists from Myanmar working in the country's Mandalay-Pyin Oo Lwin District, Southern Shan State, where they were investigating Devonian ocean chemistry, gold enrichment and the provenance of sediments in the Sibumasu Terrane using U-Pb detrital zircon and pyrite chemistry of Devonian formations.

- Multi-client industry research on 'Characterizing pyrite chemistry of black shales hosting stratiform Zn-Pb-Ag and stratiform Cu deposits: Application to mineral exploration'.
- Publication of previous research on using pyrite chemistry to discriminate ore types.

- Various PhD projects on using pyrite geochemistry to determine metal paragenesis.

The first of these sub-projects is a collaboration with DGO Gold who funded a case study on pyrite chemistry in the Tapley Hill Formation throughout the Stuart Shelf. The aims

of this nine-month research project have been to use a new technology developed at CODES – laser analysis of sedimentary pyrite – to produce criteria for exploration vectoring of sediment-hosted copper-cobalt ores on the Neoproterozoic Stuart Shelf, and to use this method to define targets for further deposits. Three stratiform Cu-Co deposits, Myall Creek, Mt Gunson and Emmie Bluff, occur on the Stuart Shelf in a NNW-trending corridor 40 km wide and at least 300 km long. Copper sulfides occur at the base of the Neoproterozoic Tapley Hill Formation black shales where they on-lap the Mesozoic Pandurra Formation redbeds. Forty-two drill holes were sampled, followed by detailed paragenetic studies and laser ICP-MS analysis of sedimentary pyrite.

Laser pyrite chemistry in the Tapley Hill Formation has been highly successful in defining the ore body halo footprint, and developing vectors to ore. Anomalous trace elements in pyrite extends about 10 km beyond the deposits. The Pb isotope 207/206 ratio measured on pyrite also provides a target signature that is distinct from the background Pb. Two new target areas were defined by the research.

The multi-client industry research sub-project proposal on 'Characterizing pyrite chemistry of black shales hosting stratiform Zn-Pb-Ag and stratiform Cu deposits: Application to mineral exploration' attracted seven sponsor companies and one geological survey. We are hoping for more companies and surveys to become involved. The project is planned to commence in mid-2019. The focus will be split 50/50 between a) case studies on sediment-hosted Zn-Pb and Cu districts, and b) characterising pyrite chemistry in greenfield black shale formations to test their potential to host stratiform mineralisation.

Dan Gregory, now at the University of Toronto, has led the development of a comprehensive paper on characterising pyrite chemistry of different ore types based on the CODES pyrite LA-ICP-MS database. Machine learning techniques have been applied to enable the discrimination. This paper is due for publication in *Economic Geology* in mid-2019.

TECTONIC AND MINERAL RESOURCES OF MYANMAR TERRANES

Leader: Khin Zaw

Team members: Ross Large, Charles Makoundi, Sebastien Meffre, Jay Thompson

Collaborators: Tony Barber, Mohd Basril Iswadi Bin Basori, Clive Burrett, Pol Chaodumrong, Cho Cho Aye, Mike Crow, Hai Thanh Tran, Akira Imai, Somboon Khositanont, Kit Chun Lai, Phisit Limtrakun, Robert Moritz, Tin Aung Myint, Abhisit Salam, Lin Sutherland, Chakkaphan Sutthirath, Ye Myint Swe, Ian Watkinson, Sabin Zahirovic

This research builds on previous 'Ore deposits of SE Asia' projects (2008–2017) and the Geological Society of London (GSL) publication called *Myanmar: Geology, Resources and Tectonics* edited by A.J. Barber, Khin Zaw and M. Crow. This publication draws on the project leader's extensive geological experience in Myanmar over the past 40 years.

The new project focused in 2018 on the geochronology, metallogenesis and deposit styles such as porphyry-epithermal, Sn-W, orogenic Au and VHMS deposits of the Myanmar Region. It will look mainly at the tectonic, zircon geochronology, whole rock geochemistry, pyrite chemistry, mineralisation and metallogeny of the Western Myanmar and Sibumasu Terranes. This proposed project will be linked with the ARC Linkage project 'Geochemical, isotopic, hyperspectral and geochronological constraints on the metallogenic evolution of VHMS deposits of Australia and SE Asia: Enhancing the exploration potential and discovery'.

EPITHERMAL RESEARCH

Team members: David Cooke, Bruce Gemmell

Student: Rob Davidson

Collaborators: Kurt Allen, Stephen Redak

Rob Davidson continued his PhD research on the San Sebastian intermediate sulfidation epithermal vein system in Durango, Mexico, in 2018.

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 toward mineralisation; and date, using a range of geochronological methods on the veins, host rocks and alteration.

While not the only Mexican epithermal deposit hosted within Mesozoic sediments, there is a lack of published research addressing the alteration footprints that these types of systems leave within sedimentary rocks.

Research was focussed on the samples collected during his 2017 fieldwork, and included an initial 3D structure and geology interpretation, 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 pilot study and initiation of age dating of the regional volcanic rocks. These analytical techniques will be applied to a set of 1,502 samples from diamond drill core and RC chips systematically collected along five representative cross-sections roughly 500 metres apart. A second field season is planned for early 2019.



Masters student Carlos Diaz (background, right) and industry supervisors, Leonardo Aguilar (background, left), Steve Garwin (right) and Santiago Vaca (leaning forwards with a SolGold employee behind him) examining the discovery outcrop of the world-class Alpala porphyry Cu-Au deposit, Cascabel district, Ecuador.

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

CODES continues to have a strong emphasis on research into porphyry copper-gold deposits and related deposits. In 2018, two new Master of Economic Geology students (Carlos Diaz and Victor Torres) joined our program and are conducting research into some of the exciting new discoveries of Cu-Au mineralisation in South America.

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. Carlos is conducting a campaign of 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 will help to guide ongoing exploration in the district and broader region.

Victor Torres is investigating the Soledad tourmaline breccia complex in the Cordillera Negra of central Peru. He is being supported by Chakana Copper Corp, who are testing the economic potential of the breccia pipes. A 16,000 m drill program was initiated in 2017 to determine the geometry of several previously drilled pipes, determine the true grade profile by drilling across the pipes, define an initial inferred resource on two of the pipes, and to test several targets across the property. Exploration is ongoing, and Victor is integrating data from the new drilling program to help evaluate the origins and exploration potential of the district.



A SolGold drilling rig working in the Alpala deposit, Cascabel, Ecuador, visited during Carlos Diaz's fieldwork with geologists from SolGold.



Masters student Victor Torres pictured in mid-December 2018 examining a mineralised Cu-Au-Ag tourmaline breccia pipe called Bx3 West, one of the 18 identified breccias at the Soledad project, central Peru, which will be drilled in the next program in June 2019.

TASMANIAN TIN GRANITES

Leader: David Cooke

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

Student: Wei Hong

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.

Research activities in 2018 focussed on two draft manuscripts that detail research outcomes from the PhD study. An article focussed on the characteristics, origins and significance of unidirectional solidification textures from the Heemskirk granite was accepted for publication in *American Mineralogist*. A second manuscript that details the boron and oxygen

isotope systematics of tourmaline and quartz from magmatic-hydrothermal textures in Sn granites was accepted for publication in *Mineralium Deposita*. Both manuscripts are scheduled for

publication in 2019. A manuscript detailing fluid inclusion characteristics of the magmatic-hydrothermal textures was submitted for review by *Economic Geology*.

Looking forward

Program 1 will look to continue its diverse slate of projects into 2019, along with the commencement of some exciting new projects, as outlined above. The 'Power of pyrite' project will be launching a new sub-project focussed on pyrite mineral chemistry in black shales hosting base metal deposits. Having already attracted several industry and government sponsors, it is planned to commence in mid-2019.

David Douth is expected to submit his PhD thesis on the St Ives Goldfield in mid-May 2019.

Khin Zaw and the SE Asia research team will be aiming to commence a new multi-year project investigating the tectonic and mineral resources of Myanmar terranes. While our postgraduate students will continue their research projects, including Rob Davidson on the San Sebastian epithermal deposit, Mexico, and Yi Sun on the Lepanto QPG veins, Philippines.

It also promises to be another excellent year for scientific reporting to the wider academic community, with a number of journal articles nearing publication, and graduate student theses nearing completion.

Program Two

Geometallurgy, geoenvironment and mining

Objectives

- 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

The minerals industry faces challenges 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 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^{III}) projects collaboratively run with the JKMRRC, 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^{III} project provided a solid foundation for further research, particularly in relation to understanding mineralogical and textural controls over a range of scales, which dictate Grade Engineering® and mineral processing responses. This

research is largely being conducted 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 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 predictive geometallurgical 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 three PhD projects. 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.

Highlights

- Completion of Cassidy Harraden's PhD thesis on the geotechnical and geometallurgical assessment of drill core using Corescan automated core logging technology (sits within TMVC Theme 2).
- Publication of the *Minerals* special issue on Geometallurgy, co-edited by Dr Anita Parbhakar-Fox, Dr Simon Dominy and Dr Louisa O'Connor with several articles from CODES researchers.
- Co-chairing of the Geochemistry of Mineral Deposits Gordon Research Seminar (GRS) by Dr Angela Escolme and TMVC PhD student Ayesha Ahmed in August in New Hampshire, USA. Angela also presented on geometallurgy themes for two in-house workshops for Lepanto Consolidated Mining Ltd, Philippines, and Anglo American, Vancouver.
- Completion of Hannah Couper's Honours thesis on gold deportment at West Dome, Telfer (sits within TMVC Theme 2).
- Completion of Sarah Gilmour's Honours thesis on evaluating the environmental impacts of historical slag on Tasmania's west coast (sits within TMVC Theme 3).
- Associate Professor Ron Berry presented at a geometallurgy workshop in collaboration with MDRU in Vancouver in May.

OPPOSITE PAGE: (TOP) TMVC PhD student Sibebe Nascimento undertaking fieldwork at Macquarie Harbour on Tasmania's west coast as part of her research into the geoenvironmental characterisation of historic mine tailings. (see TMVC section of this report for further details about Sibebe's PhD research). (BOTTOM) Drill core from AngloGold Ashanti's Sunrise Dam Au deposit, Western Australia, studied by Nathan Fox in connection with his CRC ORE research.

- CODES Society of Economic Geologists (SEG) Student Chapter organised a one-day course titled 'Metallurgy for geologists' taught by Diana Drinkwater and Peter Munro of Mineralis.
- Dr Nathan Fox and PhD students Amery Jackson and Paulina Dobrowolska attended a CRC ORE workshop and planning meeting for the P1-006 'Predictive geometallurgical controls on grade by size fractionation' project in Brisbane.
- Professor David Cooke presented at the CRC ORE Annual Assembly in Brisbane, which was also attended by PhD student Paulina Dobrowolska.
- Dr Anita Parbhakar-Fox attended Process Mineralogy '18 and the 11th International Conference for Acid Rock Drainage (both of which were held in South Africa), and Dr Angela Escolme attended Resources for Future Generations, Vancouver.
- Dr Anita Parbhakar-Fox was co-awarded the Materials World Medal from the UK Institute of Mining, Materials and Minerals.

Technology transfer

Dr Angela Escolme was able to deliver a geometallurgy workshop onsite for Lepanto Consolidated Mining Ltd where the geology team was given an introduction to geometallurgy and an overview of their processing plant with consideration to challenges and opportunities. In June, Anglo American hosted Angela to provide an overview of modal mineralogy prediction from assay at their Vancouver office as part of an internal workshop and she also participated in several workshops with AMIRA P1202 sponsors as part of the project kick-off.

Building on TMVC and CRC ORE outcomes, Dr Anita Parbhakar-Fox and Dr Nathan Fox met with several new technology and software providers (e.g., Orexlore, Minerals Insights, Imago) and CSIRO – Floreat Environment Laboratories (Dr Anna Kaksonen) to discuss



Associate Professor Ron Berry presents a geometallurgy practical short course at MDRU's city campus in Vancouver, Canada, in May 2018.

applications for new technologies for predicting mineral reactions to understand geometallurgical and geoenvironmental characteristics to improve mine planning. Dr Nathan Fox, Paulina Dobrowolska and Amery Jackson participated in CRC ORE workshops where research planning was undertaken in collaboration with industry partners. Dr Anita Parbhakar-Fox also gave a public seminar in Hobart as part of the international 'Pint of Science' week where she discussed mine waste issues in Tasmania and how, as a global community, more opportunities for repurposing waste need to be sought.

Short courses

Dr Angela Escolme was instrumental in organising an SEG Student Chapter-sponsored course taught by Diana Drinkwater and Peter Munro of Mineralis, Brisbane. The course was well attended by staff, students and industry professionals – a number of whom travelled interstate for the course. Participants benefitted from Diana and Peter's extensive knowledge and experience delivered in a format accessible to geologists.

Conferences

Dr Anita Parbhakar-Fox and Dr Angela Escolme presented research outcomes from Themes 2 and 3 of the ARC TMVC Hub at a number of international conferences including the inaugural Resources for Future Generations in Canada, the Gordon Research Conference in New Hampshire, the 12th International Conference on Acid Rock Drainage in Johannesburg and Process Mineralogy '18 in Cape Town, with peer-reviewed conference abstracts and publications associated with several of these. Presentations given were on a range of topics including:

- research outcomes from Sarah Gilmour's Honours research on the geoenvironmental properties of the Zeehan and Mt Lyell slag in Western Tasmania;
- Laura Jackson's PhD research demonstrating the integration of mineral chemistry with hyperspectral data for geoenvironmental domaining;
- Dr Angela Escolme's research on calculating mineralogy from assay;
- Cassady Harraden's work on utilising Corescan data to determine geotechnical properties; and
- Dr Anita Parbhakar-Fox's experimental work on a modified net acid generation test.

The program team

LEADER ANITA PARBHAKAR-FOX

DEPUTY LEADER ANGELA ESCOLME



TEAM MEMBERS:

Ron Berry, David Cooke, Matthew Cracknell, Leonid Danyushevsky, Nathan Fox, Sebastien Meffre, Paul Olin, Michael Roach, Jay Thompson

PHD STUDENTS:

Paulina Dobrowolska, Kyle Eastman, Cassady Harraden, Amery Jackson, Laura Jackson, Javier Merrill, Annah Moyo, Sibebe Cristina do Nascimento, Yi Sun

HONOURS STUDENTS:

Rebekah Cornelius, Hannah Couper, Sarah Gilmour, Robert McLaine

Dean's Summer Scholarship student: Le Xi K ng

COLLABORATORS:

ALS GLOBAL

John Glen, Bonita Raimondo

ANGLOGOLD ASHANTI

Alvaro Barros, Vaughan Chamberlain, Nick Clarke

BRUKER AXS

Gertruida Gloy

CENTRAL SCIENCE LABORATORY (UTAS)

Sandrin Feig, Karsten Goemann

CRC ORE

Paul Revell, Steve Walters, Greg Wilkie

CSIRO

Louise Fisher, Carsten Laukamp, Mark Pearce

CURTIN UNIVERSITY

Louisa O'Connor

DEPT OF PRIMARY INDUSTRIES, PARKS, WATER AND ENVIRONMENT, TASMANIA

Alison Hughes

GOLD MINES OF WALES, UK

Simon Dominy

GRANGE RESOURCES

Tony Ferguson, Roger Hill, Ben Maynard

JULIUS KRUTTSCHNITT MINERAL RESEARCH CENTRE/UNIVERSITY OF QUEENSLAND

Cathy Evans

MINERAL INSIGHTS

Jim Kendall

MINERAL RESOURCES TASMANIA

Ralph Bottrill, Jake Moltzen

NATIONAL RESEARCH COUNCIL OF CANADA, QUEBEC, CANADA

Alain Blouin

OLYMPUS AUSTRALIA

Aaron Baensch, Jake Jarvinen

OREXPLORE

Rob Downard, Russell McChesney

PETROLAB, UK

Christopher Brough, Corinne Gardner, James Strongman

SARACEN GOLD MINES PTY LTD

Tim Sanders

TERRACORE

Phil Harris

UNIVERSITY OF BRITISH COLOMBIA, CANADA

Julie Hunt

UNIVERSITY OF CAPE TOWN, SOUTH AFRICA

Megan Becker, Dee Bradshaw, Sue Harrison

Projects

Extracting cobalt from legacy mine tailings

Controls on mineralogical fractionation at the Gramalote Au deposit, Colombia

Geometallurgical controls on mineralogical fractionation in porphyry copper deposits

Geological controls on gold fractionation at the Carosue Dam deposit, WA

LIBS analysis for geo-sensing

New technologies for ore and waste characterisation

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



Project summaries

EXTRACTING COBALT FROM LEGACY MINE TAILINGS

Leader: Anita Parbhakar-Fox

Collaborators: Sandrin Feig, Tony Ferguson, John Glen, Roger Hill, Alison Hughes, Ben Maynard, Bonita Raimundo

At the Old Tailings Dam (OTD), Savage River, western Tasmania, 38 Mt of pyritic tailings were deposited (1967 to 1982) and have since been generating acid and metalliferous drainage (AMD). Mineral chemistry analysis confirmed high concentrations of refractory cobalt in pyrite (up to 3 wt %). This research sought to determine, through a series of bench scale tests, if Co could be liberated using biohydrometallurgical techniques. Four bulk tailings samples were collected across the OTD, from up to 1.5 m depth, targeting three sulfide-bearing facies. The study was conducted in four stages: (1) bacterial adaption using BIOX[®] bacteria; (2) biooxidation optimisation with pH, temperature and Fe medium parameters tested; (3) flotation test work to produce a sulfide concentrate followed by biooxidation; and (4) Fe and Co precipitation tests. The BIOX[®] culture adapted to the bulk composite (containing 7 wt % pyrite) in ~10 days, with biooxidation occurring most efficiently at pH 1.5–1.6 and 40 °C whilst the Fe medium concentration was identified as a less-controlling parameter. Flotation produced a 71% pyrite concentrate with total oxidation occurring after 14 days of biooxidation with 99% of Co leached. At pH 3, Co was effectively separated from Fe; however, Ni and Cu were also present in the pregnant liquor solution and therefore required refining before production of cobalt hydroxide, the intermediate saleable product.



Accelerated hydrogen peroxide testing on mine waste materials conducted as part of an ATSE-funded project led by Dr Anita Parbhakar-Fox on improving column feed characterisation prior to kinetic testing.



L–R: Steve Scott (MMG), Sebastien Meffre and Dean's Summer Scholarship student Le Xi K ng (Lexi) at the Bobadil tailings storage facility, Rosebery, discussing sampling plans for Lexi's Honours thesis, which will look at the potential for reprocessing the tailings and which she will carry out in 2019.

This study showed that adopting a geometallurgical approach to tailings characterisation can identify if mine waste has commodity potential and how best to extract it, therefore unlocking the potential for unconventional rehabilitation of AMD-affected sites. The results have assisted the Tasmanian Government and Grange Resources in deciding on the future management of this site.

CONTROLS ON MINERALOGICAL FRACTIONATION AT THE GRAMALOTE AU DEPOSIT, COLOMBIA

Leader: Nathan Fox

Student: Amery Jackson

Team member: Matthew Cracknell

Collaborators: Alvaro Barros, Vaughan Chamberlain, Nick Clarke, Phil Harris, Steve Walters, Greg Wilkie

Amery Jackson began his PhD project in November 2017 to evaluate the geological controls on natural fractionation of gold during breakage in drill core tests and in bulk samples. Amery has utilised a range of drill core characterisation tools including hyperspectral mineralogy and Equotip hardness analysis to determine variability in rock properties across

multiple drill core intercepts from Gramalote. The relationship between these characteristics is integrated with detailed geological logging of mineralisation and alteration paragenesis to determine the geological drivers for gold fractionation. The research outputs from the project will be to identify the site-specific geological features that control grade by size fractionation, and to generate geometallurgical indices for predicting upgrade response in other parts of the ore system.

GEOMETALLURGICAL CONTROLS ON MINERALOGICAL FRACTIONATION IN PORPHYRY COPPER DEPOSITS

Leader: Nathan Fox

Student: Paulina Dobrowolska

Team member: Michael Roach

Collaborators: Steve Walters, Greg Wilkie

Paulina joined CODES in June 2018 to carry out her PhD project investigating the geological controls on mineral fractionation in porphyry copper deposits. Paulina's project will focus on several world-class porphyry copper systems, including Los Bronces, Chile,

to identify the mineralogical and textural controls on ore breakage and mineral fractionation. The outcomes of the project will include enhanced tools for predicting amenability to mineral fractionation in porphyry copper deposits to enhance understanding of the amenability of ore domains to grade by size fractionation.

GEOLOGICAL CONTROLS ON GOLD FRACTIONATION AT THE CAROSUE DAM DEPOSIT, WA

Leader: Nathan Fox

Collaborators: Tim Sanders, Greg Wilkie

The Carosue Dam Au deposit is located in the Eastern Goldfields of Western Australia. Gold is hosted by volcanoclastic units and is spatially associated with monzonitic intrusions and an alteration style similar to alkalic porphyry deposits. A test program was implemented to evaluate the geometallurgical characteristics of drill core intervals. Physical test work using constrained crushing and sizing conditions allowed the geometallurgical attributes to be correlated to the measured Au fractionation response in high- and low-grade domains. Final reporting is due in 2019.



Participants of the inaugural Gordon Research Seminar, held at Waterville Valley, New Hampshire, in the USA. The seminar, which focussed on the geochemistry of mineral deposits, was co-chaired by Dr Angela Escolme (pictured tenth from left in front row); on her left is CODES PhD student Ayesha Ahmed (wearing dark top), who co-chaired the seminar with her. Angela's poster shown at the GRS and titled 'Productora Cu-Au-Mo deposit, Chile – a porphyry related magmatic hydrothermal breccia complex' was linked with Program 2 research.

LIBS ANALYSIS FOR GEO-SENSING

Leader: Alain Blouin (National Research Council of Canada)

Team member: Nathan Fox

Collaborator: Greg Wilkie

This is a proof of concept study to develop a Laser Induced Breakdown Spectroscopy (LIBS) and Mid-Infrared (Mid-IR) Quantum Cascade Laser (QCL) for rapid mineralogical analysis suitable for on-belt/in-line sensing of ores. Contributions to the project include test sample selection and characterisation (MLA, XRD, XRF-ICP-MS) for the testing and calibration of the LIBS-QCL system at the National Research Council of Canada in Quebec. Research outputs will be published by the NRC-CRC ORE in *Minerals Engineering* in 2019.

NEW TECHNOLOGIES FOR ORE AND WASTE CHARACTERISATION

Leaders: Nathan Fox, Anita Parbhakar-Fox

Collaborators: Megan Becker, Christopher Brough, Rob Downard, Cathy Evans, Louise Fisher, Corinne Gardner, Gertruida Gloy, Karsten Goemann, Sue Harrison, Jim Kendall, Russell McChesney, Mark Pearce, Paul Revell, James Strongman

The Orexplora Geocore X10 instrument combines X-ray high-resolution 3D imaging and accurate geochemistry analysis to provide information on the intact characteristics of drill core materials. To test potential applications, drill core materials used 1) in kinetic trials and 2) from a gold and copper system were characterised to determine if sulfides could be identified and this data used to improve geometallurgical and geoenvironmental predictions. Results showed that sulfides could be effectively identified with algorithms developed to extract 3D textural parameters and mineral associations. A new visible optics device called Minerals Insights

was also tested for identification of Au and sulfide species using materials from several porphyry deposits. Results were compared to MLA data indicating Mineral Insights was able to accurately determine particle size, shape and mineral association. Integration of automated mineralogy tools for kinetic column feed characterisation continued with biokinetic trials commenced at the University of Cape Town and laser ablation ICP-MS performed to determine absolute trace metal concentrations for the sulfides present in the waste materials collected from three mine sites in western Tasmania, Africa and Finland.

Looking forward

With the reappointment of Dr Julie Hunt at CODES to take over as leader of the CRC ORE project from May 2019, the strength of this program is expected to grow, particularly as the current students in this program progress through their research projects and new projects are initiated.

Both Julie Hunt and Ron Berry are co-editors of the forthcoming *Economic Geology* special issue on Geometallurgy with contributions from Cassidy Harraden and Angela Escolme, which is expected to be published in 2019. In November 2019, the highly successful and popular Master of Economic Geology short course on Geometallurgy will be run. This two-week course, which includes a field excursion, will include the most popular elements from previous courses as well as new material from discipline experts, and is predicted to be equally as popular as previous offerings.



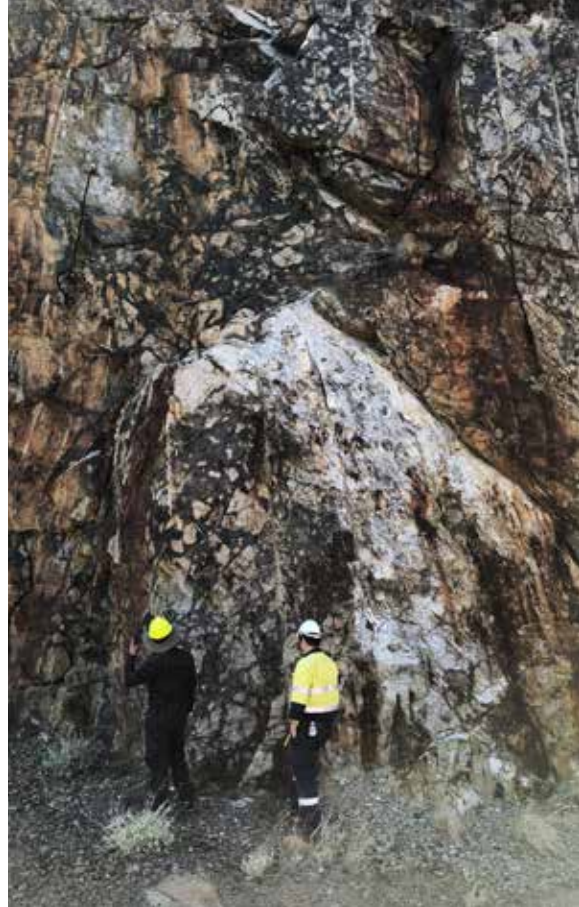
Dr Anita Parbhakar-Fox trench sampling sediments in Macquarie Harbour where mine tailings from Mount Lyell have accumulated due to historic riverine disposal practices, part of PhD research conducted by TMVC student Sibele Nascimento.

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.





Uncovering Northwest Queensland's hidden potential: Mary Kathleen open pit, NW Queensland, looking southeast. Uranium is contained in thin, shallowly dipping veins cutting through the host rock.

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

In 2018, Emeritus Professor Ross Large's ground-breaking research career, and particularly his recent work

on trace elements in ancient oceans, was recognised by the award of the Royal Society of Tasmania Medal, which is awarded to a scholar for substantial original research in their subject matter. This prestigious award is fitting recognition of the contribution that Ross has made to the field of economic geology.

Ongoing projects within Program 3 include the Kansanshi gold project, funded by Kansanshi Mining, and the ARC Linkage project entitled 'Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia'.

The investigation of Paleoproterozoic sediment-hosted base metal and IOCG deposits of northern Queensland began in earnest in 2018, with the start of field and analytical work on the mineral chemistry of these important deposits, with CODES researchers actively collaborating with scientists from the Geological Survey of Queensland, University of Queensland, CSIRO and

James Cook University to stimulate mineral exploration and discovery in one of Australia's premier mineral provinces.

Publications in 2018

During 2018, a number of papers were published by Program 3 researchers. Particular highlights include the paper by Indrani Mukherjee, Ross Large and co-authors on 'The Boring Billion, a slingshot for complex life' published in *Nature Science Reports*, which presented a new hypothesis on controls on evolution processes during the middle Proterozoic. A paper by John Mering (University of Waikato, supervised by Shaun Barker) published in *Economic Geology* showed that accurate paleotemperatures can be determined from carbonate minerals in hydrothermal ore deposits using 'clumped' isotope. The 'clumped' isotope approach has significant potential implications for studying sedimentary basins and their associated ore deposits.

OPPOSITE PAGE: (TOP) Participants on an exploratory field trip in July 2018 that showcased NW Queensland ore deposits inspecting a megabreccia at the Mary Kathleen U-REE deposit. The dark-coloured matrix of this unit is composed of garnet; garnet is one of several minerals that CODES researchers will analyse throughout the NW Queensland joint project with the Geological Survey of Queensland and the University of Queensland. (BOTTOM) Metre-scale folds in schist, Osborne Cu-Au deposit, NW Queensland. This unit forms part of the western wall of the open pit and partially hosts the Cu-Au ore.

The program team

LEADER SHAUN BARKER

DEPUTY LEADER JEFF STEADMAN



TEAM MEMBERS:

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

PHD STUDENTS:

Alexander Cherry, David Douch, Peter Duerden, Umer Habib, Jacob Heathcote, Christopher Leslie, Elena Lounejeva, Indrani Mukherjee, Thomas Schaap, Tristan Wells

MASTERS STUDENTS:

Eyob Endemeskel, Brendan Hardwick, Kyle Hughes, Corey Jago, Sitthinon Kultaksayos, Peerapong Sritangsirikul

HONOURS STUDENTS:

Tomas Andrews, Darcy James, Ben Ridgers, Riquan Ropli, Mark Sinfeld

COLLABORATORS:

AUSTRALIAN NATIONAL UNIVERSITY

Janaina Avila, Trevor Ireland, Marc Norman

CAMECO RESOURCES

Penny Sinclair, Ben Walsh

CENTRAL SCIENCE LABORATORY (UTAS)

Sandrin Feig

CSIRO

James Austin

CURTIN UNIVERSITY

William Collins

EMMERSON RESOURCES

Grant Osborne

FIRST QUANTUM MINERALS

Tim Ireland, Louis van Heerden

FLINDERS UNIVERSITY

John Long

GEOFORSCHUNGSZENTRUM POTSDAM, GERMANY

Rainer Thomas

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

IRISH CENTRE FOR RESEARCH IN APPLIED GEOSCIENCES (ICRAG), IRELAND

Murray Hitzman, Sean Johnson

MACQUARIE UNIVERSITY

Elena Belousova, Nathan Daczko

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 CALIFORNIA RIVERSIDE, USA

Dan Gregory

UNIVERSITY OF DELHI, INDIA

Mihir Deb

UNIVERSITY OF MELBOURNE

Roland Maas

UNIVERSITY OF MISSOURI, USA

Ray Coveney

UNIVERSITY OF NEW MEXICO, USA

Karl Karlstrom

UNIVERSITY OF PORTSMOUTH, UK

David Loydell

UNIVERSITY OF QUEENSLAND

Rick Valenta

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 chemistry
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

In 2018 Indrani Mukherjee gained her PhD and published a paper in *Nature Science Reports* on 'The Boring Billion, a slingshot for complex life on Earth'. Indrani presented a new hypothesis that it is ocean trace element nutrients rather than atmosphere oxygen that has controlled evolutionary processes through the middle Proterozoic. The paper has been particularly well received.

Ross Large prepared an invited paper for a special issue of the *American Geophysical Union*, based on a

large data set of sulfur isotopes in sedimentary pyrite through time, collected in a collaboration with his PhD students and Trevor Ireland from ANU. The research demonstrates a correlation between the temporal variation in sedimentary pyrite sulfur isotopes and trace element chemistry with Large Igneous Province events (LIPS). If correct, this finding will rewrite the book on sulfur isotope trends in the ocean through time.

Ross and the team have been investigating further the development of a proxy for atmosphere oxygen concentration based on trace element ratios in sedimentary pyrite. This represents the 'Holy Grail' in deep time geochemistry and has become a highly controversial subject. In particular, 'was the Proterozoic atmosphere very depleted in oxygen ($< 0.2\% \text{ O}_2$), or was the oxygen concentration much higher ($2\text{--}20\% \text{ O}_2$)?'.

The global impact of the CODES research on understanding ocean and atmosphere chemistry through time has been recognised by an invitation from Elsevier to Ross Large to write a chapter on the 'Evolution of the Earth's atmosphere' for the next edition of the *Elsevier Encyclopedia of Geology*. Ross was also awarded the Royal Society of Tasmania Medal in 2018, for his career research achievements.

KANSANSHI GOLD

Leader: Robert Scott

Student: Jacob Heathcote

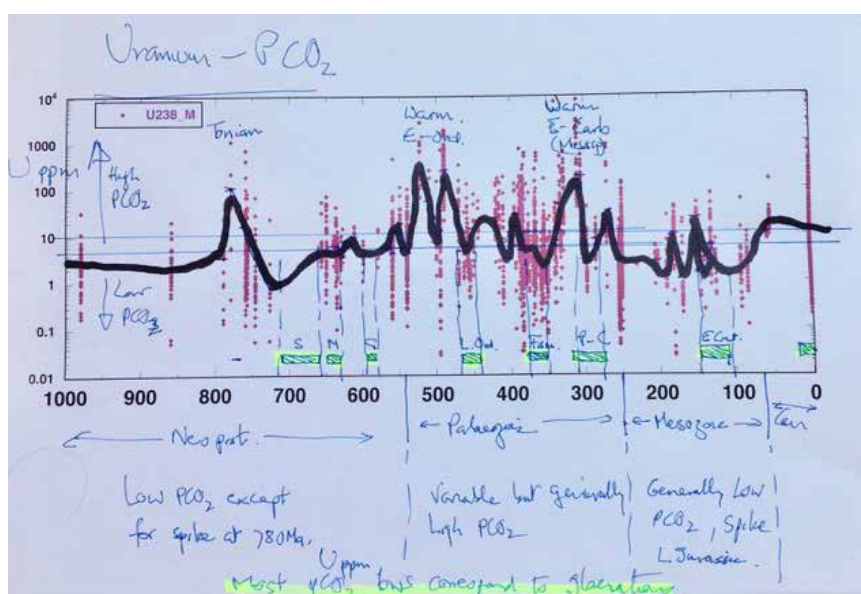
Collaborators: Tim Ireland,
Louis van Heerden

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.

The Kansanshi mine, which is a globally significant copper producer, also produces around 100,000 oz Au per year, from sheeted arrays of quartz-carbonate-sulfide veins up to 10 m wide.

The primary objectives of the project are to:

- improve deposit-scale understanding of gold distribution, mineral associations and paragenesis, in both primary (sulfide zone) and secondary (oxide zone) ores; and
- identify field-based geological criteria (e.g. alteration assemblages, vein composition and/or texture, structural features, etc.) that both help identify and predict the distribution and extent of gold mineralised zones.



Workings showing Ross Large's initial speculative plot of PCO_2 proxy using the uranium content of black shales through time from the 'Trace elements in ancient oceans' project.

Through a combination of pit mapping, core logging, and detailed petrographic analysis (optical microscopy, SEM, LA-ICP-MS) of over 230 samples Jacob has developed a robust paragenesis for gold, sulfide and gangue minerals at the deposit. His study has revealed 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, Irina Zhukova

Students: Peter Duerden, Umer Habib, Kyle Hughes, Corey Jago, Kathryn Job, Sitthinn Kultaksayos, Christopher Leslie, Ben Ridgers, Riquan Ropli, Peerapong Sritangsirikul, Thomas Schaap, Tristan Wells

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

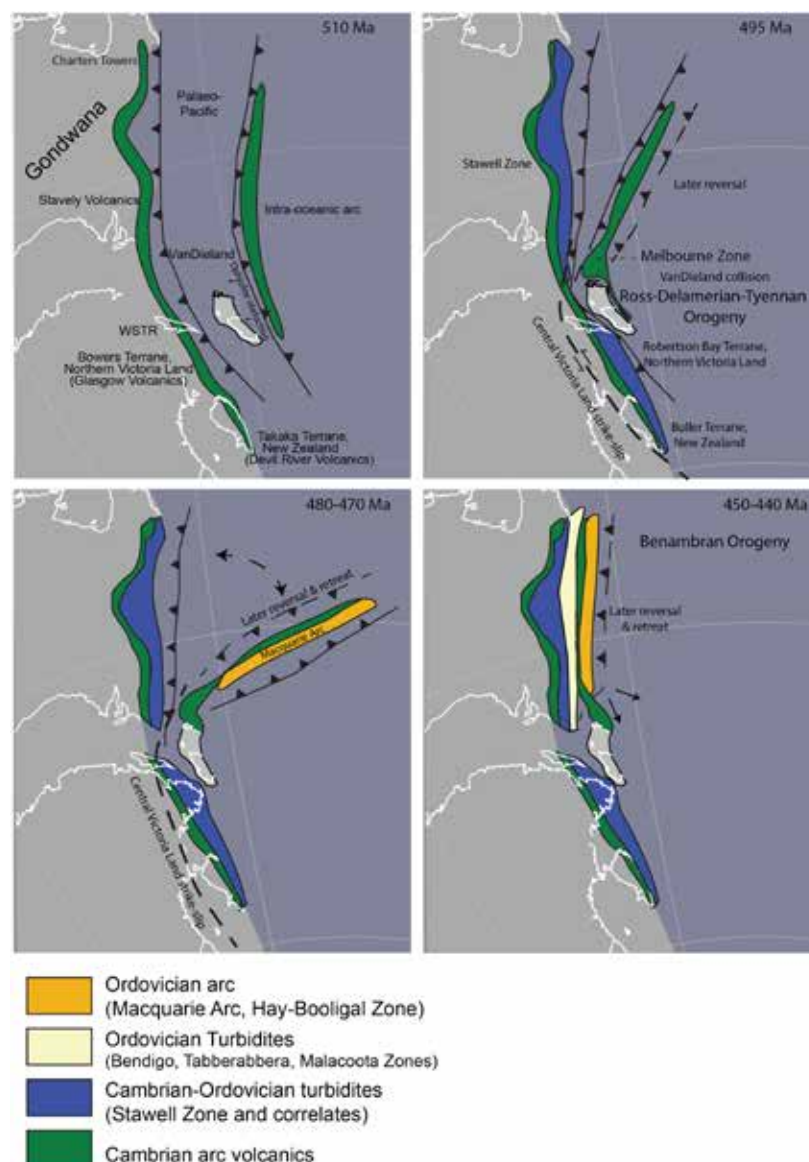
This ARC Linkage project aims to improve economic mineral discoveries through an increased understanding of the geology and tectonic evolution of the Lachlan Orogen in southeastern Australia, and to integrate that knowledge with existing geological information to subsequently develop predictive and explanatory models.

The project commenced in mid-December 2016.

Fieldwork and the acquisition of new geochemical, geochronological and geophysical data compilation activities continued in 2018. Results were presented at various conferences throughout the year. Highlights include:

- discovering new areas of Cambrian volcanics in central NSW and showing that these rocks underlie the Macquarie Arc;

This diagram illustrates snapshots of the new tectonic reconstruction for the Lachlan Orogen, showing pivotal processes from the Cambrian to the Silurian, and is part of Thomas Schaap's PhD research into 'Plate tectonic modelling of the Early Palaeozoic evolution of South Eastern Australia'.



- collecting mineral chemistry from NSW, Victoria and Tasmania to highlight prospective areas;
- developing new igneous porphyry fertility techniques that are specifically tailored for the Macquarie Arc;
- collecting new geochronology data sets (U-Pb, Re-Os) that resolve some of the problems in dating mineralisation and tectonic events;
- developing new tectonic reconstructions in G-Plates that help resolve some of the long-standing controversies; and
- acquiring new paleomagnetic data to test these correlations.

The project is due to finish at the end of 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 northwestern America;

- define Tasmania's place within the Nuna Supercontinent;
- provide new insights into the Cambrian tectonic setting of the Gondwana Pacific margin;
- refine the depositional age of turbidites comprising the Oonah Formation and their correlation with Mesoproterozoic turbidites exposed on King Island.

Most of the activity in 2018 was focussed on refining the age and the stratigraphy of the Neoproterozoic units in Tasmania. The study showed that detrital zircons can be used very effectively to identify and correlate all the units in the Neoproterozoic sedimentary rocks. A paper will be submitted shortly summarising this work.

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

This project is investigating the relationship between variation of oxygen in the atmosphere and the cycles of basin-hosted ore deposits. Oxygen cycles have been estimated using the chemistry of sedimentary pyrite through time. Redox sensitive trace elements in pyrite, particularly Se, Mo, Co, Sb and Tl, have proved to be the best indicators of oxygen variation. A paper is in preparation relating to sedimentary copper and zinc-lead genesis to cycles in atmosphere oxygen through time. This work was also presented at international conferences in Vancouver, New Hampshire and Sydney during 2018.

MINERAL GEOCHEMISTRY VECTORING: UNCOVERING NORTHWEST QUEENSLAND'S HIDDEN POTENTIAL

Leader: Shaun Barker

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

Collaborators: James Austin, Vladimir Lisitsin, Rick Valenta

In 2017, CODES was invited to participate in a new research initiative, the Strategic Resources Exploration Program, which is being led by the Geological Survey of Queensland (Department of Natural Resources and Mines) and the University of Queensland. This research program involves a consortium of researchers from several organisations, including CSIRO and James Cook University, and aims to stimulate exploration and discovery of new resources in the Northwest Queensland Mineral Province. CODES is a key participant in this collaboration. Shaun Barker began work on this project in 2018. Shaun has significant experience in pyrite and carbonate mineral chemistry from sediment-hosted hydrothermal systems. Jonathan Cloutier was appointed in late 2018 from the University of St Andrews, Scotland, and will begin work in February 2019 on this project as a postdoctoral research fellow alongside Jeff Steadman, who began work on this project in late 2017.

In 2018, CODES began generating new mineral chemistry data from a variety of IOCG (Ernest Henry, SWAN and others) and sediment-hosted base metal deposits (Lady Loretta) in NW Queensland, with an initial focus on magnetite and pyrite minerals. Our initial results collected

in 2017 from the Lady Loretta deposit demonstrated that pyrite in the ore horizon at Lady Loretta shares similar chemical characteristics to pyrite from that defined from the HYC deposit (recently published CODES research by Indrani Mukherjee and Ross Large). Meanwhile, pyrite from the SWAN IOCG system contains high concentrations of cobalt. Gold and copper in the SWAN deposit are found within late fractures in both pyrite and magnetite, providing valuable paragenetic information on the relative timing of Cu-Au mineralisation at that deposit.

As the mineral chemistry project continues in 2019, the trace element chemistry of a variety of other minerals including chlorite, epidote, carbonate minerals and apatite will be evaluated. Through our mineral chemistry analyses, we seek to extend the hydrothermal alteration footprint of economically significant deposits in the Northwest Queensland Mineral Province and aid the aims of the Strategic Resources Exploration Program to expand mineral resource exploration and development. Researchers from CODES are collaborating closely with researchers from CSIRO, sharing sample materials and expertise on mineral assemblages and mineral chemistry.

Looking forward

2019 will see the continuation of our flagship project, 'Mineral geochemistry vectoring: Uncovering Northwest Queensland's hidden potential', funded by the State of Queensland through the Department of Natural Resources, Mines, and Energy. This project is part of the Strategic Resources Exploration Program, a wider Queensland Government-funded research initiative. New samples will be collected from IOCG and sediment-hosted deposits in 2019, along with the collection of extensive new mineral chemistry data from pyrite, magnetite, apatite, calcite, dolomite, chlorite and epidote in order to evaluate how the alteration footprint of these deposits can be extended to help improve exploration success.

Crucial to the success of this project is the appointment of Dr Jonathan Cloutier, who will arrive in early 2019. Jonathan has a broad range of mineral deposit experience and has worked extensively in Australia and North America, including on sediment-hosted copper deposits. Jonathan's depth of experience will be critical to ensuring the success of this project.

Program Four

Magmatic and volcanic processes

Objective

This program aims to investigate volcanic processes and products, 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, 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

International profile

One highlight of the year was the highly successful research voyage on board the *RV Investigator* to the Tasman Sea in December 2018–January 2019. 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. This voyage was led by Associate Professor Jo Whittaker (IMAS), and included Dr Rebecca Carey, Dr Karin Orth, Dr Martin

OPPOSITE PAGE: (TOP) Earth Sciences and IMAS PhD and undergraduate students were on board the RV Investigator for the voyage to the Tasman Sea in late 2018 (see page 45). They were central to the success of the voyage, plotting the GIS data, and describing over one tonne of volcanic and sedimentary rocks dredged from 16 seamounts. From left: Fionualla Campbell, Zali Potts, Stephanie Morrish, Tom Schaap, Sian Tooze. (BOTTOM) CODES PhD student Adam Abersteiner looks for chromites in obducted peridotites during fieldwork at Cape Kamchatka, far eastern Russia, August 2018, as part of his research into kimberlites and diamonds.

Jutzeler and PhD student Tom Schaap as well as three Earth Sciences undergraduates.

Publication of an article ('The largest deep-ocean silicic volcanic eruption of the past century') by Carey et al. in *Science Advances* in January 2018 was another highlight. This article had significant international interest with over 1,600 pdf downloads, 3,000 views of the full article and 12,000 abstract reads in the month after publication.

Student achievements

Another highlight has been our student achievements. PhD student Adam Abersteiner was awarded a prestigious Max Banks Research Scholarship in Earth Sciences in 2018. This award was established in memory of Dr Maxwell R Banks AM, an esteemed faculty member at the University of Tasmania Department of Geology from 1947 to 1990. This top-up scholarship is awarded based on academic merit to a PhD student studying in the discipline of Earth Sciences at the University of Tasmania, with a particular focus on geology.

Eyob Andemeskel was awarded his Masters degree for his work on the Rosebery Group in the Mount Read Volcanics, and Sam Holt and Fumihiko Ikegami had papers published in international peer-reviewed journals.

International workshops/presentations

This year Dr Martin Jutzeler led an International Ocean Discovery workshop with a group of international researchers at the Fall Meeting of the American Geophysical Union in Washington DC. Martin is working with colleagues to develop a deep-sea drilling pre-proposal to address major outstanding questions about modern submarine silicic volcanism and architectures.

During August through to October, Professor Vadim Kamenetsky and PhD student Adam Abersteiner travelled to Kamchatka (Far East Russia), Novosibirsk and Irkutsk (Siberia) as part of a collaborative project with Russian academics. Here they attended the 10th Biennial Workshop on Japan-Kamchatka-Alaska Subduction Processes, conducted extensive fieldwork and sample collection, and established numerous collaborative

projects relating to kimberlites and basaltic volcanism.

Dr Adam Soule, the Chief Scientist for Deep Submergence at the US National Deep Submergence Facility, came to UTAS in April 2018 to work with Dr Rebecca Carey and Dr Martin Jutzeler and IMAS researchers through the Vice Chancellor's Visiting Scholar program. While here, he gave a presentation to students in KEA101 and a public lecture about the present and future use of underwater robots for research.

Professor Jocelyn McPhie led a field trip in the Gawler Range Volcanics for the Australian Geoscience Council Convention in Adelaide in October. Dr Rebecca Carey was a keynote speaker at that convention, presenting the recent research on understanding the role of hydrostatic pressure on submarine eruptions.

Publications in 2018

During 2018, 34 papers were published in international peer-reviewed journals by researchers within Program 4; 20 of them by the igneous petrology, geochemistry and studies of Olympic Dam group led by Professor Vadim Kamenetsky, and 14 by the volcanology group led by Dr Rebecca Carey. The majority of these articles were published in A* and A journals.

The highlights among Program 4 publications include a paper published in *Science Advances* by Dr Rebecca Carey, Dr Martin Jutzeler and Professor Jocelyn McPhie referred to above, and a paper published by Professor Vadim Kamenetsky and Dr Maya Kamenetsky ('Catastrophic events in the Quaternary outflow history of Lake Baikal') in *Earth Science Reviews*.

The program team

LEADER REBECCA CAREY

DEPUTY LEADER VADIM KAMENETSKY



TEAM MEMBERS:

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

PHD STUDENTS:

Adam Abersteiner, Nathan Chapman, Alex Cherry, David Douth, Evan Draayers, Matt Ferguson, Jodi Fox, Sam Holt, Fumihiko Ikegami, Colin Jones, Brian McNulty, Naomi Potter, Nathan Steeves, Daniele Vergani, Sally Watson (IMAS)

MASTERS STUDENT:

Eyob Andemeskel

HONOURS STUDENTS:

Bridie Le'Gallais, Ryan McMann, Rhiannan Mundana, Riquan Ropli

DEAN'S SUMMER RESEARCH SCHOLARSHIP STUDENTS:

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Kristen Fauria, Daniel Fornari, Adam Soule

Projects

Volcanology research related to ore deposits

Subaerial and submarine volcanology and natural hazards

Sedimentary volcanology

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

Boninite petrogenesis: Hunter Ridge, SW Pacific

Subduction magmatism in the SW Pacific

Magma petrogenesis

VHMS research – modern

VHMS research – ancient



Project summaries

VOLCANOLOGY RESEARCH RELATED TO ORE DEPOSITS

Leader: Rebecca Carey

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

Students: Eyob Andemeskel, David Douch, Ryan McMann, Riquan Ropli

Collaborators: Ray Cas, Matthew Crawford, Kim Denwar, Rob Duncan, Leon Grimbeek, Andrew McNeill, Gary Sparks

Modern volcanic arcs provide constraints on the physio-chemical factors for seafloor ore deposits and the paleoenvironment setting of ancient volcanic-hosted sulfide deposits. We are applying new knowledge of modern volcanic architectures to ancient mineralised volcanic successions with industry partners and collaborators.

In 2018 Eyob Andemeskel was awarded his Masters from the University of Tasmania. Eyob's thesis was on the Rosebery Group of the Mount Read Volcanics. Eyob used lithofacies, lithogeochemical and structural analysis to establish local and regional correlations of strata prospective for VHMS mineralisation



This photo, taken by Rebecca Carey, shows an eruptive vent and lava channel from a fissure in the Leilani Estates on the Big Island of Hawaii in June 2018. This eruption was the largest in the modern history of Kilauea volcano and devastated the community, destroying 2,500 homes.



Panorama of a salt lake near Kokatha in the Gawler Ranges, South Australia, taken during CODES PhD student Matt Ferguson's fieldwork to collect samples from some of the most voluminous felsic lavas in the world for his study of the magmatic-hydrothermal evolution of rocks in the Gawler Craton.

in the Mount Read Volcanics. This project was supervised by David Selley and Rebecca Carey. Eyob is now working in Western Australia and we wish him the best of luck!

David Douch's PhD project on the controls on gold mineralisation at the Invincible gold deposit has provided a wealth of new understanding on the volcano-sedimentary Neoproterozoic 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 is in the final stages of his project.

This year two Honours students graduated: Ryan McMann supervised by Paul Olin and Professor Ray Cas (Monash) on the Golden Mile Dolerite, with collaborative support from the Geological Survey of Western Australia (GSWA); and Riquan Ropli supervised by Sebastien Meffre, Jeff Steadman and Professor Rob Duncan (Geological Survey of Victoria). Riquan examined the volcanology of Cambrian geological units in central Victoria.

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: Jodi Fox, Sam Holt, Fumihiko Ikegami, Naomi Potter, Daniele Vergani, Fionnuala Campbell, Yun Fann Toh, Stephanie Morrish

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, Jack Simmons, Adam Soule, Kenichiro Tani, Rex Taylor, James White, Joanne Whittaker, Richard Wysoczanski

2018 was a highly successful year for the volcanology team. Together we published 14 journal articles, including two articles by PhD students Fumi Ikegami and Sam Holt. Other highlights included developing new collaborations during an International Ocean Discovery Program workshop that Martin Jutzeler held in Washington DC, and the 2018 voyage to the Tasman Sea that was

highly successful and will lead to an exciting decade of future research.

Our PhD and Honours students have been outstandingly productive. Sam Holt and Daniele Vergani have submitted their theses for assessment, and Jodi Fox will submit in January 2019. Jodi hosted a field workshop at Cape Grim associated with the Australian Institute of Geophysicists as a part of the Tasmanian Geoscience Forum in Stanley. Naomi Potter submitted her paper on the February 2013 eruption of Etna volcano, Italy, to the *Journal of Volcanology and Geothermal Research* in late 2018.

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

SUBMARINE SILICIC VOLCANISM: HAVRE 2012 ERUPTION, KERMADEC ARC, NEW ZEALAND

In addition to the publication in *Science Advances*, this project has produced a further four publications in prestigious geological journals including *Geology*. Rebecca Carey and Martin Jutzeler have submitted proposals for two ship-time voyages to go back to Havre to understand the volcanic architecture of the volcano and also assess the disturbance and recovery of the hydrothermal systems and the biological communities.

LARGE IGNEOUS PROVINCE VOLCANISM: KERGUELEN PLATEAU

Big Ben volcano on Heard Island is one of three hotspot volcanoes globally. Rebecca Carey is the geoscience lead for a multidisciplinary research project designed to understand the volcanism of the Kerguelen Plateau.

PhD student Jodi Fox is leading the study of the geological history of Heard and McDonald Islands on the Kerguelen Plateau together with Jocelyn McPhie, Trevor Falloon and IMAS collaborators. Together with tsunami modellers at New Zealand's National Institute for Water and Atmospheric Research, we are using the sector collapse scar and deposit of Big Ben to determine tsunami dynamics in the Indian Ocean and potential impacts.

HOTSPOT VOLCANISM: 1983–1986 AND THE 2018 ERUPTION OF KILAUEA VOLCANO

Sam Holt's PhD research on pyroclasts from explosive fountaining eruptions has determined a new parameter of vesicularity as a proxy for the amount of time that the pyroclast was in the fountain. This research was published in the *Journal of Volcanology and Geothermal Research* in 2018. We are collaborating with researchers at the University of Oregon to understand the development of the insulating crust on

lava lakes, and how the lid modulates the surface manifestation of bubbling on the lava lake surface.

This year Kilauea volcano on the Big Island of Hawaii had its biggest eruption on the East Rift Zone ever recorded. This event began on 3 May, and continued through to August. It was a complex event with eruptive vents along 17 fissures, some of which were erupting magma at $>100\text{m}^3\text{s}^{-1}$. Rebecca Carey was invited to go with the team from current affairs TV program *60 Minutes* to Hawaii to provide the geological background and volcanology expertise for a feature about the eruption. Rebecca was able to see first-hand the impacts of the event on surrounding communities and the >2500 destroyed homes.

Adjunct researcher Gerrit Olivier and Rebecca Carey are working together on understanding the onset of the 2018 eruption of Kilauea volcano using seismic velocity data. Current research suggests that 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. Daniele Vergani has submitted his PhD for assessment, which includes studies of lava–water interaction explosions, lava fountaining and the eruption and collapse of the summit caldera.

KUTCHARO CALDERA, HOKKAIDO, JAPAN

Jocelyn McPhie and long-term CODES collaborator Dr Yoshi Goto have produced a new map and interpretation of Kutcharo caldera, Hokkaido, Japan. Kutcharo is the largest Quaternary silicic caldera in Japan, and formed in response to nine large-volume explosive eruptions, the most recent of which was at ~34 ka. Of major importance in this research is the recognition that Kutcharo has a resurgent dome and that the caldera structure is coupled with regional faults related to the wider convergent margin setting. The results were published this year in the *Geological Society of America Bulletin*.

SURTSEY INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Surtsey is a small volcanic island formed by eruptions over a four-year period beginning in 1963. The volcano was drilled in 1979 and again in 2017. Logs of the 2017 drill core show that 'dry' explosions operated alongside 'wet' explosions driven by interaction with seawater. Co-existence of these two eruption scenarios was not evident in the historical records of the activity. Comparison of the 1979 and 2017 drill cores has revealed the rapid rate of diagenetic and hydrothermal alteration; the initially loose pyroclastic deposits were partly lithified in 1979 but now are almost entirely lithified and much of the glass has devitrified. An abstract summarising results of volcanological analysis of the Surtsey 2017 drill core has been accepted for presentation at the European Geophysical Union General Assembly (Vienna, 2019) and a manuscript giving a comprehensive account of the drilling operation and scientific themes has been submitted to *Scientific Drilling*.



Participants on the Australian Geoscience Council Convention field trip through the Gawler Range Volcanics, enjoying a quarry exposure of the Lake Gairdner Rhyolite, October, 2018. L to R: Matt Townsend, João Motta, Rosemary Hegarty, Liann Deyssing and field trip leader Professor Jocelyn McPhie. .



Close up of lava flow from the 2013 Tolbachik volcano eruption photographed during Professor Vadim Kamenetsky and CODES PhD student Adam Abersteiner's field trip to the Russian Far East in 2018. This eruption produced 0.54 km³ of basaltic trachyandesite lava which covered a total area of 36 km² with a maximum thickness of 70m, and is regarded as one of the most voluminous historical outpourings of basic lava in a subduction-related environment. The observed texture is called 'pahoehoe'.

CASCADE SEAMOUNT AND THE BALLENY MANTLE PLUME

Honours student Rhiannan Mundana, together with Associate Professor Joanne Whittaker and Rebecca Carey, are using *RV Investigator* data to understand the geological history of the Cascade Seamount on the East Tasman Plateau. Rhiannan's research has demonstrated that the Cascade Seamount was at, or very close to, sea level at ~35 Ma, before subsiding to its current depth of 650 mbsl as the Balleny Mantle Plume moved southwards with time. The subsidence rate is important – as subsidence was essential to the opening of the Tasman Gateway between Tasmania and Antarctica and the initiation of the Antarctic Circumpolar Current. Rhiannan, Joanne and Rebecca are currently writing up this research for publication.

Joanne Whittaker (IMAS) and 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. Karin Orth, 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.

NATURAL HAZARDS

In August 2018, Rebecca Carey and colleagues from the Centre for Rural Health and IMAS hosted a workshop titled: 'Partnering with interdisciplinary experts on disaster preparedness and management to develop a collaborative research agenda to minimise risk and improve the future resilience of Tasmanian communities'. Researchers from across the University and the Tasmanian Community of Practice in disaster resilience, response and management attended. The goals of the workshop were to define a Tasmanian-centred research agenda for the University of Tasmania in natural hazards and disasters, identify vehicles for funding this research across government and industry on short and long timescales, and identify teaching and training needs in this field

across the state. This workshop was highly successful with 34 identified topical research projects, 34 funding bodies identified for disaster research and 26 teaching and training needs identified at all levels across the state. Four interdisciplinary research projects (up to \$1 million each) with external stakeholders are already under discussion as a result of this workshop. Rebecca and colleagues were also awarded a \$5,000 grant from the Environment, Resources and Sustainability Research Theme to continue to develop the outcomes of this workshop with the Community of Practice.

SEDIMENTARY VOLCANOLOGY

Leader: Martin Jutzeler

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

Collaborators: Cathy Busby, Fabio Caratori-Tontini, Ray Cas, Cornel de Ronde, Sue DeBari, James Gill, James Hunt, Steffen Kutterolf, Geoffroy LaMarche, Michael Manga, Robert Marsh, Ed Pope, James Shreeve, Adam Soule, Christian Timm, Erik Van Seville, James White, Joanne Whittaker, Richard Wysoczanski

The Sedimentary Volcanology project encompasses research on eruption, transport and deposition dynamics at modern volcanoes and in ancient successions with the aim of improving the reconstruction of volcanic architecture in ancient analogues. Sub-projects include:

PROVENANCE OF CALDERA-FORMING DEPOSITS IN THE IZU-BONIN ARC

In 2018 Martin Jutzeler and co-Principal Investigator Rebecca Carey obtained a \$10,000 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 Sumisu Rift in the Izu-Bonin arc. These LA-ICP-MS analyses will complement preliminary analyses on the microprobe. This study will provide additional data to narrow down the source of gigantic pumice-rich beds to specific nearby calderas, and thus allowing further study on transport

processes associated with caldera-forming submarine silicic eruptions.

VOLCANIC AND CLIMATE-INDUCED SOURCE OF HEMIPELAGIC MUD IN ISLAND ARCS

Martin Jutzeler took an active role during 2018 in a multidisciplinary study led by Professor James Gill at UCSC, addressing the provenance of very thick Miocene to modern successions of very fine-grained hemipelagic mud in the Izu-Bonin rear-arc. This study shows evidence through geochemistry and componentry that the microparticles forming most of the hemipelagic mud are chiefly products from local rear-arc volcanism, and do not originate from organic marine snow. These volcanic particles are chiefly <60 microns, making them particularly difficult to study and identify. Interestingly, the overall local contribution of hemipelagic mud shifts during glacial periods, with most of the sediment chemical composition pointing towards a Chinese loess source. Heightened accumulation of this foreign component during glacial periods points towards a modification of the path of the Kuroshio current due to climate change since the Miocene. This study demonstrates the role of climatic variations and ocean currents as external contributors to the morphology of volcanic arcs, locally modifying sedimentation rate and the composition of fine sediments.

ORIGIN OF GIANT SEDIMENT WAVES ON SUBMARINE CALDERA VOLCANOES

Martin Jutzeler co-led a study, published in *Earth and Planetary Science Letters* (EPSL) during 2018, that identified the origins of widespread seafloor waveforms surrounding modern submarine silicic caldera arc volcanoes. Using bathymetry and seismic reflection data, the team identified the morphological characteristics of two waveform end-members. The deposits derived from caldera-forming explosive eruptions are made of widespread, fanning out, upward-migrating cyclic steps and anti-dune deposits, suggesting extreme fluxes of deposition from Froude supercritical density currents. In contrast, landslide-derived deposits are funnelled, can be backward rotated, and linked to arcuate headwalls. This study is aligned with ore exploration, through identification of

key volcanic facies aimed at improved volcanic architecture reconstruction in marine settings.

During the year Martin Jutzeler and co-Principal Investigator Rebecca Carey submitted a Marine National Facility proposal for shiptime aboard the *R/V Investigator* in 2020. The aim of this voyage is to link the behaviour of deep submarine eruptions with the morphology of their deposits. The project will investigate the architecture of three modern submarine silicic calderas in the Kermadec arc, north of New Zealand, using seismic reflection and shallow coring. The calderas sit at various water depths, and this study will tackle the interdependency of magma flux to hydrostatic pressure. Outputs from this study include modelling of sediment mass fluxes during such eruptions, and thus the production of the first-ever hazard mapping scheme for submarine volcanoes globally (tsunami and sediment flows). This project will identify the true nature of sediment waves on the flank of these calderas and evaluate the tsunamigenic potential of submarine volcanism. Further, high-resolution seismic transects will enable new ore vectoring strategies for exploration in Australia and provide essential data to propose an International Ocean Discovery Program (IODP) expedition to drill these calderas.

In 2018 Martin Jutzeler received a \$9,000 seed grant from UTAS to organise an international workshop to frame a deep-sea drilling pre-proposal to the IODP. The workshop was held in December in Washington DC, USA, just before the AGU Fall Meeting. The aim of the workshop was to identify the major scientific questions relative to modern submarine silicic caldera volcanism. The major specific aims include characterisation of the volcanic architecture, relationship between magmatic and hydrothermal systems, magma evolution, and collection of the entire stratigraphy of the proximal sediment wave deposits. This IODP pre-proposal will be submitted in late 2019.

PUMICE RAFTS

Research on pumice rafts on several fronts is being led by Martin Jutzeler. Pumice rafts are floating accumulations of pumice clasts derived from submarine and coastal volcanism, and are dispersed over thousands of kilometres by surface ocean

currents and wind. In collaboration with oceanographers at the National Oceanography Centre Southampton (UK) and the University of Utrecht (Netherlands), the team explored the statistical dispersal of pumice rafts at a global scale, based on surface ocean model hindcast. Martin is also leading another research topic on pumice rafts, using abrasion experiments in wave tanks that recreate pumice-to-pumice attrition in the open sea. Results show compelling evidence for voluminous production of fine material that would accumulate as fine tephra on the seafloor. Both studies explore the role of pumice rafts on local climate and biochemical cycles, and their consequences for pelagic and benthic communities. These studies are also providing strong links with volcanic architecture and ore exploration, by identifying ultra-distal marine facies derived from high-intensity submarine eruptions, such as that produced by the Havre submarine caldera in 2012.

PEGMATITES AND PEGMATITE-RELATED ORES

Leader: Paul Davidson

Collaborators: Walter L. Pohl, Adolf Rericha, Rainer Thomas

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 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.

This year two papers – ‘Genetic significance of the 867 cm⁻¹ out-of-plane Raman mode in graphite associated with V-bearing green grossular’ by Rainer Thomas, Adolf Rericha, Walter L. Pohl and Paul



Participants of an IAVCEI Commission on Submarine Volcanism Field Workshop in Shimane, Japan, August 2018; CODES PhD student Jodi Fox attended this workshop as part of her research into submarine volcanism, which sits within the 'Subaerial and submarine volcanology' project of Program 4. Jodi won the Fieldwork category of the inaugural CODES Christmas Photo Competition with this photo.

Davidson, and 'Shaw meteorite: water-poor and water-rich melt inclusions in olivine and enstatite' by Rainer Thomas and Paul Davidson – have been published in *Mineralogy and Petrology*.

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

Leader: Vadim Kamenetsky

Team members: Maya Kamenetsky, Sebastien Meffre, Jay Thompson

Student: Adam Abersteiner

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

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

Outcomes in 2018 included genetic constraints for a number of continental magmatic provinces (South Africa, Arctic Siberia, NW Canada and eastern Finland) and included several publications in high-impact journals (*Chemical Geology* and *Journal of Petrology*).

A particular emphasis was on petrologically unique Udachnaya-East kimberlite (Siberia, Russia), which contains fresh olivine, along with abundant alkali-rich carbonates, chlorides, sulfides and sulfates in the groundmass. The mineralogical and geochemical features and the compositions of melt inclusions in unserpentinised and altered kimberlite types are compared in our study. Melt inclusions hosted in olivine, monticellite, spinel and perovskite from all kimberlite varieties contain identical daughter phase assemblages that are dominated by alkali-carbonates, chlorides and sulfates/sulfides. This enrichment in alkalis, chlorine and sulfur in melt inclusions demonstrates that these elements were an intrinsic part of the parental magma. We demonstrate that 'contamination models' are inconsistent with petrographic, geochemical and melt inclusion data. Instead we propose that the Udachnaya-East kimberlite crystallised from an essentially H₂O-poor, Si-Na-K-Cl-S-bearing carbonate-rich melt.

The study of monticellite-rich kimberlites from Leslie pipe (Canada) and Pipe 1 (Finland) supports that CO₂ degassing in the latter stages of kimberlite emplacement into the crust is largely driven by the reaction between olivine and the carbonate melt. The proposed decarbonation reactions may be a commonly overlooked process in the crystallisation of monticellite and

exsolution of CO₂, which may in turn contribute to the explosive eruption and brecciation processes that occur during kimberlite magma emplacement and pipe formation.

The origin of high-Mg melts is addressed in the study of olivine-hosted melt inclusions from picritic volcanic rocks of the Siberian Large Igneous Province. The high abundances of volatile elements, including H₂O (up to 3 wt%), fluorine, chlorine and sulfur, taken together with directly measured major and lithophile trace elements were used to estimate the compositions of primary melts and conditions of their generation in the mantle. It is advocated that high-Mg melts form by volatile fluxing of the asthenospheric mantle rather than by decompression melting under relatively dry conditions of a rising abnormally high-temperature mantle plume.

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, Victor Sharygin



This image shows the products of reaction (cuprospinel, hematite and tenorite) between hot gases and solidifying magma in the lava tube of the 2013 Tolbachik eruption, seen under magnification. It was published in 2018 in the journal Minerals as part of Vadim Kamenetsky's contribution to an article on the 2012–2013 eruption of the Tolbachik Volcano in Kamchatka, Russia.

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 2018, our research on perovskite accumulation in the Afrikanda alkaline-ultramafic complex (Kola Peninsula, NW Russia) was published in *Contributions to Mineralogy and Petrology* (Potter et al.). This paper presents textural and compositional varieties of perovskite, which is a common accessory mineral in many mafic and ultramafic rocks, but perovskite deposits are rare, and studies of perovskite ore deposits are correspondingly scarce. We classify perovskite into three types based on crystal morphology, inclusion abundance, composition,

and zonation. Perovskite in some rocks is represented by fine-grained, equigranular, monomineralic clusters and networks, but has fine- to coarse-grained interlocked and massive textures in other rocks. Electron backscatter diffraction reveals that some perovskite grains are composed of multiple subgrains and may represent stages of crystal rotation, coalescence and amalgamation. We propose that exclusively sub-solidus processes can lead to the development of coarse-grained and massive perovskite. A combination of characteristic features identified in the Afrikanda perovskite (equigranular crystal mosaics, interlocked irregular-shaped grains, and massive zones) is observed in other oxide ore deposits, particularly in layered intrusions of chromitites and intrusion-hosted magnetite deposits and suggests that the same amalgamation processes may be responsible for some of the

coarse-grained and massive textures observed in oxide deposits worldwide.

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

Leader: Vadim Kamenetsky

Team members: Leonid Danyushevsky, Maya Kamenetsky, Paul Olin

Student: Adam Abersteiner

Collaborators: Kathy Ehrig, Andrey Gurenko, John Mavrogenes, Nick Nekrylov, Jung-Woo Park, Thomas Rodemann, Dmitry Savelyev, Michael Zelenski

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.

Magma unmixing into separate sulfide and silicate melts is a key process in the formation of magmatic sulfide ore deposits. Our paper in *Lithos* (Zelenski et al.) presents sulfide inclusions in olivine from the Tolbachik volcano (Kamchatka) that preserve the original chemical composition of the segregated sulfide melt. Studied sulfide globules display a variety of textures ranging from homogeneous to fine-grained to coarse-grained and lamellar. They depend on the cooling rates of olivine phenocrysts that are estimated to vary by five orders of magnitude. The Fe:Ni:Cu ratio also controls the resulting texture, whereas the size of the globules does not have any significant effect. The morphology and textural patterns of individual grains indicate that fine-grained textures resulted from the rapid breakdown of a homogeneous solid phase, which the sulfide melt solidified into during extremely rapid quenching. The presence of large or abundant small pores in sulfides indicates the separation of an appreciable amount of dissolved fluid from the sulfide melt during crystallisation. Sulfides in the form of thin foils and planar swarms in healed cracks can be assigned to cyclic pressure changes that resulted in phenocrysts rupturing and healing.

A complementary study has been published in *American Mineralogist* (Savelyev et al.). It is the first detailed report of the crystallised sulfides melts in the Cretaceous oceanic picrites in the Kamchatka Mys ophiolite in Eastern Kamchatka (Far East Russia). Sulfide melts are present as inclusions in olivine (87.1–89.6 mol% Fo) and interstitial to the groundmass minerals (clinopyroxene, plagioclase and Ti-magnetite). The sulfide melt inclusions in olivine and the groundmass are composed of several sulfide phases that correspond to the monosulfide (Fe–Ni; Mss) and intermediate (Fe–Cu–Ni; Iss) solid solutions. Several types of micron-sized Pd–Sn, Pt– and Au–Ag phases are recorded within the matrix sulfides, commonly along phase boundaries and fractures. Major elements (S, Fe, Cu, Ni, Co), platinum group elements (PGE) and gold analysed in the homogenised olivine-hosted sulfide melt inclusions, and phases identified in the matrix sulfides record the range of magmatic sulfide compositions. The most primitive sulfide liquids are notably enriched in Ni and Cu ((Ni+Cu)/Fe > 0.5), continuously evolve with crystallisation of (e.g., increasing Cu/Ni and Au/PGE) and demonstrate metal fractionation between Mss and Iss. The compositions of individual sulfide phases are strongly affected by the noble metal (PGE, Au) ‘nuggets’ that exsolve at subsolidus temperatures and form during serpentinisation of the rocks. We conclude that the budget of noble metals in the studied picrites is controlled by sulfides, but the abundances of Pt and Au are influenced by mobility in post-magmatic alteration. Our data can also be used for modelling sulfide saturation at crustal pressures and understanding behaviour of the noble metals in primitive oceanic magmas.

OLYMPIC DAM

Leader: Vadim Kamenetsky

Team members: Maya Kamenetsky, Jocelyn McPhie, Sebastien Meffre, Jay Thompson

Student: Alex Cherry

Collaborators: Yuri Amelin, Kathy Ehrig, Karsten Goemann, Roland Maas

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 Cherry et al. in *Precambrian Research* and the *Australian Journal of Earth Sciences* highlight the completion of the ARC Linkage project ‘The supergiant Olympic Dam U–Cu–Au–REE ore deposit: towards a new genetic model’.

The Olympic Dam Breccia Complex (host to the Olympic Dam Cu–U–Au–Ag deposit) is derived largely from granite (Roxby Downs Granite) but includes clasts and domains derived from surficial facies (felsic volcanic rocks and bedded clastic facies). New high-precision CA–TIMS geochronology is used to constrain the ages of the granite, the volcanic rocks and bedded clastic facies. The felsic volcanic rocks (1594.73 Ma ± 0.30 Ma) are slightly older than the granite (1593.87 Ma ± 0.21 Ma). These ages, together with the absence of any older country rock in the breccia complex, suggest the felsic volcanic rocks that were originally present at Olympic Dam were intruded by the granite. The deposition of the bedded clastic facies (tuffaceous mudstone) has been constrained to 1590.97 ± 0.58 Ma, indicating the presence of a basin around 3 Ma after emplacement of the granite and felsic volcanic rocks. The granitoid-dominated provenance of some of the bedded clastic facies implies that ca. 1590 Ma granitoids were exposed when the bedded clastic facies were accumulating. Faults are proposed to have been responsible for the segmentation and incorporation of the bedded clastic facies into the Olympic Dam Breccia Complex.

The Olympic iron oxide–copper–gold province in South Australia contains numerous deposits and prospects, including the Acropolis prospect with magnetite–apatite veins. The apatite grains in the veins contain zones with abundant inclusions of other minerals (including monazite and xenotime). The LA–ICP–MS U–Pb age of inclusion-rich apatite yields both near-concordant analyses that are within error of the inclusion-free apatite and host volcanics (ca 1.59 Ga) as well as highly disturbed (discordant) analyses. The most concordant analyses of monazite (Th–Pb) inclusions and xenotime (U–Pb) inclusions and rim grains indicate an alteration event occurred

at ca 1.37 Ga and possibly also at ca 500 Ma. The disparity in age of the inclusion-rich apatite and the REE–phosphate inclusions (and rim grains) is suggested to be owing to the apatite being initially recrystallised at ca 1.59 Ga and modified again by a later event that also formed (or coarsened) most of the inclusions. The ages of the two post-1.59 Ga events that appear to have affected the Acropolis prospect are important in interpreting potential evolution and upgrade of the Olympic Dam deposit. The earlier (ca 1.37 Ga) age corresponds best with metamorphic–magmatic–hydrothermal activity in Laurentia, consistent with the proximity of Laurentia and the Gawler Craton inferred from palaeogeographic reconstructions. The later (ca 500 Ma) event corresponds to the Delamerian Orogeny and has been shown by prior studies to have also affected the Olympic Dam deposit.

BONINITE PETROGENESIS: HUNTER RIDGE, SW PACIFIC

Leader: Leonid Danyushevsky

Team member: Trevor Falloon

Students: Evan Draayers, Bridie Le’Gallais

Collaborators: Karsten Goemann, Roland Maas

Evan Draayers continued work on his PhD research project, aimed primarily at providing new insights into the petrogenesis of high-Ca boninite and related lavas from the Hunter Ridge, SW Pacific, largely through detailed investigation of phenocryst mineralogy and lava geochemistry.

During 2018, the work has focussed on establishing genetic relationships between spatial and temporal data on the lavas with variations in their isotope geochemistry, mineral chemistry and the degree of enrichment in incompatible trace elements. These results will be combined in a revised model of boninite petrogenesis.

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 2018 the focus was on magma genesis at the southern termination of the Hunter Ridge, a unique tectonic setting associated with a recent initiation of subduction of the South Fiji Basin crust under the actively spreading North Fiji Basin. A paper published in *Earth and Planetary Science Letters* has described the unique associations of magmatic rock erupted in this setting, and their implications for the models of processes occurring within subduction zones.

MAGMA PETROGENESIS

Leaders: Trevor Falloon, David Green

In the absence of funding specifically identified for this strategic research, there has been little progress in obtaining new analytical data during 2018. Priority was given to:

- Completion of documentation of unpublished experiments on lherzolite at pressures to 6 GPa and with variable water contents.
- Completion of data compilation of experimental study which calibrated the olivine+orthopyroxene+clinopyroxene+ilmenite+/-garnet+/-spinel mineral assemblage as a function of P, T, and fO₂.
- Compositions of near-solidus (<5% melt fraction) melts with dissolved C, H, O, N, S at 1-6 Gpa.

The studies continue to demonstrate how a lherzolitic composition for the upper mantle is able to provide an extraordinary range of parental magmas from high-SiO₂ boninites through olivine-rich picrites to alkali-rich, low SiO₂ ankaramites, olivine melilitites and sodic-dolomitic carbonatites. By controlled experiments (P, T, compositional variation of C, H, S, O) on parental magmas, they can be assigned to specific locations in the 'Plate Tectonic' cycle. Results from this strategic research underpin interpretations of specific magmatism in the geological record.

VHMS RESEARCH – MODERN

Leader: Bruce Gemmell

Team members: Heidi Berkenbosch, Rebecca Carey, Martin Jutzeler, Sebastien Meffre

Collaborators: Cornel de Ronde, Andrew McNeill, Adam Soule

Submarine volcanic arcs provide at least 10% of volatile gas discharge globally, and coupled with physiochemical factors, produce a huge diversity in mineral type. Arcs therefore provide many modern analogues to ancient volcanogenic sulfide deposits.

BROTHERS VOLCANO, KERMADEC ARC

Heidi Berkenbosch completed the edits on a paper detailing the trace element mapping, using synchrotron radiation XRF and LA-ICP-MS of Cu- and Zn-rich black smoker chimneys from Brothers Volcano, Kermadec Arc. Heidi determined that in two Zn-rich chimneys, Cu distribution varies from Cu-bearing sphalerite with chalcopyrite disease to distinct chalcopyrite-lined channels, implying a progression of chalcopyrite replacement of sphalerite. Conversely, the two Cu-rich chimneys have different styles of massive chalcopyrite lining their conduits. The first displays elongate chalcopyrite grains that radiate into and infill the conduit; these radial grains may be related to decreased fluid flow during sealing of the chimney at both its top and bottom. The second style involves multiple, concentric chalcopyrite laminations (0.25–1 mm) inside the conduit, which progressively narrowed the orifice as they were deposited. Fine (15–40 µm) trace element rings are revealed within and between laminations that exhibit variable contents and distributions of Co, Ni, Zn, As, Se, Mo, Ag, Cd, Sn, Te, Au, Tl, Pb, Bi, and U. The presence of U in the rings specifically indicates seawater ingress into the chimney interior despite it vigorously discharging 274°C fluids at the time of sampling. 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. We compared

enrichment factors of trace element rings to those of fumarole condensates studied at subaerial arc and rift volcanoes and molten S pooled atop a submarine back-arc volcano. Our enrichment factors show remarkable consistency with the other volcanoes and indicate Au, Te, Bi, Cu, Ag, and Se in Brothers' chimneys were magmatically derived. This paper has been accepted and will be published in *Economic Geology* in early 2019.

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

Rebecca Carey is leading a ship-time proposal to revisit Havre volcano in 2020–2021 to investigate its hydrothermal systems, in particular to characterise their flux and chemical compositions of fluids. This research is being conducted together with Dr Adam Soule from the Woods Hole Oceanographic Institution and Dr Cornel de Ronde from GNS Science. If the voyage proposal is successful, we will use CTD profiles and a remotely operated vehicle to detect, measure and sample the fluids emitted.

VHMS RESEARCH – ANCIENT

Leader: Bruce Gemmell

Team members: Ron Berry, Rebecca Carey, Martin Jutzeler, Ross Large, Jocelyn McPhie, Sebastien Meffre, Khin Zaw

Students: Brian McNulty, Nathan Steeves

Collaborators: Mohd Basril Iswadi Bin Basori, Mark Hannington, Andrew McNeill, Jim Mortensen, Mike Vicary

The genesis of volcanic-hosted Cu-Pb-Zn-Ag-Au massive sulfide deposits is being investigated across the spectrum of massive sulfide deposit types, from typical seafloor VHMS (Zn-Pb-Cu-Ag-Au) deposits, through sub-seafloor shallow-water, replacement gold-rich epithermal styles, to deep sub-volcanic intrusion-related Cu-Au-rich styles.

In 2018, research was undertaken on deposits in the Mount Read Volcanic Belt (Tasmania), Greens Creek (Alaska), Myra Falls (Canada) and Malaysia.

In collaboration with Mark Hannington from the University of Ottawa, Nathan Steeves completed his PhD investigation of the mineralogy, metal distribution and geometallurgical characteristics of the complex ore bodies at the Greens Creek VHMS deposit in Southeast Alaska. The Greens Creek Zn-Pb-Ag-Au volcanogenic massive sulfide (VMS) deposit is located on Admiralty Island, southeast Alaska, USA. The deposit has a global resource (combined resource, reserve and past-production) of 24.2 Mt at 13.9% Zn, 5.1% Pb, 658 g/t Ag, and 5.1 g/t Au, and is one of the most Au- and Ag-rich massive sulfide deposits in the world. Nathan proposed a new genetic model for Greens Creek. Late Triassic slow to ultraslow back-arc or intra-arc detachment rifting caused uplift and exhumation of a cold, metamorphosed Carboniferous (340–330 Ma) tholeiitic mafic volcanosedimentary sequence (\pm ultramafic rocks) and emplacement of shallow level intrusions. Long-lived, low intensity hydrothermal activity at a sediment-covered rift circulated a low temperature (150–250°C), weakly acidic (pH 4–5) hydrothermal fluid. This fluid scavenged metals from highly fractured and permeable metamorphosed footwall rocks and possibly from older Devonian metasedimentary and felsic metavolcanic rocks. Ore formed initially as low temperature exhalative white smoker deposits during sedimentation (stage 1) and continued after burial to form higher temperature sub-seafloor replacement-style massive sulfide deposits (stage 2). Hydrothermal fluid moved laterally within and below turbidites and hemipelagic muds with low cross-strata permeability, altering and replacing porous and permeable, highly reactive dolomitised sediments. Periodic ingress of oxidised seawater into pore space containing sulfate-reducing bacteria during waning periods of hydrothermal activity fed the production of H_2S and the formation of abundant organic matter. Seawater drawdown through massive sulfide periodically formed low temperature, oxidising, near-neutral pH, sulfur-saturated fluid, which carried Cu, Ag, Au, \pm As as bisulfide complexes to the seawater interface, near barite-rich margins, and precipitated a unique Cu-Ag-S mineral assemblage.

Brian McNulty neared the completion of his PhD research 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 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 2018 Brian published a paper, entitled 'Lithological discrimination of altered volcanic rocks based on systematic portable X-ray fluorescence analysis of drill core at the Myra Falls VHMS deposit, Canada' in the *Journal of Geochemical Exploration*.

VHMS research in Southeast Asia, particularly in Malaysia, continued in 2018. Mohd Basril Iswadi Basori published a paper entitled 'Textures and trace element composition of pyrite from the Bukit Botol volcanic-hosted massive sulphide deposit, Peninsular Malaysia' in the *Journal of Asian Earth Sciences*. The deposit occurs in a package of Permian coherent felsic volcanic and volcanoclastic rocks. Mineralisation shows distinct ore zonation, forming a stringer to massive sulfide zone at the footwall followed by barite lenses and exhalate layers (Fe-Mn ore) at the top. Mineralogy is characterised

by pyrite as the major sulfide mineral, with minor chalcopyrite, sphalerite, and rare galena; traces of gold, silver- and tin-bearing minerals also occur in the massive sulfide and barite ores. LA-ICP-MS analysis, combined with the textural characteristics, of pyrite provides evidence for significant variations of trace elements in different pyrite types at Bukit Botol. The concentrations of As, Se, Te, Cu, Zn and Pb decrease from the early pyrite 1 to the late stage pyrite 3, and the Co/Ni ratios vary for the three pyrite types. The combined textural and compositional data of pyrite suggest that the hydrothermal fluid responsible for mineralisation evolved from an early, high temperature, reduced, low pH and desulfurised fluid to more S-rich, oxidised, high pH and cooler fluid.

A project aimed at improving the age and geochronological constraints on the development of the Mount Read Volcanic Belt (MRV) continued, in collaboration with Jim Mortensen (UBC), and Andrew McNeill and Mike Vicary (both from MRT). Outcomes to date include the U-Pb dating of zircons, which produced many new dates that have helped to constrain the timing of the development of the MRV and associated VHMS mineralisation. A second phase of age dating throughout the MRV has been completed and results are being compiled for inclusion in a paper to be submitted to *Economic Geology*.

Looking forward

In 2019 we are looking forward to the submission of seven PhD student theses in Program 4: Adam Abersteiner, David Douth, Matt Ferguson, Jodi Fox, Fumihiko Ikegami, Brian McNulty and Naomi Potter. We wish them the best as they wrap up their PhD studies.

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

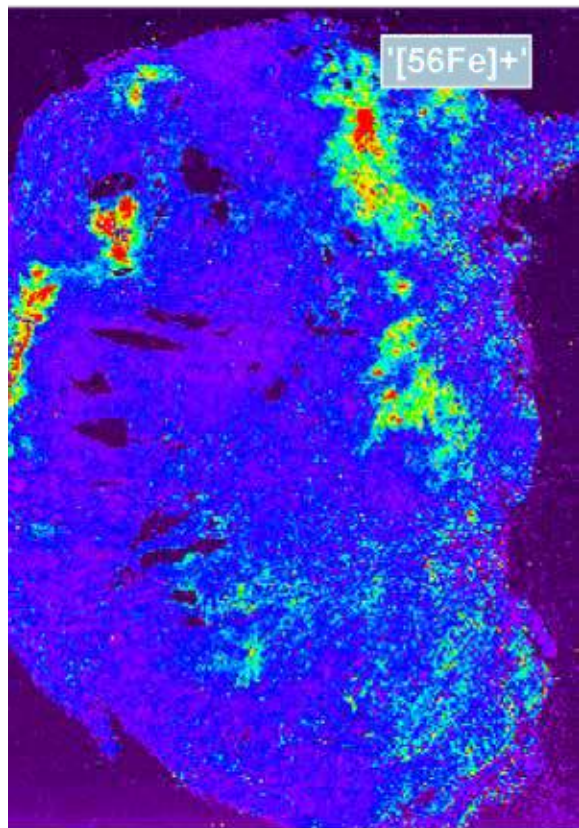
Vadim Kamenetsky and Adam Abersteiner will visit collaborators in Russia during 2019 to obtain samples of chromitites and supergiant Cu-Ni-PGE Noril'sk deposit for their future projects (ARC Discovery and ARC DECRA).

Program Five

Analytical research

Objectives

- 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 2018, a significant proportion of research activities were focussed on projects that underpin the research occurring within the ARC TMVC Research Hub.

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.

Highlights

Research

- New collaboration has started with the University of Kiel, focussed on the application of nano-powder pressed pellets as reference materials for LA-ICP-MS.
- Development commenced of applications for quantification of compositions of micro-inclusions in minerals using ICP-TOF-MS.

Equipment

A working prototype of the fast-response, low-dispersion ablation cell for LA-ICP-MS set-up has been applied to imaging of element distribution in geological and biological materials.

Software

LADR, the new data reduction software for LA-ICP-MS, has been commercialised by UTAS in collaboration with Norris Scientific. Software is now available globally.

Staff

The team welcomed Dr James Tolley as a Research Fellow in LA-ICP-MS. Prior to joining CODES Analytical Laboratories James completed his PhD in geochemistry and petrology at the ANU.

In January 2018 TMVC student Nanda Mrabawani started her PhD focussing on developing quantitative methods for LA-ICP-MS analyses of minerals.

Conferences

Team members were involved in a number of major conferences and workshops in 2018, including a Workshop on Laser Ablation data reduction (China), the European Workshop on Laser Ablation 2018 (France), Geoanalysis 2018 (Australia); and the Goldschmidt Conference and related workshop entitled 'Mineral-Hosted Melt Inclusions: How do we read the stories they have to tell?' (USA). In total, team members produced over 20 conference abstracts.

An invited presentation at the Laser Ablation Workshop in China described the latest developments in the geological application of laser ablation. A keynote at the workshop, also entitled 'Mineral-Hosted Melt Inclusions: How do we read the stories they have to tell?', summarised the main developments in this field over the past 20 years.

OPPOSITE PAGE: (TOP) This image is an elemental map of a thin section of a human brain sample. Elemental bio-imaging was conducted with a technique similar to that used for geological samples and the investigation of element zoning. This image was collected as part of a collaboration with the atomic medicine group at the University of Technology Sydney (UTS) looking at various metal distributions in cancer. CODES houses a state-of-the-art time-of-flight mass spectrometer that allows for a significant increase in laser mapping speed, improved resolution of images and a larger element list than is done on more traditional mass spectrometers. The UTS group is using these laser maps to better understand how different elements affect how cancers grow and respond to treatment. (BOTTOM) Dr James Tolley performing a sample exchange in the geochronology laser ablation laboratory at CODES.



Program 5 team members for 2018: L–R: Jay Thompson, Ivan Belousov, Sasha Stepanov, Leonid Danyushevsky, Paul Olin (standing), James Tolley (standing) and Elena Lounejeva.

The program team

LEADER LEONID DANYUSHEVSKY

DEPUTY LEADER SEBASTIEN MEFFRE



TEAM MEMBERS:

Ivan Belousov, Angela Escolme, Elena Lounejeva, Paul Olin, Sasha Stepanov, Jay Thompson, James Tolley

PHD STUDENTS:

Nanda Mrabawani, 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

Pavel Plechov

NORRIS SOFTWARE

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



The triennial International Association of Geoanalysts conference was held at Macquarie University in Sydney during July 2018; CODES team members to attend were Leonid Danyushevsky, Paul Olin, Ivan Belousov, Jay Thompson and Elena Lounejeva.

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



Jeff Steadman and Irina Zhukova inspect the sample chamber of an LA-ICP-MS at CODES, while Aleksandr (Sasha) Stepanov (seated) programs a series of LA-ICP-MS analyses.

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 2018 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.

A manuscript covering an investigation of robust plasma conditions focussed on deriving internally consistent values for international reference materials is in the final stages of preparation and we aim to submit this in 2019.

FUNDAMENTALS OF LASER ABLATION

Leader: Leonid Danyushevsky

Team members: Sebastien Meffre, Paul Olin, Jay Thompson, James Tolley

Student: Nanda Mrabawani

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 2018, research continued within the project, which is jointly funded by Laurin Technic. The focus was on the characterisation of ablation processes in silicate minerals. Key research activities focussed on:

- Developing approaches to quantitative analyses of plagioclase and apatite for a wide range of trace elements. This research is part of Nanda Mrabawani's PhD project.
- Developing applications for imaging of trace-metal distributions in biological tissues using time-of-flight mass-spectrometry (TOF-MS) coupled to the low dispersion ablation cell.

- Developing applications 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.



Fusion of rock powders mixed with borate flux at ~ 1000°C using CLAISSSE M4 FLUXER TM during sample preparation for chemical analysis of rocks via X-ray fluorescence (XRF). The melt is released into a flat mould and, after cooling, results in a glass disk ready for XRF analysis of major chemical constituents.

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

Collaboration began in 2018 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 2018, 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, Sebastien Meffre

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 effects of various analytical parameters on the accuracy and precision of U-Pb dating of zircon was published in the *Journal of Analytical Atomic Spectrometry*.

Throughout the year the focus was on developing applications for U-Pb dating of 'non-traditional' minerals, such as epidote and calcite.

LA-ICP-MS DATA REDUCTION SOFTWARE

Leader: Leonid Danyushevsky

Team members: Angela Escolme, Sebastien Meffre, Sasha Stepanov, Jay Thompson

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 2018 were directed towards developing algorithms for advanced U-Pb dating applications and for quantitative gold deportment in concentrates of zoned pyrite.

OPPOSITE PAGE: Supergene copper mineral samples prepared as round mounts for characterisation studies.

Looking forward

The team will further develop its analytical research in 2019, and continue working in close collaboration with the TMVC Research Hub. Developments are expected to include:

- Investigating the applicability of the LA-ICP-TOF-MS instrument for imaging trace metal distribution in biological tissues.
- Collaboration with Bristol, Grenoble, Kiel and Quebec universities and Moscow State University on the characterisation of a wide range of mineral reference materials.
- 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 focusses 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, multielement 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, 2018 highlights for Program 6 include:

- Successful completion of Martin Gal's project on analysis of ambient microseismic signals using a new approach for processing passive seismic array data.
- Preparation of publications from Esmaeil 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 magnetotelluric measurements by Tom Ostersen in his PhD study.
- Development of new code to model 3D seismic wave propagation in near-mine environments due to non-point sources by Stewart Jackson in his Honours study.

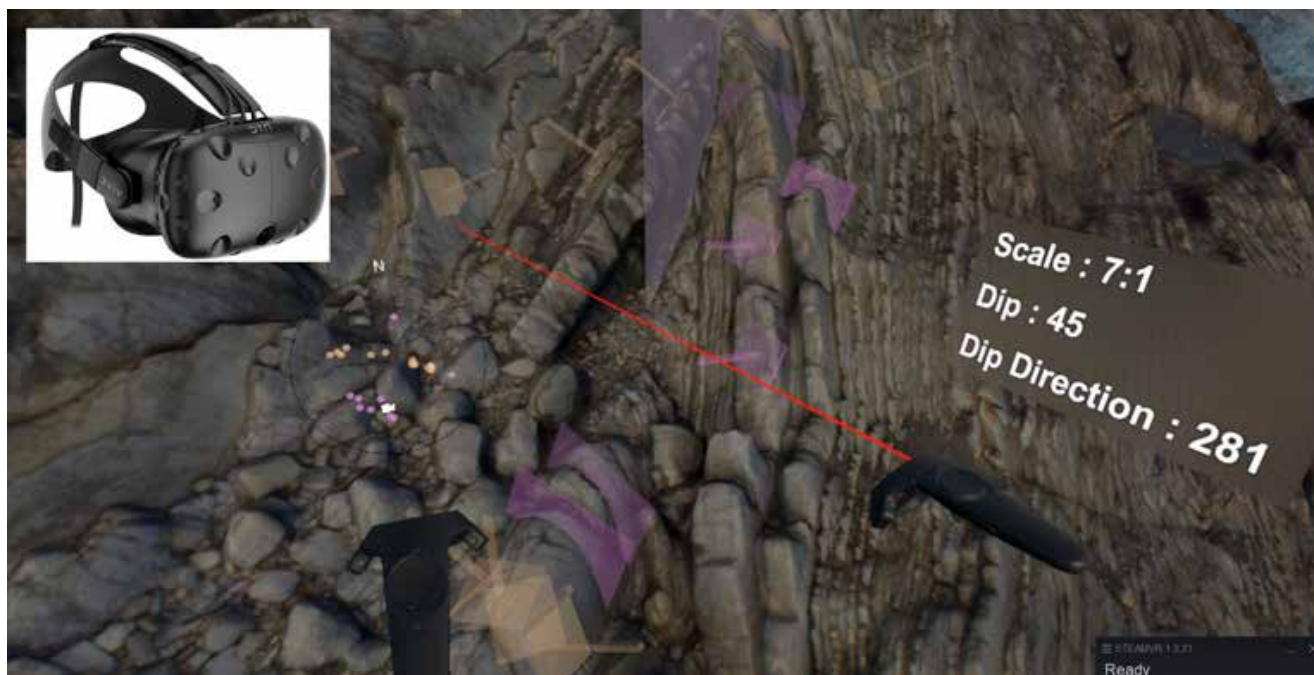
OPPOSITE PAGE: (TOP) Photo-realistic virtual 3D model of flow banded rhyolite, Rotorua, NZ, taken from Michael Roach's Virtual Geology project. (BOTTOM) Esmaeil Eshaghi following his PhD graduation ceremony in 2018. Esmaeil, whose PhD was titled 'The geophysical investigations of Tasmania at multiple scales', actually graduated in 2017 but returned to take part in a graduation ceremony last year.

In the field of computational science and data visualisation, the major achievements of 2018 were:

- Development of new software for virtual reality and augmented reality analysis of geological data sets.
- Roll-out of unsupervised machine learning algorithms for regional- and local-scale mapping and prospectivity modelling under the Hydrogeological Landscape (HGL) Framework.

In the area of technology transfer a major highlight was:

- In May/June 2018 Professor Anya Reading completed a visit to the UK where she gave seminars at the University of Oxford and University of Cambridge. The academic visits focussed on the ongoing research of her Program 6 group, in particular the use of seismic signals to reveal shifting patterns of storms in the Southern Ocean.



The Virtual Geology project is developing software for analysis of geological features in immersive reality. This image shows a screen capture of a virtual reality session in GeoVisVR showing interactive measurement of structural features; the insert shows an HTC Vive virtual reality headset.

The program team

LEADER MICHAEL ROACH

DEPUTY LEADER MATTHEW CRACKNELL



TEAM MEMBERS:

Esmail Eshaghi, Martin Gal, Anya Reading

PHD STUDENTS:

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

HONOURS STUDENTS:

Stewart Jackson, Tim McDonald

COLLABORATORS:

CSIRO OCEANS AND ATMOSPHERE FLAGSHIP

Mark Hemer

FIRST QUANTUM MINERALS

Tim Ireland, Chris Wijns

GEOLOGICAL SURVEY OF SOUTH AUSTRALIA

Kate Robertson, Stephan Thiel

GEOSCIENCE AUSTRALIA

Patrice de Caritat

GHD

Hugh Tassell

INSTITUTE OF MINE SEISMOLOGY

Gerrit Olivier, Brian Salmon

MINERAL RESOURCES TASMANIA

Mark Duffett

UNIVERSITY OF CANBERRA

Alie Cowood, Leah Moore

UNIVERSITY OF TASMANIA, SCHOOL OF TECHNOLOGY, ENVIRONMENTS AND DESIGN

Christopher Lueg

UNIVERSITY OF UTAH, USA

Keith Koper



John Bishop of Mitre Geophysics (standing) discusses new results from an industry, state government and UTAS collaboration with PhD student Thomas Ostensen (centre) and Michael Roach. Others present were team members Anya Reading, Matthew Cracknell, and Mark Duffett (Mineral Resources Tasmania).

Projects

Geophysical investigations of Tasmania at multiple scales

Integrating geology and geophysics for resources targeting

Geodata analytics, visualisation and decisions

Seismic array investigations of ocean storms

Virtual Geology

Magnetotelluric imagery of the Earth's crust and mantle

Elastic modelling of seismic wave propagation in mine environments

Project summaries

GEOPHYSICAL INVESTIGATIONS OF TASMANIA AT MULTIPLE SCALES

Leader: Anya Reading

Team members: Esmaeil Eshaghi, Michael Roach

Collaborator: Mark Duffett

This project concluded in 2018 with research documenting the PhD research of Esmaeil Eshaghi (who graduated in 2017) being prepared for publication. In particular, our understanding of the upper crustal architecture of north and northwest Tasmania was improved through better constrained rock properties, such as density and magnetic susceptibility, property and geometry modelling. This enabled the 3D geometry of lithological units, for example granite bodies potentially associated with mineralisation, to be investigated and refined.

INTEGRATING GEOLOGY AND GEOPHYSICS FOR RESOURCES TARGETING

Leader: Matthew Cracknell

Team member: Anya Reading

Collaborators: Patrice de Caritat, Alie Cowood

In collaboration with Geoscience Australia's Minerals Division and the University of Canberra's Institute of Applied Ecology, this project has developed methods for the meaningful integration of geoscience data for regional resource targeting and management. The focus of this project has been the investigation of approaches for appropriate handling of geoscience data with different scales and spatial supports (geometries). This has ultimately contributed to the development of novel pre-processing methods that facilitate bringing data together and unique visualisation and analysis methods that aid the interpretation of resulting models.

In 2018, collaborations with the University of Canberra have continued the application of unsupervised clustering for local- and regional-scale land management mapping projects within the Hydrogeological Landscape

(HGL) Framework. The roll-out of automated HGL mapping in several regions across New South Wales is ongoing. While these computer-assisted mapping methods were specifically developed for defining land management zones the learnings gained from this project have implications for geologically focussed mapping projects.

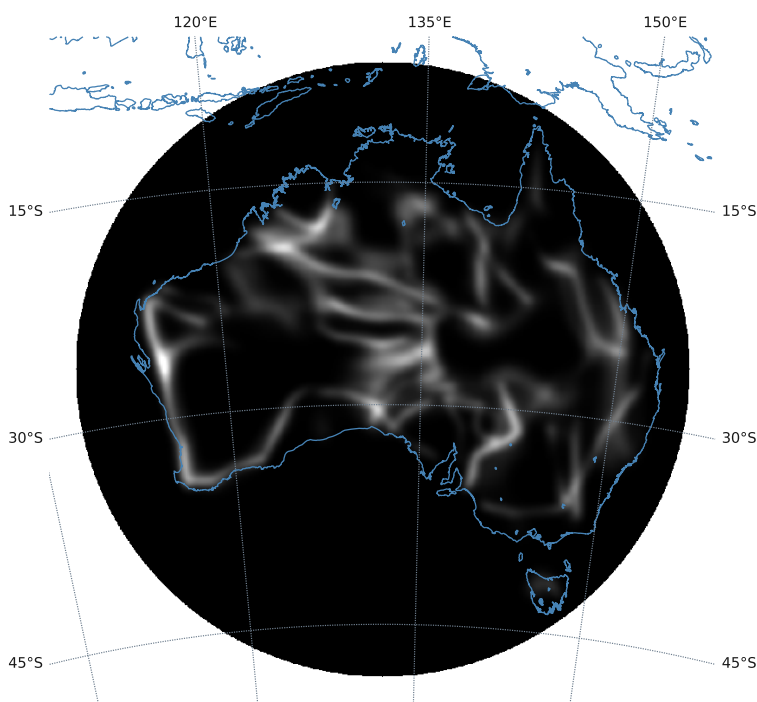
GEODATA ANALYTICS, VISUALISATION AND DECISIONS

Leader: Anya Reading

Student: Peter Morse

Collaborator: Christopher Lueg

This project expands the scope of research undertaken within CODES and the Discipline of Earth Sciences into geodata analytics and innovative visualisation strategies. During 2018, PhD student Peter Morse continued computational work on both colour usage and interactive volumetric visualisation tailored to data sets in geoscience. A number of innovations were explored during 2018 including the use of L-A-B colour spaces which enable the linearity of a data space to be better matched to the inherently non-linear colour perception of a human analyst.



This image shows probabilistic detection of deep lithospheric boundaries from multiple geophysical data sets. The method is developed for use in the Antarctic interior, but is here tested on Australia. The image was submitted for publication in a co-authored paper by Tobias Staal in 2018, and formed part of his PhD research within Program 6.

SEISMIC ARRAY INVESTIGATIONS OF OCEAN STORMS

Leader: Anya Reading

Team member: Martin Gal

Collaborators: Mark Hemer, Keith Koper

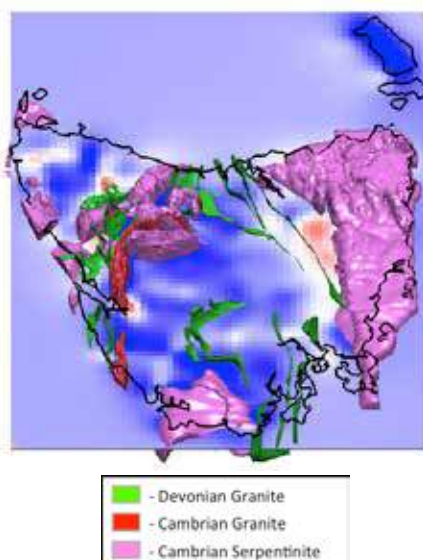
This project concluded in 2018 with a further publication documenting the pulse-like nature of seismic microseism signals and an invited review chapter contributed to a book published by Cambridge University Press. This research progress followed earlier success in the project where postdoctoral researcher Martin Gal developed a seismic array technique that does not require averaging over time and hence allows us to view the seismic wavefield in refined detail. Computational work for this research was done in 2018 under the final year of ARC DP150101005. A summary publication is being prepared to assess the changes in wave climate and hence inform risk management for coastal communities.

VIRTUAL GEOLOGY

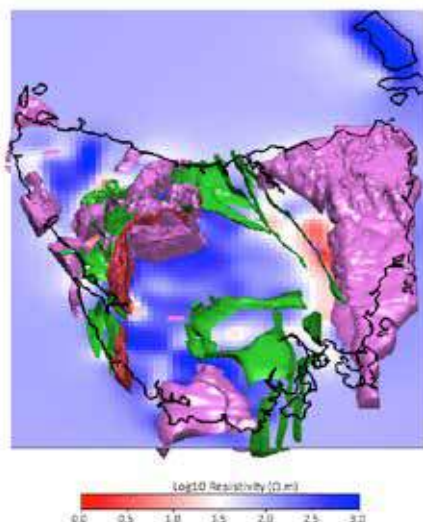
Leader: Michael Roach

This project builds on the outcomes of the AusGeol Virtual Library of Australia's Geology project that was externally funded until 2017.

5.5 km depth slice



7.4 km depth slice



Images taken from Thomas Ostensen's PhD research showing that the resistivity structure of the Tasmanian upper crust is largely determined by pore space fluid content of rocks. The most resistive parts of the crust correspond to regions extensively intruded by low porosity crystalline granites in southwestern and eastern Tasmania. Highly conductive regions reflect terrain boundaries where crustal-scale thrust faults associated with Cambrian serpentinites have led to the formation of fracture-related porosity and thus reduced resistivity.

A main focus of new work in 2018 was on development of software for analysis of geological features in immersive virtual reality using HTC Vive headsets. The new freeware application, GeoVisVR, facilitates structural analysis and annotation of 3D photo-realistic geological models within a full VR environment. It allows the user to easily move within the virtual environment and make measurements using the VR hand controllers.

The potential applications of marker-base augmented reality have also been explored through generation of some

trial applications to display 3D objects and associated audio commentary using smart phones and tablets.

The focus of virtual data collection in 2018 moved from field-base localities to digitisation of specimens. Much of the UTAS first-year teaching collection has now been digitised as 3D photorealistic virtual models. Significant progress has also been made with digitisation of museum-quality economic geology specimens from UTAS and staff collections with the aim of producing mining and exploration-related virtual teaching materials.



FAR LEFT: Photo-realistic virtual 3D model of a sample of fluorite-cemented breccia showing information hot spots developed as part of Michael Roach's Virtual Geology project. LEFT: Another photo-realistic virtual 3D model of folded flow-banding in dacite at Karekare, NZ.

MAGNETOTELLURIC IMAGERY OF THE EARTH'S CRUST AND MANTLE

Leader: Anya Reading

Student: Thomas Ostensen

Team members: Matthew Cracknell, Michael Roach

Collaborators: Mark Duffett, Kate Robertson, Stephan Thiel

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) is a national initiative 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. The computing was impacted by flooding (May 2018) that affected the UTAS high-performance computing infrastructure.

Final interpretation, including integration with updated geophysical data sets for Tasmania, is now underway. 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 is being employed to investigate relationships between the newly determined conductivity structures at depth, and

crustal architecture such as granite bodies. This will inform both mineral and geothermal prospectivity for Tasmania.

ELASTIC MODELLING OF SEISMIC WAVE PROPAGATION IN MINE ENVIRONMENTS

Leader: Martin Gal

Student: Stewart Jackson

Collaborators: Gerrit Olivier, Brian Salmon

Stewart Jackson's Honours project, which concluded in mid-2018, involved the development and testing of new code to numerically model 3D elastic wave propagation in mine

environments. The project was undertaken in collaboration with the Institute of Mine Seismology to facilitate full-waveform inversion of seismic arrivals from mining-induced seismic events. Stewart's code implemented a 4th order implicit finite difference approximation of the elastic wave equation. The code was tested using a detailed 3D physical property model of the Renison Tin Mine in western Tasmania, and successfully simulated the recorded seismograms from local seismic events. A novel and significant aspect of Stewart's new code is the ability to model wavefields resulting from distributed non-point sources that more accurately represent movements on small faults than solutions provided by pre-existing software.

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 data sets at a wide range of scales.

Geological visualisation development in 2019 will focus on new applications for visualisation in geological education at undergraduate, postgraduate and professional levels. Some new developments will be conducted in collaboration with staff from the University of South Australia and this work has recently received funding (December 2018) from the Australasian Institute of Mining and Metallurgy Education Endowment Fund. This AusIMM supported project will include development of a virtual resource that documents all aspects of the Savage River mining operation from exploration to ship loading; this will involve integration of a wide range of media into a single coherent virtual tour.

From a geophysical perspective, Tom Ostensen will complete his PhD project on the crustal and upper mantle electrical structure of Tasmania in 2019. Tom's new 3D electrical models will provide a fresh perspective on the intermediate and deep structure of Tasmania.

A new area of significant geophysical focus will be on characterisation and analysis of the stability of mine tailings facilities. This work will be undertaken in conjunction with the Institute of Mine Seismology and the engineering/environment consultancy GHD, and will involve a combination of novel seismic data collection and analysis approaches coupled with numerical modelling of seismic wave propagation in this complex environment. Stewart Jackson's PhD project, which commenced in December 2018, will focus on these new seismic methods and data analysis techniques.



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.

OPPOSITE: (TOP) Reconnaissance surveying the northern lobe, King River delta, western Tasmania, prior to geophysical analysis and field sampling conducted as part of Sibeles Nascimento's PhD research. (BOTTOM) Lejun Zhang reviewing open pit geology maps at Tujuh Bukit mine in Indonesia with Viki Arianda (obscured) and Mochammad Hafid Rahadi of PT Merdeka Copper Gold Tbk, during fieldwork for AMIRA project P1202 during 2018.

Highlights

As the TMVC entered its penultimate year in 2018, several sub-projects were brought to successful conclusions. The ongoing positive impacts of the TMVC research program are reflected in nine new industry funders joining the Hub, with additional industry funding being secured from our existing and new industry partners, and two new staff, seven PhD students, two MSc students and seven Honours students recruited to the TMVC in 2018.

Notable achievements during the year included new PhD student Javier Merrill receiving an Australian Minerals Industry Research Scholarship from the Minerals Tertiary Education Council to support his research, and Jing Chen winning the best student talk on porphyry, skarn, and epithermal deposits at the 14th National Conference on Mineral Resources of China, held in Shijiazhuang, Hebei Province, China. There were also several keynote and invited presentations and workshops at various conferences around the world across all the Hub themes. The Haddon Forrester King Medal, a career award for life-long achievement, was presented to TMVC Director Professor David Cooke at a ceremony at the Australian Academy of Science's Shine Dome in Canberra in September 2018. Professor Cooke conducted a speaking tour of Australia in conjunction with receiving the award, giving presentations to academia, government and industry in all of Australia's states and territories.

The major sub-project of the TMVC (AMIRA P1153) was brought to a successful conclusion in June 2018. Final sponsors' meetings were held in Australia and the USA, and technology transfer workshops were run in Canada, Sweden, the USA, Chile and the UK, along with a four-day sponsors' field meeting at Yerington, Nevada. Sponsors were provided with new tools, workflows and software to facilitate exploration in green rock and lithocap environments.

The success of P1153 led to additional industry funding being secured for a new sub-project (AMIRA P1202) which commenced in July 2018. P1202 will unify all of the research themes of the TMVC (early exploration, geometallurgical and geoenvironmental characterisation, data analytics and microanalytical innovation) as the

culmination of the TMVC research program. The additional industry funding secured by P1202 has ensured that TMVC postdoctoral and professional staff and new PhD students will be able to continue working on the TMVC research program after ARC funding ends in mid-2020.

Another major sub-project was initiated in Theme 1 during 2019. The exploration footprint of low sulfidation epithermal veins are being investigated at Cerro Negro, Argentina, to develop new methods to aid discovery and to aid in mine planning. The project is being funded by new industry partner Goldcorp and led to the recruitment of a new postdoctoral research fellow to the Hub in 2018 (Francisco Testa).

The major highlight for Theme 2 in 2018 was the completion of Cassady Harraden's PhD study. This study involved close collaboration of the academic team with industry partners at Corescan and Newcrest to develop methods to extract morphological, mineralogical and geotechnical parameters from Corescan data. The project also evaluated the application of microXRF, LA-ICP-MS and LIBS techniques to measuring Au and sulfide grain sizes. The geotechnical methods developed through this research are currently being upscaled by Corescan and the resulting outputs will become routine deliverables for Corescan's industry, government and academic clients. Corescan is also currently reviewing the results of the grain size work and assessing the value and logistics of upscaling these methods for commercial applications.

The Theme 3 research team made significant advances in the characterisation and prediction of mine wastes from active mine sites and legacy sites. Several student projects were completed, and others were initiated. Our research outputs were delivered to partners and the broader industry and academic communities through conference presentations, workshops and journal articles.

2018 was a particularly productive year for student projects, with the submission of 13 theses: three PhD, one Masters and nine Honours. Our publication outputs included 23 refereed journal articles, one book chapter, 36 conference presentations and 82 reports to industry.

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, Nathan Fox, Bruce Gemmell, Wei Hong, Ross Large, Elena Lounejeva, Sebastien Meffre, Paul Olin, Evan Orovan, Anita Parbhakar-Fox, Anya Reading, David Selley, Sasha Stepanov, Stephanie Sykora, Francisco Testa, Jay Thompson, Lejun Zhang

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LAURIN TECHNIC: Michael Shelley

NEWCREST MINING: Anthony Harris

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CHINA UNIVERSITY OF GEOSCIENCES – WUHAN:
Jian Ma

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HEFEI UNIVERSITY OF TECHNOLOGY: Xin Xiao

**GUANGZHOU INSTITUTE OF GEOCHEMISTRY,
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Rosana Balangue



TMVC PhD student Kyle Eastman reviewing drill core from the Tumpangpitu porphyry at Tujuh Bukit, Indonesia.

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)

- Applying the explorers' toolbox to discover porphyry and epithermal Cu, Au and Mo deposits (AMIRA P1153)
- 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
- Honours projects at the Prince Darwin, Glen Lyell and western Tharsis prospects, Tasmania, and the Mount Cassidy porphyry prospect, Queensland
- Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits (AMIRA P1202) – Modules 1-3

THEME 2: OPTIMISING GEOMETALLURGICAL PREDICTION

- Geotechnical and geometallurgical assessment of the Cadia East deposit using Corescan automated core logging technology
- Geological and geometallurgical characterisation of QPG veins, Mankayan District, Philippines
- Geology and geometallurgical characterisation of the high Au, low Cu material at West Dome, Telfer
- Characterising supergene copper mineralogy using hyperspectral techniques
- Quantification of gold-bearing pyrite in processing samples from Lihir gold mine
- 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

- Integrated waste classification for best practice AMD prediction
- 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
- Mineralogical and geochemical characterisation of historical slag: Evaluating environmental impacts and economic significance

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
- Line scan technologies for drill core
- 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 ICPMS applied to complex matrices

Project summaries

THEME 1: DETECTING PROXIMITY TO ORE (FOOTPRINTS)

APPLYING THE EXPLORERS' TOOLBOX TO DISCOVER PORPHYRY AND EPITHERMAL CU, AU AND MO DEPOSITS (AMIRA P1153)

Leaders: David Cooke, Bruce Gemmell

Team members: Mike Baker, Ivan Belousov, Matthew Cracknell, Evan Orovan, Lejun Zhang

Students: Ayesha Ahmed, Jing Chen, Nic Derome, Amos Garay, Emily Gorner, Rachel Harrison, Josh Phillips, Francisco Testa, Jennifer Thompson, Joseph Vrzovski

Collaborators: Huayong Chen, Jinsheng Han, Peter Hollings, Shiwei Wang, Noel White, Jamie Wilkinson, Fan Yu, Taofa Zhou

AMIRA P1153 was conducted in collaboration with researchers from Lakehead University, the Natural History



Participants of the AMIRA P1153 Yerington field trip meeting: (L–R) Back row: Wolfram Schuh (Freeport), Debora Passos de Araujo (Rio Tinto), Richard Patterson (Rio Tinto), Mike Baker, Lejun Zhang, Radoslav Kehayov (Rio Tinto); middle row: Ayesha Ahmed, Paul Agnew (Rio Tinto), Angela Afonso Rodrigues (Monash), Mario Valdez (MMG), Kyle Eastman, David Cooke, Ingemar Arellano (Freeport), Kyle Lewis (Freeport); front: Tim Ireland (First Quantum) behind grass, Emily Smyk.

Museum, Guangzhou Institute of Geochemistry, and Hefei University of Technology. Analysis of the geochemical signals recorded in hydrothermal alteration halos provided explorers with new methods for assessing district fertility (how large?) and vectoring information (how far, and in what direction?), allowing 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 particular relevance to exploration involving drilling under post-mineralisation cover, or in areas where outcrop is limited or difficult to access.

P1153 successfully concluded in June 2018 with a final sponsors' review meeting at CODES. Sponsors were provided with numerous final reports, an extensive geochemical database, new software to aid exploration targeting, new workflows for geochemical exploration, and new interpretations of the exploration significance of mineral geochemistry data.

In addition to the project's final sponsors' meeting, in 2018 the research team delivered several workshops in Canada, Chile, Sweden and the UK to facilitate the transfer of project outcomes to key industry stakeholders. The team also delivered a one-day technology transfer workshop in Reno, USA, that was followed by a four-day field trip to the Yerington district in Nevada. Journal articles arising from this sub-project in 2018 included Ahmed et al. (*Journal of Geochemical Exploration*) and Testa et al. (*Remote Sensing*) and Testa et al. (*Minerals*).

P1153 postgraduate research projects continued at several study sites (Ayesha Ahmed – Yerington, USA; Amos Garay – Las Bambas, Peru; Josh Phillips – Resolution, USA; Jennifer Thompson – Grasberg and Batu Hijau, Indonesia; Emily Gerner and Joseph Vrzovski – Hemlo, Canada; Nic Derome – Red Lake, Canada). Josh Phillips and Joseph Vrzovski submitted their theses in December 2018. The other postgraduate students will submit their theses in 2019.

PYRITE FOOTPRINTS

Leader: David Cooke

Team members: Leonid Danyushevsky, Angela Escolme, Anthony Harris, Sebastien Meffre, David Selley, Sasha Stepanov, Stephanie Sykora, Lejun Zhang

Students: Xue Gao, Cleodette Lagata, Bin Lin, Jian Ma, Xin Xiao, Chao Wu

Collaborators: Rosana Balangue, Karyn Gardner, Fiona Karaut, Zhanke Li, Paul Napier

Results from Stephanie Sykora's PhD study of the Lihir gold deposit in Papua New Guinea (PNG) were published in two articles in *Economic Geology*, which documented the structural evolution of mineralisation, and the gold deportment in pyrite. Stephanie's gold deportment study was followed up later in 2018 with a pilot study by Angela Escolme and Leonid Danyushevsky (Quantification of gold-bearing pyrite in processing samples from

Lihir gold mine). A pilot study of the pyrite footprint of the Runruno alkalic epithermal gold deposit, Philippines, has been initiated by Angela Escolme and David Cooke in collaboration with Rosana Balangue and PhD student Cleodette Lagata at the University of the Philippines. Samples are currently en-route with analytical work to be conducted in 2019. Jian Ma published the results of the pyrite footprints study at Fengtai, China, in *Ore Geology Reviews* in 2018.

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

Leader: Lejun Zhang

Team members: Mike Baker, Wei Hong

Student: Ben Kowaluk

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

This sub-project was conducted 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.

Two field campaigns were conducted by Lejun Zhang, Mike Baker and Ben Kowaluk that involved mapping, sampling and documentation of geological field relationships. Samples were analysed by reflected light and transmitted light petrography, whole rock, mineral texture and cathodoluminescence techniques.

This sub-project provided the first detailed documentation and synthesis of the geology, alteration and mineralisation of the Hadamiao gold porphyry system. It 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.



MAGMATIC-HYDROTHERMAL TRANSITION FEATURES IN SN GRANITES OF TASMANIA

Leader: Evan Orovan

Team members: David Cooke, Wei Hong, Sebastien Meffre, Jay Thompson, Lejun Zhang

Students: Colin Jones, Emmet O'Keefe

Collaborators: Ralph Bottrill, Andrew McNeill

The project is investigating magmatic-hydrothermal transition textures in a number of granite plutons throughout Tasmania, targeting barren, mineralised, and both S- and I-type granites. Petrogenetic questions

involving pluton construction, magma mingling and schlieren are being addressed, and these features are being linked back to metallogensis and exploration significance.

Wei Hong completed a manuscript for *American Mineralogist* on quartz UST textures in western Tasmanian granites, to be published early in 2019. Colin Jones commenced a PhD study on the petrogenesis of eastern Tasmanian granites in November 2018. He completed several field excursions, presented a poster at the GSA Earth Sciences Student Symposium and an oral presentation at the AusIMM/AIG/ GSA Tasmania Geoscience Forum. His PhD study involves collaboration with researchers from Mineral Resources Tasmania and Geoscience Australia.

Tujuh Bukit open pit mine, southeast Java, Indonesia.



Emmet O'Keefe completed an Honours study of the genesis of the Trial Harbour skarn in western Tasmania. Emmet unravelled a complicated skarn paragenesis that included early prograde anhydrous calcic and iron-magnesian skarn assemblages that were overprinted by several retrograde hydrous assemblages. Minor Zn-Pb mineralisation and an unusual association with Ni were paragenetically constrained. Through careful mineral mapping and Ar-Ar and U-Pb age determinations, Emmet was able to relate the complex and unusual skarn formation with the emplacement of the red Heemskirk granite into host rocks with variable provenances, including ultramafics, dolostones and wackes.

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 Brivido, German Escorza, Cesar Riveros

This sub-project commenced in 2018. It is fully funded by new TMVC funder Goldcorp, and 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 March 2018. Twenty-nine surface samples and 200 drill hole samples were collected for laboratory analysis. TerraSpec measurements were collected from each sample location, and also from surrounding areas and the data were processed by aiSIRIS™.

Two reports were delivered to the project sponsor in 2018.

Geochronology, alteration mineral texture and chemistry studies will be conducted during the first half year of 2019. A second field campaign will be conducted early in 2019.

HONOURS PROJECTS AT THE PRINCE DARWIN, GLEN LYELL AND WESTERN THARSIS PROSPECTS, TASMANIA, AND THE MOUNT CASSIDY PORPHYRY PROSPECT, QUEENSLAND

Leaders: Mike Baker, Lejun Zhang

Team members: David Cooke, Evan Orovan

Students: Fatin Amni Mohamed Amin, Xin Ni Seow, Matthew Vincent

Collaborators: John Hooper, Charles Hughes, Andrew McNeill, Jonathan Robberson, Jim Yaxley

Several Honours studies related to the footprints of mineralisation and/

or mineralising events/processes were conducted in Tasmania and Queensland in 2018. Studies of the Prince Darwin prospect, and Glen Lyell and Western Tharsis deposits in western Tasmania as well as the Mount Cassidy prospect in central Queensland involved mapping, core logging and sampling, petrography, short wavelength infra-red (SWIR) spectral analysis, XRD, SEM, whole rock and mineral geochemistry and LA-ICP-MS.

The Prince Darwin study by Xin Ni Seow determined that REE mineralisation is primarily hosted in allanite, a REE-rich epidote group mineral. Heavy sulfur isotope values from pyrite associated with key alteration stages are consistent with the significant involvement of Cambrian seawater in mineralisation. Fatin Mohamed characterised advanced argillic alteration and related mineralisation at the Glen Lyell and Western Tharsis orebodies,

confirming that high-sulfidation-style mineralisation occurs at Glen Lyell. Matthew Vincent defined two key areas within the Mount Cassidy exploration tenement that are prospective for Au mineralisation, based primarily on the results of SWIR soil and mineral chemistry analysis. These two areas lie on the edge of a zone of anomalous Au delineated by multi-element whole rock geochemical analysis.

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, Jay Thompson

Students: Camila Arcos, Patrick Hamilton, Andrew Jedemann, Mitch Marcelissen, Emily Smyk, Yi Sun

Collaborators: Laurent Ailleres, Robin Armit, Scott Halley, Peter Hollings, Jose Piquer, Noel White

AMIRA P1202 commenced in July 2018 and follows on directly from AMIRA P1153. It is designed to bring together the major research themes of the first three years of the TMVC into our final, major sub-project that will deliver industry transformational workflows to our research partners.

P1202 is a collaboration with researchers from Lakehead University, Monash University and the Universidad Austral de Chile. This three-year sub-project will develop new methods for discovering porphyry and/or epithermal deposits through improved geochemical detection of far-field and near-mine ore deposit footprints.

The P1202 project seeks to develop new tools and workflows that facilitate cost-effective exploration programs and resource assessments for porphyry, epithermal, skarn and other ore deposit types at the regional, district and near-mine scales. It will also seek to refine existing geochemical and geological tools



Francisco Testa setting up the portable TerraSpec Halo, Cerro Negro low-sulfidation epithermal gold district, Patagonia, Argentina, during fieldwork in March 2018 for research within Theme 1.



Angela Escolme (left) and Lejun Zhang (standing at right) onsite with members of the Merdeka geology team at Tujuh Bukit, Indonesia.

for fertility assessments, to establish whether a tenement contains a significant mineral resource and to ensure that deposits are discovered more quickly and at less cost. The project has four research modules, involving green rocks (Module 1), lithocaps (Module 2), magmatic minerals (Module 3) and the transition zone (Module 4). Within the TMVC program structure, the first three modules of P1202 constitute its footprints sub-project, whereas Module 4 is the geometallurgy sub-project.

P1202 currently has 12 sponsors of Modules 1–3 (Anglo American, BHP, Boliden, Codelco, FMG, Freeport, Glencore, Merdeka, Newmont, Newcrest, Rio Tinto and Teck), four of which also sponsor Module 4 (BHP, FMG, Merdeka and Newcrest).

In 2018, the P1202 research team commenced research on several study sites, including localities in Australia, Indonesia, the Philippines, Sweden, Chile, Canada, and the USA. Several of these sites are being investigated by postgraduate students recruited to work on Modules 1–3: Emily Smyk and Yi Sun (CODES); Andrew Jedemman, Patrick Hamilton and Mitch Marcelissen

(Lakehead); and Camilla Arcos (Austral). More students are likely to join the team in 2019.

THEME 2: OPTIMISING GEOMETALLURGICAL PREDICTION

GEOTECHNICAL AND GEOMETALLURGICAL ASSESSMENT OF THE CADIA EAST DEPOSIT USING CORESCAN AUTOMATED CORE LOGGING TECHNOLOGY

Leaders: Sebastien Meffre, Ron Berry

Team members: Matthew Cracknell, Neil Goodey, Anthony Harris

Student: Cassady Harraden

Collaborators: Ronell Carey, James Lett

This PhD project by Cassady Harraden aimed to use Corescan™ data to extract geotechnical parameters from drill core, as well as determine which microanalytical techniques would be best used in conjunction with the Corescan™ system to assess gold and copper grain size. The grain size assessment included a contribution to TMVC project 'T2b: Line scan

technologies for drill core' and a contribution to TMVC project 'T2c: Integrating chemical and mineralogical data layers for element deportment'. Protocols to extract morphological and mineralogical geotechnical parameters have been developed. These parameters can then be modelled in 3D and integrated with the Cadia Mine's current structural, geotechnical and geometallurgical models. Research in 2018 completed the reporting on the application of microXRF, LA-ICP-MS and LIBS to measuring Au and sulfide grain size.

Micro-XRF is suitable for measuring chalcopyrite grain size at a rate compatible with hyperspectral scanning devices (about 3 m/min). The sampling rate was approximately an order of magnitude too slow for an accurate measure of Au deportment, but we expect hardware development to close this gap within the next five years. LA-ICP-MS can measure Au deportment for fine grain Au deposits on samples extracted from the core trays. The laser-induced breakdown spectroscopy (LIBS) needs more work on the software to retrieve higher quality compositional data from the LIBS spectra. Cassady submitted her thesis in May and after corrections graduated in October 2018. A paper on the 'Use of automated core



L–R: Lejun Zhang, Yi Sun, Angela Escolme (all CODES/TMVC) and Leo Subang (Lepanto Consolidated Mining Company) in Mankayan, Philippines, at the ‘Spanish Tunnels’ and type locality for luzonite where they are collecting samples for Yi Sun’s PhD study, which is primarily focussed on the QPG veins at Lepanto. Yi is working within Program 1, the TMVC and AMIRA project P1202.

logging technology for geotechnical assessment’ was submitted to *Economic Geology* in 2018 and is in review. On graduation Cassidy was employed by one of the industry partners.

GEOLOGICAL AND GEOMETALLURGICAL CHARACTERISATION OF QPG VEINS, MANKAYAN DISTRICT, PHILIPPINES

Leaders: Lejun Zhang, Angela Escolme

Team member: David Cooke

Student: Yi Sun

Collaborators: Mervin Delos Santos, Leo Subang

This PhD project is focussed on a quartz-pyrite-gold (QPG) vein and breccia system in the Mankayan District, Philippines. The aims of the project are: 1) Understanding the geology, alteration patterns, mineral textures, chemistry and the genesis of the QPG system; 2) Test and develop geological and

geochemical vectors to high-grade gold mineralisation zones; and 3) Investigate alteration patterns, ore texture and mineral assemblages that may impact on metallurgical processes. Special focus will be given to understanding the deportment of gold and other valuable and deleterious trace elements in the complex mineralogy.

This project was initiated late in 2017 with the first field season completed in February 2018. Yi Sun undertook detailed geological logging, underground mapping, sample collection and SWIR analysis. In mid-2018, the sub-project was rolled into AMIRA P1202, and going forward will be reported as part of that sub-project.

GEOLOGY AND GEOMETALLURGICAL CHARACTERISATION OF THE HIGH AU, LOW CU MATERIAL AT WEST DOME, TELFER

Leaders: Angela Escolme, Ron Berry

Team members: David Cooke, Anthony Harris, Sebastien Meffre

Student: Hannah Couper

Collaborators: James Biggam, Karyn Gardner

The focus of this Honours project, initiated in mid-2017, was to determine the gold deportment in low copper, high gold material from the Telfer’s West Dome ore body in order to recognise value-add opportunities in current processing protocols.

The project included two weeks of fieldwork at Newcrest’s Telfer copper-gold mine where Hannah completed detailed core logging and sampling. A detailed analytical program consisting of petrographic characterisation, mineral liberation analysis and LA-ICP-MS was completed. Hannah was able to identify discrete gold deportment styles associated with paragenesis and degree of weathering, which informed potential new processing

opportunities. The sub-project was completed in May 2018.

CHARACTERISING SUPERGENE COPPER MINERALOGY USING HYPERSPECTRAL TECHNIQUES

Leader: Angela Escolme

Team members: Ron Berry, Sebastien Meffre

Collaborators: David Green, Carsten Laukamp, Angus McFarlane, Jake Moltzen

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. In 2018 full characterisation and collection of SWIR spectra was initiated for the sample suite in order to begin building a spectral library.

QUANTIFICATION OF GOLD-BEARING PYRITE IN PROCESSING SAMPLES FROM LIHIR GOLD MINE

Leader: Angela Escolme

Team member: Leonid Danyushevsky

Collaborator: Karyn Gardner

The Lihir gold mine, PNG, contains both gold-rich epithermal pyrite and gold-poor porphyry stage pyrite. Epithermal pyrite overgrowths have led to high-gold rims forming on barren cores. Understanding the occurrence and proportion of high-gold pyrite is important in processing considerations.

This new project followed on from AMIRA P1153, and was initiated and completed in 2018. It aimed to develop new LA-ICP-MS protocols for quantification and characterisation of gold-bearing pyrite in processing samples from Newcrest's Lihir gold mine. A cost-effective method for LA-ICP-MS analysis and data reduction, which allows for fast throughput, was developed. New protocols enable the accurate measurement of gold-

bearing rims down to two microns thickness on crushed material. The methodology also allows for reporting on pyrite grain size, proportion of gold-bearing pyrite, thickness of gold-bearing rims and the concentration of gold and arsenic in pyrite.

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

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

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

Students: Camila Arcos, Kyle Eastman, Patrick Hamilton, Andrew Jedemann, Mitch Marcelissen, Javier Merrill, Angela Rodrigues, Emily Smyk, Yi Sun

Collaborators: Laurent Ailleres, Robin Armit, Scott Halley, Peter Hollings, Jose Piquer, Noel White

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 four sponsors of Module 4 (BHP, FMG, Merdeka, and Newcrest). Module 4 is a new research initiative involving both near-mine exploration vectoring and geometallurgical assessments of the transition zone, where clay and mica alteration overprints 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 2018, the P1202 Module 4 research team commenced research on several study sites, including localities in Indonesia, Chile, Argentina and Fiji. Several of these sites are being investigated by newly recruited postgraduate students Kyle Eastman and Javier Merrill (CODES), and

Angela Rodriguez (Monash). More students are expected to join the Module 4 team in 2019.

THEME 3: MINIMISING GEOENVIRONMENTAL RISKS

INTEGRATED WASTE CLASSIFICATION FOR BEST PRACTICE AMD PREDICTION

Leader: Anita Parbhakar-Fox

Team members: Matthew Cracknell, Nathan Fox

Students: Rebekah Cornelius, Laura Jackson

Collaborators: Megan Becker, Christopher Brough, Susan Harrison, Gregory Joslin, Jake Moltzen, Seth Mueller

Defining the acid forming potential during the exploration stages of a mining project is critical for financial modelling and waste management planning. However, at such early stages, there are limited resources for evaluating the geoenvironmental characteristics of future waste materials. Considering this, several new methodologies were developed in 2018. First, continuing to add value to the hyperspectral data collected in the project undertaken with Boliden at the Lil-Laverberget porphyry, Sweden, we developed the new *Hy-Gi* which enables Hylogger data to be used for the domaining of geoenvironmental risk. These results were published in the Geometallurgy special issue of *Minerals*. In this special issue we also published the results of a cross-theme collaboration with Matthew Cracknell, whereby we sought to automate the acid rock drainage index. Machine learning algorithms were developed and tested on materials being used in the PhD study currently being undertaken by Laura Jackson.

The international collaboration with the Australian Academy of Technology and Engineering continued with waste materials from three different sites in Africa, Europe and Australia tested. New biokinetic tests and sized



PhD student Stephen Kuhn presenting material at the Machine Learning Workshop at AEGC Sydney, February 2018.

automated mineralogy experiments were performed in addition to accelerated static tests at UTAS. The preliminary results were presented at Process Mineralogy 2018 and all data will be evaluated in early 2019 and final recommendation presented to the ASTM Committee by Q2 2019.

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

Leader: Anita Parbhakar-Fox

Team members: David Cooke, Matthew Cracknell, Nathan Fox

Student: Laura Jackson

Collaborators: Ronell Carey, Mary Harris, 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 2018, PhD student Laura Jackson focussed on how the geoenvironmental domaining index (GDI) can be used with other data sets to enable robust waste classification with a new methodology proposed. The integration of Corescan and laser-ablation ICP-MS data was explored with results presented at the International Conference on Acid Rock Drainage (ICARD) in Pretoria, South Africa. Automation of the acid rock drainage index (A-ARDI) was developed and tested using samples from this project in a workflow designed by Matthew Cracknell with results published in the Geometallurgy special issue of *Minerals*. Laura's PhD thesis will be submitted in Q2 2019.

UTILISING INDUSTRIAL WASTE MATERIALS FOR AMD CONTROL

Leader: Anita Parbhakar-Fox

Team members: David Cooke, Sebastien Meffre

Student: Annah Moyo

Collaborators: Michael Reid, Clint Siggins

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 a new sub-project being undertaken by Annah Moyo. This PhD study commenced in December 2018, and is being funded by Mineral Resources Tasmania. Several industrial waste materials including red muds, green liquor dregs, boiler ash and spent shells are being sourced from across Tasmania and Victoria to test as AMD ameliorants. Mine waste materials are to be collected in early 2019 at several sites across Tasmania representative of high AMD and low AMD environments. Following the initial characterisation of waste materials in a series of static tests, they will be loaded into long-term (100 week) kinetic cells where different packing combinations will be evaluated. Once positive responses (i.e., neutralisation of AMD) have been identified they will be nominated for a field trial.

GEOMETALLURGY OF HISTORIC MINE WASTE: EVALUATING OPTIONS FOR REPROCESSING

Leader: Anita Parbhakar-Fox

Team members: David Cooke, Matthew Cracknell

Student: Sibebe Nascimento

Collaborator: Jennifer Parnell

Strategic mine waste planning has only been actively pursued in the past decades, with historic 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 km² 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 and her supervisors completed three site visits in 2018, collecting sediment samples across the site and conducted geophysical surveys (EM, seismic and IP). As part of this work, Sibebe and the team trialled a new method of imaging trenches in 3D to support field observations as when working in such sites, slumping of trenches is potentially likely which can be prohibitive to logging. In 2019 Sibebe will continue to characterise these materials in the geochemical laboratory but has already identified that pyrite contains high concentrations of cobalt. In 2019 Sibebe will commence flotation and biooxidation test work to determine the best methodology to recover cobalt and other metals.

MINERALOGICAL AND GEOCHEMICAL CHARACTERISATION OF HISTORICAL SLAG: EVALUATING ENVIRONMENTAL IMPACTS AND ECONOMIC SIGNIFICANCE

Leader: Anita Parbhakar-Fox

Team members: Nathan Fox, Paul Olin

Student: Sarah Gilmour

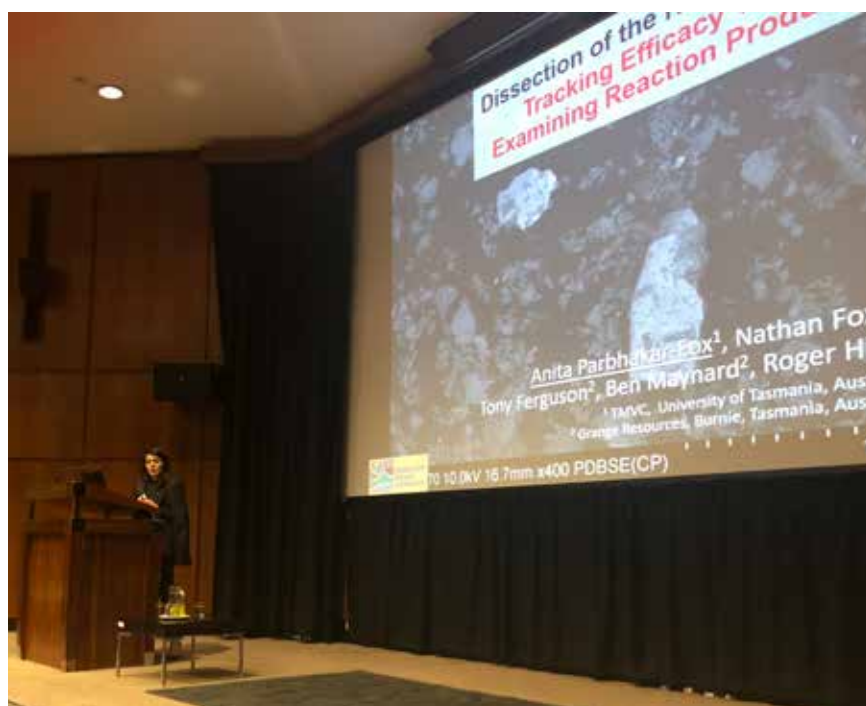
Collaborators: Geoff Cordery, Kim Denwer, Jennifer Parnell

Mine waste materials, produced by several large-scale mines, are abundant in western Tasmania. For example, at the Mt Lyell mine more than 312 Mt of ore at a grade of 1 to 2% Cu were produced during its operation, from Cu-Au VHMS ore bodies around Queenstown. Ore was smelted onsite at Queenstown with 2 Mt of slag dumped on-site. In contrast, the Zeehan ore fields were well endowed with Ag and Pb, with an estimated total ore production of at least 14,000 tonnes of Ag-Pb by 1893. Ore from the Zeehan ore fields was smelted 3 km south of Zeehan leaving over 450,750 t of slag behind. Today, a significant quantity of slag remains at both sites, therefore

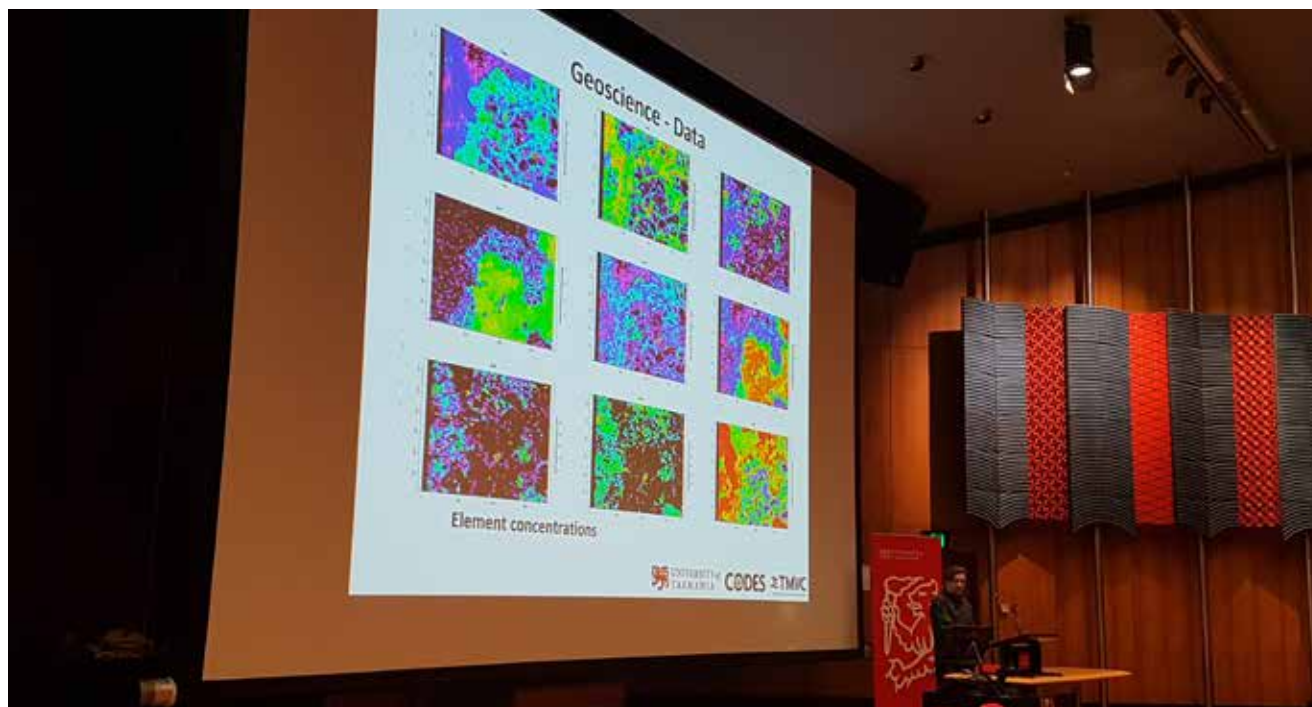
this study undertaken by Honours student Sarah Gilmour aimed to assess the geoenvironmental risks posed to surface and groundwaters and, through mineral and chemical characterisation, to determine if there is potential for reprocessing these wastes as part of integrated rehabilitation strategies.

The Queenstown slags are granulated and vitreous with a matrix of (Si-Fe-Ca-Mn-Zn-O) glass and Cu-Fe-sulfides. Copper and Zn concentrations are between 0.56 % and 0.61 % and 1.79 % and 2.47 % respectively. Copper is dominantly present as Cu-Fe sulfides (30-40 %) and is present in the glass in minor quantities (0.5 to 2 %). The Cu-Fe-sulfides occur as disseminated spheroidal blebs which mineralogically resemble chalcopyrite. These blebs range in diameter (<1 µm to >500 µm) and are proportionately low in this glass dominated slag. The low content of Cu suggests its efficient recovery by the unique pyritic smelting process employed from 1896 to 1921.

The Zeehan slags are hard and siliceous with a matrix of (Si-Fe-Ca-Mn-Zn-O) glass and euhedral and lath-like crystals of (Ca-Fe) olivine, (Ca-Mn-Zn-Fe) clinopyroxene, Zn-Fe-spinels and Zn-sulfides. At Zeehan the



Anita Parbhakar-Fox presenting at the 12th International Conference on Acid Rock Drainage (ICARD), in Johannesburg, South Africa. She presented results about work on exploring the integration of Corescan and laser-ablation ICP-MS data.



Matthew Cracknell giving a presentation at the UTAS Data, Knowledge and Decisions: Research Theme Forum, a public event held during October and designed to introduce UTAS researchers and their projects to a wider audience. His talk was about his work within the TMVC Underpinning Technologies theme.

Zn grade varies between 14 % and 18 % with minor Mn, Al and Pb. Zn is dominantly hosted in dendritic Zn-sulfides and glass but is also elevated in crystalline olivines, pyroxenes and dendritic Fe-spinels.

The sulfide content of the historic slag piles, calculated as maximum potential acidity values (between 84 and 146 kg H₂SO₄/t for Zeehan and between 26.2 and 10.7 kg H₂SO₄/t for Queenstown), indicates that both sites have potential AMD risks with the Zeehan site presenting higher concentrations of leached metals.

The results from this study suggest identified potential risks associated with these historic wastes with a need for active remediation. Provided the reprocessing and extraction of the Zn from Zeehan (via chemical leaching using H₂SO₄) and the base metals (via bioleaching using bacteria) from Queenstown is economically viable the new waste produced would theoretically be environmentally benign and therefore suitable as a construction material. Once the slag materials are treated, any associated geoenvironmental risks will decrease and efforts can begin on the rehabilitation of the surrounding soils, water pathways and vegetation that may have been impacted by the dumps.

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 2018, the third prototype of the fast response cell was developed. The design was informed by testing done on the previous prototype in 2017. Testing of the third prototype involved conducting analyses and assessing the behaviour of the fast-washout instrumentation set-up during routine

analytical runs. The initial testing runs have indicated that the current data reduction software is unable to efficiently process the data acquired with the new cell design. Changes have been discussed with TOFWERK and a new release of the data reduction software was made available in late 2018 which will allow testing of the prototype to continue in 2019.

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

Collaborator: 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 that add 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 available data products.

In 2018, project outputs included an article published in the open access journal, *Minerals*, titled ‘Automated Acid Rock Drainage Indexing from Drill Core Imagery’ that combined research on identification of sulfides and quantification of mineral textures in Corescan RGB photographs. This research solidifies collaborations between Corescan staff and Theme 3 TMVC researchers and PhD students, and documents a practical application of feature extraction and analysis for rapidly and consistently estimating indices of rock acid forming potential. Matthew Cracknell was invited to speak at the ‘AI/ Machine Learning: Opportunities and Challenges for Mineral Exploration’ workshop at AEGC2018 in Sydney. His presentation, ‘Unsupervised Clustering of Geoscience Data’, guides those new to the application of machine learning methods to mineral exploration on best-practice data handling, processing and analysis. With close to 50 participants, this workshop was one of the more popular post-conference events at AEGC2018. In October, Matthew Cracknell and several PhD students hosted a three-day workshop for First Quantum Minerals (FQM). The aim of this workshop was to introduce the fundamental concepts of machine learning and encouraging uptake of TMVC developed algorithms and workflows for mineral exploration by FQM employees.

LINE SCAN TECHNOLOGIES FOR DRILL CORE

Leader: Ron Berry

Team member: Sebastien Meffre

Student: Cassady Harraden

Collaborators: Richard Hark, Thomas Rodemann

The aim of this project was to assess the suitability of various line scan capable technologies for use on drill core as support for hyperspectral scanning machines. Factors assessed include achievable pixel size, acquisition speed, suitability to produce a grain size proxy for gold and base metal sulfides, and accuracy. Data processing of laser Raman, micro-XRF and LIBS technologies were completed on representative samples of drill core. The laser Raman technology was deemed to be unsuitable for analysis of sulfides in drill core. LIBS will only reach its potential in this area after the development of more sophisticated software capable of handling the variable plasma conditions produced by LIBS in this environment. The time required for this development is not easy to predict.

The micro-XRF method, as currently available, is suitable for line scan analysis of sulfides. Analyses collected in 80 milliseconds (200 µm spot size) were suitable for recognition of mineralogy not detected in infrared spectra, for use as training data, and for calculation of the CuS grain size that might be suitable as a proxy for flotation recovery. A gold grain size proxy requires hardware development and is still a few years away. The results were presented to Corescan in 2018 and they are considering options for commercial scale testing.

INTEGRATING CHEMICAL AND MINERALOGICAL DATA LAYERS FOR ELEMENT DEPARTMENT

Leaders: Sebastien Meffre, Matthew Cracknell, Leonid Danyushevsky, Ron Berry

Team members: Ivan Belousov, Nathan Fox, Paul Olin, Sasha Stepanov

Students: Cassady Harraden, Laura Jackson

This project aims to integrate mineralogical and chemical data from various spectral and analytical techniques in order to extract information on element department, 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 Hot Chili’s La Productora Deposit in Chile utilising synchrotron, MLA and LA-ICP-MS methods were compared in order to investigate element department. Processing is expected to be completed in 2019.

The initial results on these samples suggest that significant challenges remain with producing mineral department data from complex samples. In 2018, a new sample set was sourced to further test the integration of mineral chemistry and department data from different techniques. A set of samples which have been characterised using the micro-XRF (Bruker Tornado) from the Carlin deposit will be analysed using MLA and LA-ICP-MS in 2019.

INTERPRETING STRUCTURAL AND GEOCHEMICAL PATTERNS USING MACHINE LEARNING

Leaders: Matthew Cracknell, Anya Reading

Student: Shawn Hood

Collaborator: Michael Gazley

This PhD project aims to develop novel approaches for interpreting large data sets of metalliferous-ore exploration and mining data. To achieve this, computational methods are being used to represent and interpret geological patterns in three dimensions. More specifically, machine learning methods are being developed and tested for the statistical inference of structural and geochemical patterns around hydrothermal ore deposits. This research encompasses three main aims:

- Investigation of metasomatic alteration using clustering and classification of geochemical data



David Cooke and Angela Escolme absorbed in a presentation at the Evolution Chile Explore Congress 2018, held in Santiago, Chile, during October.

to construct models of element migration.

- Creation of models of permeability networks in complex structural environments using automated statistical inference of structural geology data.
- Creation of three-dimensional ore deposit prospectivity models by combining statistical geochemical and structural models.

These research activities involve automated workflows developed using open source software and aim to rapidly generate repeatable and objective three-dimensional models of geologically relevant features with input from geoscientists. A chief goal is to produce practical workflows that fit seamlessly into existing industry methodology for defining ore bodies, especially in brownfields environments. During 2018, PhD student Shawn Hood published results in the *Journal of Geochemical Exploration* outlining a novel approach for the identification of protolith and altered equivalent lithologies. This work forms the basis for robust statistical estimation of element mobility in hydrothermally controlled ore deposits, research

that Shawn Hood summarised in a presentation at RFG2018, Vancouver, Canada. Other outputs from this project include numerous reports to industry partners such as Saracen Mining Ltd and Gold Fields Australasia.

GEOLOGICAL FEATURE DISCOVERY FROM QUANTITATIVE DATA INTEGRATION (ALGORITHM DEVELOPMENT)

Leader: Anya Reading

Team member: 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 2018, a paper was published on geophysical reconnaissance-stage research with demonstration studies incorporating geochemical sampling and preliminary ground-based mapping following through the year with two further papers submitted/ in preparation. Significant progress was made for a case study in North America whereby the interim products of a machine learning exercise highlight the most likely areas for the occurrence of key lithologies. This represents very valuable progress in the application of machine learning methods to areas with lithological units that are difficult to distinguish.

Visualisation development activities also took place with the development of interactive software which enables insights to be drawn from contour maps allowing for a better understanding of human colour perception and the confidence levels in the data set. A demonstration study is described in a paper in preparation and the extension of the work to 3D through the balance of luminosity and

transparency is ongoing through the work of Peter Morse.

The project leader, Professor Anya Reading, gave an invited presentation at the first meeting on Machine Learning in Solid Earth Geoscience in Santa Fe, New Mexico (February 2018), on 'Optimising Insights from machine learning in geoscience', and contributed as co-Director to the institute-wide UTAS Research Theme on Data, Knowledge, Decisions.

METHOD DEVELOPMENT FOR LASER-ABLATION ICPMS APPLIED TO COMPLEX MATRICES

Leader: Leonid Danyushevsky

Team members: Elena Lounejeva, Jay Thompson

Student: Nanda Mrabawani

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. 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.

During the year work began on developing quantitative methods of analysis of apatite and plagioclase. Suitable quantities of mineral specimens of apatite and bytownite plagioclase (approximate composition of An₆₀) were acquired. The specimens have been crushed to 1–3 mm fraction and their homogeneity in major and minor element contents assessed using electron microprobe at the CSL. Splits of the specimens have been milled to powder and submitted for bulk analysis by XRF and solution ICP-MS at CODES Analytical Laboratories. LA-ICP-MS method development for these two minerals will commence in 2019.

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 23 refereed journal articles and one book chapter, provided 82 reports and 11 on-site presentations to industry, and delivered 36 conference presentations and five 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 the UTAS Data, Knowledge and Decisions: Research Theme Forum, a public event held in October, and the 'Pint of science' in May.

Professor David Cooke conducted a speaking tour of Australia in conjunction with his receiving the Haddon Forrester King Medal, giving presentations to academia, government and industry in all of Australia's states and territories.

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 be the focus of activity for many Theme 1 and 2 researchers. 2019 will see field campaigns at sponsor study sites and a major program of data acquisition, as well as sponsor review meetings in Hobart (June, November) and Santiago (October).

Theme 1 is also hopeful of one to two new PhD projects commencing in the Cerro Negro district as part of a further extension to the study initiated by Francisco Testa in 2018.

Theme 3 will see PhD students Annah Moyo and Sibebe Nascimento continue with their studies in Tasmania. Annah will be collecting mine waste materials from several sites around the state, followed by characterisation in a series of static tests. Sibebe will be conducting additional geophysical surveys at Macquarie Harbour, as well as commencing flotation and bio-oxidation test work on collected sediment samples.

Underpinning Technologies researchers will further investigate the development and application of Corescan derived textural indices to diverse applications such as brownfields ore deposit exploration and geometallurgical process control. Research on optimising workflows and applying the visualisation development work to improving the way that insights are gained from high dimension geochemical data is also expected to be completed. PhD candidate Nanda Mrabawani will commence LA-ICP-MS method development for apatite and bytownite plagioclase as part of her project, and testing of the third prototype of the high-throughput laser cell will continue in collaboration with Laurin Technic.

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

Conference-related activities and journal publications will remain a key avenue for TMVC staff and students to present Hub research outcomes. Representation at several key conferences will occur during the year, including at Pacrim (Auckland), IUGG (Montreal), SGA (Glasgow) and SEG (Santiago). Publications in key research journals such as *Economic Geology* and *Chemical Geology* are also expected.

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



Participants in the Exploration Field Skills Mapping Camp pictured at the Iron Blow Lookout in Queenstown, Tasmania, in February 2018.

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

It was another good year for the Training and education program, with healthy enrolments for the HDR and Master of Economic Geology programs, and increased enrolments in the Honours program and associated coursework components. There were ten new admissions to the HDR program, which included two Australian students. About half of the current HDR student cohort are Australian, and half from overseas (from a total of 16 countries). Five PhD students and one MSc student graduated in 2018, and a further six PhD students have theses under examination.

It was one of the busiest years on record for the Master of Economic Geology program, with the largest ever intake of new (19) and returned (1) students, and healthy enrolments in all three short courses. Unit enrolments were up 23% on last year, and 82% on 2016 enrolments. Seven more students completed the Master of Economic



MEconGeol students in the Bluestone Bay mapping area pictured during the 2018 Ore Deposit Models and Exploration Strategies short course (October/November).

Geology degree in 2018. The main highlight of the MEconGeol teaching program in 2018 was a special three-day symposium to commemorate the career contribution of our much-loved and highly respected colleague, Garry Davidson, who passed away in April 2017. The symposium kicked off our final short course for the year: 'Ore Deposit Models and Exploration Strategies' in late October. The symposium addressed deposit genesis and exploration strategies for the ore deposit types that Garry had devoted so much of his working life to characterising and understanding; namely IOCG, uranium, sediment-hosted Pb-Zn and copper, Broken Hill-type, volcanic-hosted massive sulfide and orogenic gold deposits. It was attended by 130 people with presentations from 28 of Garry's former colleagues, students and collaborators.

Another important event hosted by CODES and the Discipline of Earth Sciences was the very successful second GESS Symposium (known as GESSS-TAS) which took place on 16 November. More than 80 people registered for the symposium, which featured keynotes from Dr Mark Curran

(ACE CRC), Dr Jacqueline Halpin (IMAS), and Dr Peter McGoldrick (CODES). Several CODES students also presented findings from their research projects.

Twenty-three students were enrolled in the Honours program in 2018. This included eight mid-year starters from 2017, and two who commenced mid-2018, and will complete their degrees in 2019. A particularly pleasing outcome was the large number of First Class results achieved by the students in 2018.

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. 35% of the



TMVC PhD student Ayesha Ahmed presenting during the Ore Deposit Models and Exploration Strategies MEconGeol short course which took place in November/December at CODES. She is speaking about the vertical zonation of alteration and mineralisation through the Yerington porphyry Cu district.

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 half of HDR students are from overseas, from a total of 16 different countries. In marked contrast to 2017, when five of the eight students starting PhDs were domestic candidates, in 2018, only two of the ten new PhD students were Australian. The decrease in domestic candidates may be a reflection of improving employment conditions in Australia's minerals industry.

There were 56 students enrolled in the HDR program during 2018 (54 PhD and 2 MSc), including ten new arrivals. The new enrolments were Australian students Stewart Jackson and Colin Jones, and international students Peter Berger (USA), Paulina Dobrowolska (Poland), Kyle Eastman (USA), Umer Habib (Pakistan), Javier Merrill (Chile), Annah Moyo (Zimbabwe), Nanda Mrabawani (Indonesia) and Emily Smyk (Canada). Six HDR students graduated in 2018: Cassady Harraden, Rachel Harrison, Indrani Mukherjee, Subira Sharma and Nathan Steeves were all awarded PhDs, while Eyob Andemeskel was awarded an MSc. A further six students have PhD theses under examination, or were making final corrections following examinations in 2018. Two PhD candidates withdrew, 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, JCU, 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 strong enrolments in all three short courses, and the largest ever intake of new (19) and returned (1) students to the program. Seven students – Kenneth Bush, David Groombridge, Sitthithon 'Gun' Kultaksayos, Thomas Langley, Thomas Ralston, Juan Diego Rojas Lopez and Christopher Shanley – all either completed their degrees or graduated in 2018. The total unit enrolment of 69 across the three short courses offered in 2018 was the equal second highest in a calendar year, and just two short of the all-time record MEconGeol unit enrolment in 2013. However, a noteworthy aspect of 2018 enrolments is that only 17% were from cross-institutional students, down from a high of 32% in 2013. The increase in MEconGeol unit enrolments in 2018 (up 23% on 2017, and 82% on 2016 numbers) is thus largely driven by the increase in numbers and activity of UTAS-based MEconGeol students. Indeed, 2018 saw the greatest

number of UTAS-based student enrolments in our coursework since the commencement of the MGM. However, while the MEconGeol program at UTAS remains strong, James Cook University has ended its equivalent Masters program, and in February 2018 delivered its final unit for the MGM program.

The three UTAS-based short held during 2018 were:

VOLCANOLOGY AND MINERALISATION IN VOLCANIC TERRAINS

In March, Rebecca Carey, Martin Jutzeler and David Cooke led a group of 22 Masters students (a record enrolment for this unit) and two other participants on a ten-day field trip to New Zealand's North Island to examine modern volcanic systems for the 'Volcanology and Mineralisation in Volcanic Terrains' short course. Following the New Zealand component, Rebecca and Martin were joined by Andrew McNeill (MRT) and Robert Scott for a five-day excursion to the west coast of Tasmania to examine the well mineralised and altered Cambrian Mt Read Volcanics. This hands-on field-based short course provides an excellent introduction to the processes and products of different eruption styles, contrasts in scale and structure of volcanoes, identification of key volcanic facies associations, and interpretation of facies variations. Mineralisation and alteration processes related to hydrothermal systems in subaerial and submarine volcanic environments and implications for mineral exploration are also addressed.

EXPLORATION IN BROWNFIELD TERRAINS

In June, 19 Masters students and one industry participant attended the 'Exploration in Brownfield Terrains' short course, led by Michael Roach and Robert Scott. This unit is designed to bring students up to date with the latest exploration techniques and approaches to compiling and working with historical data sets. Exploration in data-rich environments, close to existing mines, has become a preferred method of enhancing company resources in recent years. This trend has led to strong interest in this course, which covers cutting-edge technologies in geophysics, geochemistry and 3D visualisation, and guides participants in the analysis of real data from world-class mineralised districts. The unit is taught by a combination of CODES staff

(Michael Roach, Matthew Cracknell, Nathan Fox, and Robert Scott) and guest presenters from the government and minerals industry. In 2018, the guest presenters were David Green (MRT), Scott Halley (consultant), Terry Hoschke (consultant and Adjunct at CODES), Ned Howard (Evolution Mining), Andrew McNeill (MRT), Steve Turner (Newmont Mining Corporation) and Tony Webster (South32 and Adjunct at CODES).

ORE DEPOSIT MODELS AND EXPLORATION STRATEGIES

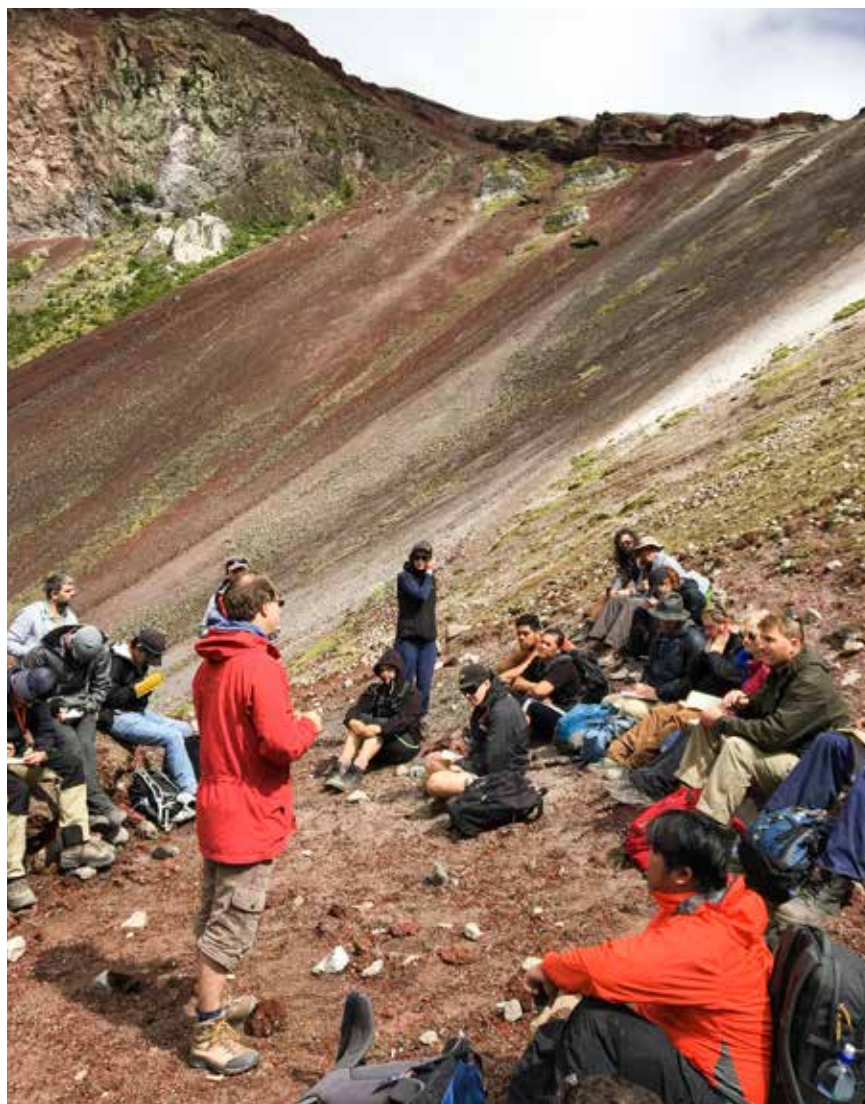
In October, the 'Ore Deposit Models and Exploration Strategies' course began with a very special event to commemorate the career contribution of our much-loved and highly respected colleague, Garry Davidson, who passed away in April 2017. The three-day Garry Davidson Symposium

was attended by 130 people, including 28 enrolled Masters students, making this by far the best attended short course held at CODES in over a decade. Garry was remembered as a dedicated teacher and an innovative, insightful researcher with an insatiable curiosity and infectious passion for the Earth sciences. In keeping with the objectives of the short course, the symposium addressed the genesis of, and exploration for, the ore deposit types that Garry had devoted so much of his working life to characterising and understanding; namely IOCG, uranium, sediment-hosted Pb-Zn and copper, Broken Hill-type, volcanic-hosted massive sulfide and orogenic gold deposits. There were 30 talks, presented by 28 of Garry's former friends, colleagues, students and collaborators.

Following the symposium, the 28 Masters students and 18 other participants stayed on for the remaining eight days of the short course which was presented by CODES staff and invited lecturers Professors Zhaoshan Chang and Noel White. Entire days were devoted to skarns, granite-related Sn-W deposits and Tasmanian ore deposits, porphyry Cu-Au-Mo deposits, high-sulfidation epithermal deposits and lithocaps, low- and intermediate-sulfidation epithermal deposits and Carlin-type gold deposits. Another highlight of the short course was a one-day field trip to the Freycinet Peninsula led by David Cooke and Evan Orovan, during which participants examined spectacularly exposed features formed in Devonian granites that mark the magmatic-hydrothermal transition. On the final day, teaching staff handed over to the Masters students who, working in groups of three, presented a series of talks on ore deposit types that had not previously been covered during the short course.

The program for 2019

- 8–19 March: Ores in Magmatic Arcs – Indonesia (KEA707)
- 3–14 June: Ore Deposit Geochemistry, Hydrology and Geochronology (KEA709)
- 11–26 October: Ores in Magmatic Arcs – South America (KEA707)
- 4–15 November: Geometallurgy (KEA711)



Martin Jutzeler teaching Masters students from within the 1886 crater of Tarawera volcano, New Zealand, during the 'Volcanology and Mineralisation in Volcanic Terrains' short course (KEA708).

Honours Program

In 2018, twenty students were enrolled in the Honours program, which was coordinated by Martin Jutzeler. Of these students, eight were mid-year starters from 2017, ten were February-starters in 2018, and two commenced mid-2018 and will complete their degrees in 2019. Of the active projects in 2018, two were computer- or lab-based, nine were related to Tasmania, eight to mainland Australia, and one was based in Inner Mongolia. Sponsoring companies and organisations in the Honours Program included the AusIMM, the Australian Research Council, Copper Mines of Tasmania, Corona Minerals, CSIRO-Marine National Facilities, Evolution Mining, Geological Society of Australia, Geological Survey of Victoria, Geological Survey of Western Australia, Inner Mongolia Mining Technology Research Institute, Institute for Marine and Antarctic Studies, Institute of Mine Seismology, Mineral Resources Tasmania, MMG, New South Resources, Newcrest Mining, Peking University, Perilya, Signature Gold, Venture Minerals and the UTAS

Foundation (CockerTwo Scholarship). In addition, some projects were supported by internal, university-based funding from the Discipline of Earth Sciences and the TMVC. CODES thanks all sponsors for their valued support. These sponsorships continue to be vital to the success of the projects, and the development of the students during a crucial phase of their studies.

Honours Coursework Program – VIEPS

In 2018, 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: Mike Baker, Evan Orovan, Robert Scott

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.

Thirteen students attended the camp in 2018. The eight-day camp, held in February, began with a day at the Mineral Resources Tasmania core library in Hobart, where the students logged 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 km² 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 ~5 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.



In 2018 Honours students joined KEA348 students during the Environmental Geology Field Techniques course run by Anita Parbhakar-Fox; they are seen here at the Savage River mine where they were learning about how mine waste is managed in western Tasmania.



Rob Scott (third from left) and Andrew McNeill (MRT, second from left) introducing the practical session on Tasmanian mineral deposits at the MRT core library in Mornington. This exercise was part of the MEconGeol 'Ore Deposit Models' short course that took place in October.

ORE DEPOSIT MODELS

Course leader: David Selley

Course presenters: Mike Baker, Stuart Bull, Angela Escolme, Ross Large, Brian McNulty, Evan Orovan, Robert Scott, Lejun Zhang

From 14–18 May, ten 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 May, 20 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 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 H₂O 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: Anita Parbhakar-Fox

Course presenters: Matthew Cracknell, Nathan Fox

The Environmental Geology Field Techniques (EGF) 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 a day-and-a-half of lectures at CODES, followed by field site studies conducted in western Tasmania. The five participants joined KEA348 (Environmental Geology) students to learn about how mine waste is managed in western Tasmania with visits to Copper Mines of Tasmania, Rosebery and Savage River mines. Students were then given the opportunity to examine historic

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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. Sediments were also collected at each location to help students develop a source to sink understanding of metal transport in this riverine system.

Next, students visited the Rosebery mine to understand the challenges of mine waste management for an active operation. Students were given a series of lectures followed by a visit to the drill core shed and a visit to the new 2-5 dam where tailings are disposed of via sub-aqueous methods to reduce their potential for oxidation. Students were given an opportunity to also discuss mineral processing methods with the site's metallurgical team. Following this visit, students were taken to the Zeehan slag pile where they were introduced to a new mine waste type and were asked to consider viable options for rehabilitating this site. As the weather did not permit the field exercise to be undertaken, the students were given the opportunity to instead visit the Zeehan Museum and learn about the mining history of western Tasmania.

The final day of the trip took place at the Savage River mine where students were again given a practical insight into the challenges of managing mine waste at an operational site. Students were given lectures from staff on site (led by Tony Ferguson) and then given a tour of several mine waste features including a visit to the new in-field kinetic leach columns. Students then undertook their main exercise at the Old Tailings Dam 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 materials were then analysed in the following practical sessions in the geochemical laboratory where students undertook net acid generation and paste pH tests (with resulting leachates collected and analysed by ICP-MS) and assessed the bulk chemistry using the portable XRF instrument. Students were also asked to analyse the mineralogy of their samples using the X-ray diffractometry facility at the Central Science Laboratory. All collected data were shared between teams and 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 mine visits. The most significant of these assessments was the Old Tailings Dam 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:
Anita Parbhakar-Fox

Course presenters: Mike Baker, Matthew Cracknell, Nathan Fox, Evan Orovan, 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 Anita Parbhakar-Fox, 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.
- Machine Learning with Orange (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 Orange data mining 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, including the calculation and analysis of model uncertainty.
- Applications of Adobe Illustrator and Indesign software packages (Nathan Fox) to help students 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.

LEFT: Drill core of polymict breccia from Waihi gold mine, New Zealand, viewed during the 'Volcanology and Mineralisation in Volcanic Terrains' MEconGeol short course, March 2018.

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. Andemeskel, Eyob.

TAS (Masters)

Litho-chemo-stratigraphic, structural and mineral prospectivity aspects of the Rosebery Group, an enigmatic Cambrian volcano-sedimentary succession in western Tasmania.

2. Andrews, Tomas. NT

(Honours)

Pyrite trace element geochemistry and sedimentology of the Barney Creek Formation, Rosie Creek Sub-basin, NT.

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 metallogenesis of the Gawler Craton.

5. Cherry, Alexander. SA

Petrology, provenance and composition of bedded sedimentary facies in the Olympic Dam deposit.

6. Couper, Hannah.

WA (Honours)*

Geological and geometallurgical characterisation of the high Au, low Cu domain at Newcrest's Telfer Cu-Au mine.

7. Cowie, Hamish. WA (Honours)

Paragenetic and geochemical analysis of the Perimeter gold prospect, Ora Banda, Western Australia.

8. Denholm, Josh. TAS (Honours)

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

9. Douth, David. WA

Origin, geochemistry, stratigraphic and structural setting of the Archean Invincible gold deposit, St Ives gold camp, Yilgarn Craton, Western Australia.

10. Duerden, Peter. NSW

Geological framework and metallogenesis of the Northern Molong Volcanic Belt, Lachlan Orogen, New South Wales.

11. Ferguson, Matt. SA

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

12. Fox, Jodi. TAS

Submarine intraplate basaltic volcanism.

13. Gilmour, Sarah.

TAS (Honours)*

Mineralogical and geochemical characterisation of historical slag: evaluating environmental impacts and economic significance.

14. Habib, Umer. VIC, NSW

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

15. Hardwick, Brendan.

WA (Masters)

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

16. Harraden, Cassady. NSW*

Geotechnical and geometallurgical assessment by Corescan and complementary microanalytical techniques.

17. Hughes, Kyle.

NSW (Masters)

Paragenesis of the Dobroyde Deposit, central NSW.

18. Jackson, Laura. NSW*

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

19. Jago, Corey.

NSW (Masters)

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

20. Jones, Colin.

TAS (Honours)*

The magmatic hydrothermal transition at Bluestone Bay, Freycinet Peninsula, Tasmania.

21. Jones, Colin. TAS*

Petrogenesis of Devonian granites, eastern Tasmania.

22. Kultaksayos, Sitthithon (Gun). TAS (Masters)

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

23. Le'Gallais, Bridie.

TAS (Honours)

Olivine cumulates from the Whyte River Complex in Western Tasmania.

24. Leslie, Christopher. NSW

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

25. McDonald, Tim.

TAS (Honours)

Geophysical investigation of buried karst landscape, Railton, Tasmania.

26. McLaine, Robert.

TAS (Honours)*

Determining bioaccessibility risks at the historic Aberfoyle tailings site, North East Tasmania: Opportunities for effective rehabilitation.

27. McMann, Ryan.

WA (Honours)

A syn-depositional sill intrusive model for the Golden Mile Dolerite, Kalgoorlie, WA.

28. Mohamed Amin, Fatin Amni. TAS (Honours)*

Advanced argillic alteration at Glen Lyell and Western Tharsis deposits, Mt. Lyell district, Western Tasmania: Implications for the genesis of Cu-Au mineralization and district exploration.

29. Mukherjee, Indrani. NT

Pyrite trace element chemistry of black shales of the "boring billion" period.

30. Mundana, Rhiannan. TAS (Honours)

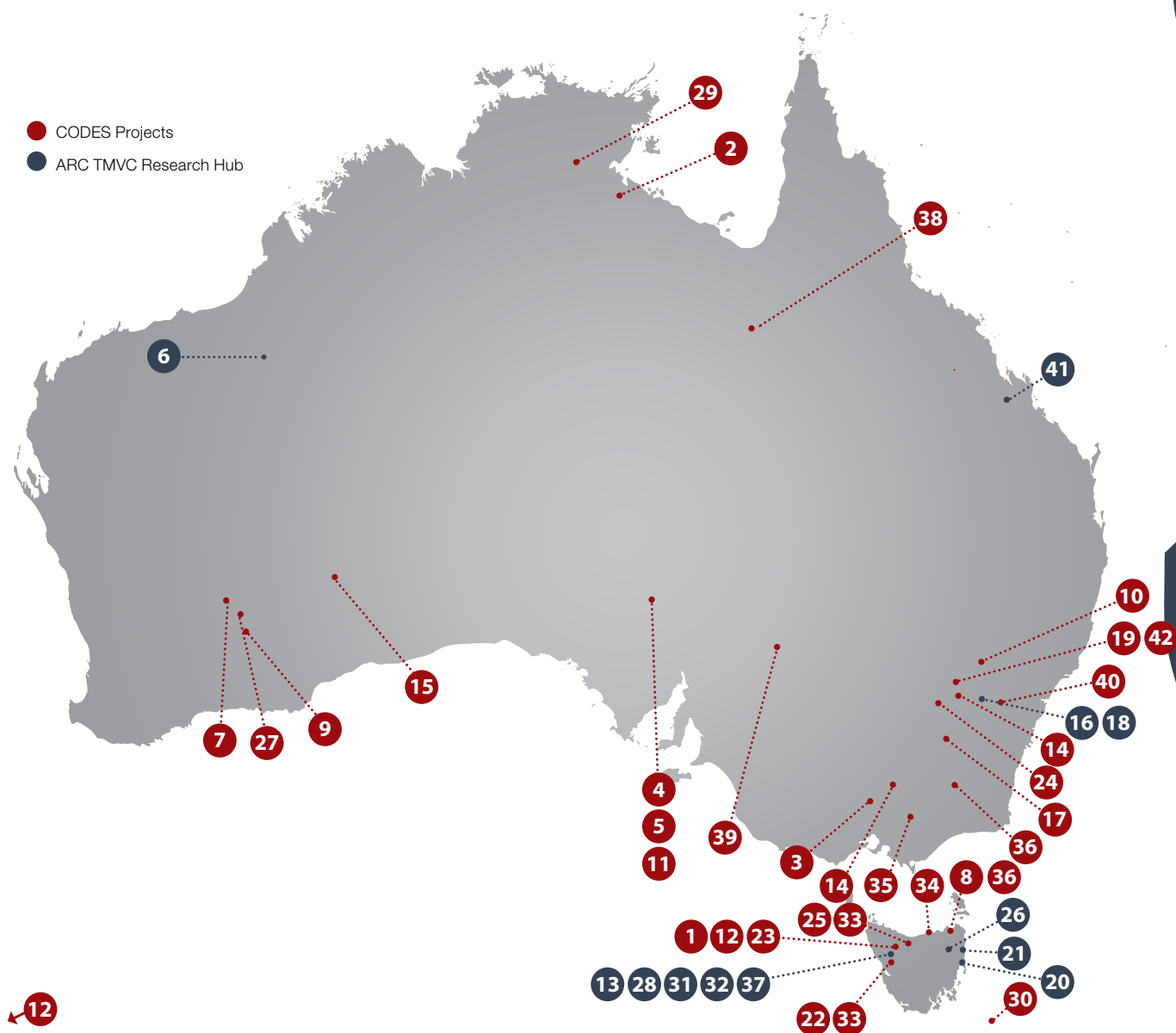
The geological evolution of the Cascade Seamount, Tasman Sea.

31. Nascimento, Sibebe Cristina do. TAS*

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

32. O'Keefe, Emmet. TAS (Honours)*

Genesis of the Trial Harbour Fe-Mg skarn.



33. Ostersen, Thomas. TAS

Geoelectric structure of the Tasmanian lithosphere.

34. Ridgers, Ben. TAS (Honours)

Pb isotopic characterisation of ore deposits and prospects from NE Tasmania.

35. Ropli, Riquan. VIC (Honours)

Age and paragenesis of the Hill 800 prospect, Victoria.

36. Schaap, Thomas.

TAS, NSW, VIC

Plate tectonic modelling of the Early Palaeozoic evolution of South Eastern Australia.

37. Seow, Xin Ni. TAS (Honours)*

Geology and genesis of the Prince Darwin prospect, Western Tasmania.

38. Sharma, Subira. QLD

Evaluation of the links between Merlin-style Mo-Re mineralisation and magmatism in the Cloncurry fold belt, Queensland: Implications for exploration.

39. Sinfield, Mark.

NSW (Honours)

Litho-structural control and origin of mineralisation at Carbonate Ridge – Broken Hill, NSW.

40. Sritangsirikul, Peerapong.

NSW (Masters)

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

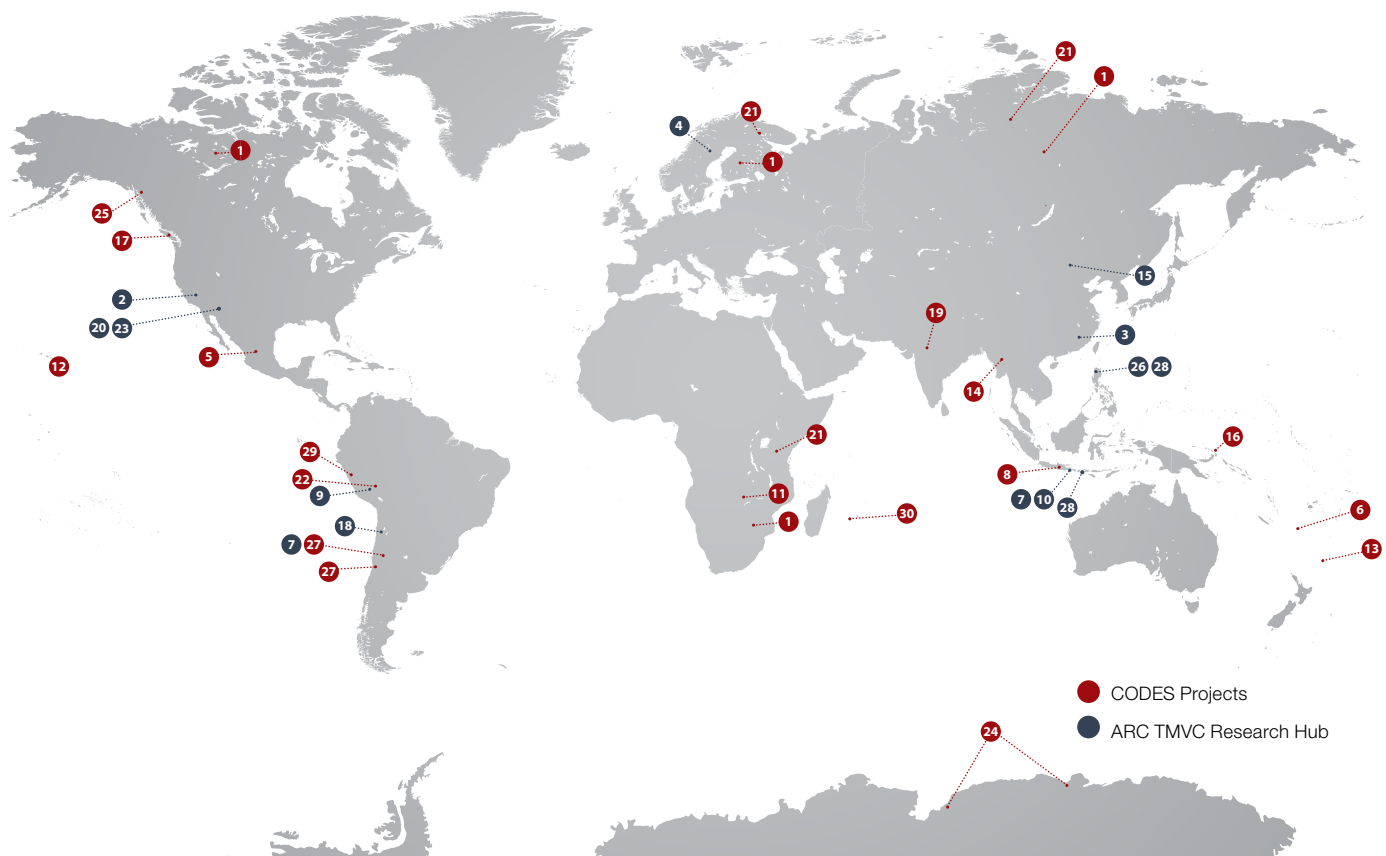
41. Vincent, Matthew. QLD

(Honours)*

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

42. Wells, Tristan. NSW

Geochemistry and cathodoluminescence of magmatic apatite and zircon as vectors to mineralised centres within the Lachlan Fold Belt.



● CODES Projects
● ARC TMVC Research Hub

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*
The effect of pressure/depth on propylitic alteration mineral chemistry in the porphyry environment.

3. Chen, Jing. CHINA*
The geology, mineralisation, alteration and structural evolution of Zijinshan ore field, Fujian Province, China.

4. Cornelius, Rebekah. SWEDEN (Honours)*
Geoenvironmental characterisation of the Lill-Laverberget Cu-Au porphyry deposit in Laver, Sweden.

5. Davidson, Rob. MEXICO
Geology and genesis of the San Sebastian vein system, Durango, Mexico.

6. Draayers, Evan. SW PACIFIC

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.

7. Eastman, Kyle. INDONESIA, ARGENTINA*
Geological and geometallurgical characterization of porphyry deposit alteration overprints.

8. Firmansyah, Arga. INDONESIA (Masters)
Geology and mineralisation of the Trenggalek district, East Java, Indonesia.

9. 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.

10. Harrison, Rachel. INDONESIA*
The Tumpangpitu porphyry gold-copper-molybdenum and high-sulfidation epithermal gold-silver deposit, Tujuh Bukit, southeast Java, Indonesia.

11. 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.

12. Holt, Sam. USA
Understanding of basaltic eruption dynamics and mechanisms: Effusive and explosive eruptions in Hawaii.

13. Ikegami, Fumihiko. NEW ZEALAND
2012 submarine silicic eruption of Havre volcano and implications for ancient submarine successions in Australia.

14. Knight, Joseph. MYANMAR
The geodynamic and metallogenic setting of base- and precious-metal mineralisation in Myanmar: Implications for Cu and Au exploration.

15. Kowaluk, Ben. CHINA (Honours)*
Geology, geochemistry and genesis of the Hadamiao Au-Cu porphyry prospect, Inner Mongolia, China.

16. Lawlis, Erin. PNG
Au-bearing pyritic ore of Lihir, Papua New Guinea: Its physiochemical character and nature of the causative fluids.

17. McNulty, Brian. CANADA

Geology of the West Block Area of the late Devonian Myra Falls VHMS District, British Columbia, Canada.

18. Merrill, Javier. CHILE*

Evaluating applications of hyperspectral data for predicting mineral processing attributes and waste characteristics of slurries.

19. Mukherjee, Indrani. INDIA

Pyrite trace element chemistry of black shales of the “boring billion” period.

20. Phillips, Joshua. USA*

Geologic and geochemical vectors to mineralisation at the Resolution porphyry Cu-Mo deposit, Arizona.

**21. Potter, Naomi.
TANZANIA, RUSSIA**

An investigation into the genesis of intrusive and extrusive carbonatitic melts.

**22. 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.

23. 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.

24. Staal, Tobias. ANTARCTICA

Seismic and geological constraints on the lithospheric structure of Antarctica.

25. Steeves, Nathan. USA

Ore genesis of the Greens Creek VHMS Deposit, Alaska: Implications for mining, milling and exploration.

26. Sun, Yi. PHILIPPINES*

Mineralogical, textural, geochemical characterisation and geometallurgical models of Lepanto Quartz–Pyrite–Gold vein and breccia system, Philippines.

**27. Testa, Francisco.
ARGENTINA, CHILE**

Tourmaline breccia pipes: San Francisco de los Andes, Argentina and Rio Blanco-Los Bronces, Chile.

**28. Thompson, Jennifer.
INDONESIA, PHILIPPINES***

Carbonate mineral chemistry in epithermal and porphyry hydrothermal systems.

**29. Torres Pachecho, Victor.
PERU (Masters)**

Geology, genesis and exploration implications of Cu-Au mineralised tourmaline breccia pipes at Soledad, central Peru.

30. Vergani, Daniele. REUNION

The 2007 explosive activity at Piton de la Fournaise volcano (Reunion): 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.

Dobrowolska, Paulina.

Mineralogical and textural controls on grade-by-size fractionation in porphyry copper deposits.

Hood, Shawn.*

Machine learning and automated geoscientific analyses for the spatial characterisation of metalliferous ore deposits.

Jackson, Stewart. (Honours)

Finite difference wavefield modelling for mine seismology.

Jackson, Stewart.

Integrating passive and active methods of seismic imaging for structural stability of tailings dams.

James, Darcy. (Honours)

Mineralogy, geochronology and whole rock geochemistry of basement to the Tasmanian 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.

Meyer, Stephen.

A model-based approach to the interpretation of seismicity associated with mass mining.

Morse, Peter.

Interactive visualisation for data inference in the geosciences.

Moyo, Annah.*

Controlling acid and metalliferous drainage at legacy sites in Tasmania using industrial waste materials.

Mrabawani, Nanda Yusentri.*

Laser Ablation applied to mineral characterisation.

Thompson, Jay.

Understanding the specifics of H₂O-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.



The CODES SEG Student Chapter was instrumental in organising the GSA Earth Science Student Symposium (known as the GESSS-TAS) in Hobart during November. Participants are pictured here outside the CODES offices.

SOCIETY OF ECONOMIC GEOLOGISTS (SEG) STUDENT CHAPTER

The CODES SEG Student Chapter at the University of Tasmania is a student branch of the Society of Economic Geologists, dedicated to pursuing and disseminating geological knowledge among its members by organising academic and social activities. The Society plays an important role at CODES, making significant contributions to the social and professional lives of students from a diverse range of backgrounds and cultures. Towards the end of each year, the students elect an executive committee that plans and oversees a comprehensive social and professional development program catering for everyone at CODES: students, researchers and professional staff alike.

Lectures and meetings

The SEG Student Chapter maintained its tradition of holding informal seminars, regular 20-minute technical talks, and short courses. Several invited speakers from academia and industry gave talks in 2018, ranging from the use of data analytics in exploration projects, to deposit characterisation studies, to reports on PhD field programs.

Highlights of the 2018 lectures and meetings include:

The joint SEG–WIMNet hosted event on 24 October: a great turnout of 55 people came to the discussion session moderated by Hannah Couper (a TMVC Honours student). A panel comprised of Kathy Ehrig, Penny Sinclair, Margy Hawke and Shawn Hood discussed the issues around gender equality and the growing role of women in the mining and minerals industries. The event was sponsored by the AusIMM, UTAS and the SEG Student Chapter.

Greg Corbett presented a two-day short course entitled ‘Epithermal Au-Ag and porphyry Cu-Au exploration’ on 5–6 April. This intensive lecture series focused on mineral exploration for epithermal and porphyry ore deposits based on 35 years of field experience. Examples of exploration techniques used in major mineral discoveries, as well as mine case studies from over 40 countries were used to delineate the characteristics of different epithermal and porphyry ore types, including alteration, mineralisation and breccias.

On 11 May Diana Drinkwater and Peter Munro from Mineralis Consulting presented a one-day short course on the impacts of mineralogy on mine production and process performance. They highlighted the importance of geometallurgical studies in project development and continuing through operations, and how to decode the behaviours and logic behind common metallurgical conventions.

On 25 May Mark Duffett, Senior Geophysicist at Mineral Resources Tasmania, was invited to deliver a lecture entitled ‘Gravity in Tasmania – Ironing out the wrinkles’; the talk was well attended by staff, and undergraduate and postgraduate students.

Conferences, exhibitions and publications

One of the key areas in which students contribute to enhancing CODES’ profile is by attending and presenting papers at domestic and international conferences. A number of the CODES SEG Student Chapter members presented at gatherings across the world during the year. These include Student Chapter members attending and presenting topics of their research at the SEG conference in Keystone, Colorado; the Gordon Research Conference and the Gordon Research Seminar (the last of which was organised by CODES SEG members Ayesha Ahmed and Angela Escolme) in Waterville Valley, New Hampshire, USA. Four Student Chapter members attended the 2018 AGCC conference in Adelaide. Three attendees gave oral presentations related to their PhDs and there were two poster presentations. Several Student Chapter members also presented at the GESSS-TAS student symposium held at CODES in November.

It was also another productive period for student outputs in terms of publications, with several refereed journal articles being produced throughout the year.

Annual field trip

The annual field trip for 2018 had been planned for the Philippines; however, due to unfortunate changes in the geopolitics of the region, the trip had to be postponed.

Social events

Social events are another important activity organised by the CODES SEG Student Chapter: they provide a chance for postgraduate students to get to know the undergraduate cohort, and for the greater student body to get exposure to researchers and industrial sponsors in a relaxed, social environment.

The Student Chapter organised multiple social barbeques and icebreakers for new Honours and Master of Economic Geology students, numerous pub evenings and movie nights, and assisted with the running of the Garry Davidson Symposium in October.

The Student Chapter also facilitated a football match in honour of the late Garry Davidson, as well as providing a BBQ and drinks for the ~120 attendees.

In late 2018 the Student Chapter instigated Frothy Fridays as a chance for CODES staff and postgraduates to enjoy a quiet beverage in the summer sun on a Friday afternoon. A walking tour of some of the craft breweries in greater Hobart was also held in August with 10–20 undergraduate and postgraduate members attending.

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 to use again in 2019. All funds raised are used to promote the Society's objective of advancing the study of mineral deposits by supporting the field trips organised by the Student Chapter. Our Chapter provides a small tea and coffee station for staff and postgraduates, with weekly milk delivery to the Chapter fridge. Payment for this is via an 'honesty box' which essentially covers costs of the service and generates a nominal amount of income for the Chapter. Additionally, the Chapter coordinates a geological equipment store, including mineral ID kits for undergraduates, hammers, hand lenses of every description, notebooks, and more. Pricing is designed so that key equipment for

fieldwork is provided nearly at cost; this service keeps students in possession of key equipment and introduces undergraduates to the SEG Student Chapter. Despite fundraising efforts, the Chapter operated at a loss (~\$9,800) in 2018 with a significant amount of funds raised supplementing the cost of a short field trip within Tasmania.

For the latter part of 2018 the Chapter ran weekly snacks and drinks which raised a few hundred dollars. All funds raised will supplement upcoming field trips. Future fundraising efforts will hopefully rebuild the Chapter budget

as well as increase staff, postgraduate and Honours student interactions.

Awards and grants

Again, CODES SEG Student Chapter members were successful in gaining awards and grants from a number of sources including:

- Tristan Wells was awarded an SEG graduate research bursary
- Joseph Behan was awarded an AusIMM EEF scholarship
- Adam Abersteiner received the Max Banks Research Scholarship in Earth Sciences.

Looking forward

The healthy level of HDR enrolments should be maintained in 2019, with the number of graduations again being balanced by the intake of new students, from both Australia and overseas. The Master of Economic Geology Program has a slightly expanded offering of four short courses in 2019, beginning with the field-based short course Ores in Magmatic Arcs delivered in Indonesia in March, led by Lejun Zhang and David Cooke. Ores in Magmatic Arcs will also be offered in October, when it will be led by David Cooke and Michael Baker and presented in South America (Ecuador and Chile). The Ore Deposit Geochemistry, Hydrology and Geochronology short course, delivered in June, is fundamentally concerned with metal transport and deposition in hydrothermal fluids and introduces participants to a wide range of geochemical, isotopic, hydrological, and geochronological techniques used in studies of ore deposit genesis and mineral exploration. This short course is led by Shaun Barker and presented by a mix of expert staff from CODES, other universities, state, national and international geological survey organisations and the minerals industry. The final short course for the year, Geometallurgy, will be held in October. This short course, to be led by Angela Escolme, covers key aspects of this highly specialised and emerging field.

Based on the large number of enquiries from prospective students, and increasing optimism in the Australian minerals industry, CODES expects to see in the healthy influx of new students into the Master of Economic Geology program experienced in 2018, repeated in 2019. In contrast, Honours enrolments are likely to remain at a modest level in the coming year, due to the recent decrease in undergraduate student numbers following the mining boom. However, if career opportunities in the minerals industry continue to improve as they have over the past couple of 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).

The success of the second Geological Society of Australia Earth Sciences Student Symposium (GESS Symposium) at CODES and the Discipline of Earth Sciences in November 2018 will see this event rolled out again in 2019. The GESS Symposium provides an important platform for students to showcase the results of their research to an audience of their peers, government and minerals industry representatives, and academics. The SEG Student Chapter is also planning to have another full schedule of social and professional development events throughout the year.

Outreach

Every year staff and students from CODES and Earth Sciences engage in a busy program of activities that are aimed at promoting the geosciences to the broader community, and encouraging younger people to think about taking up a career in this area. 2018 proved to be another busy year with activities taking place on and off campus. One of the highlights was the huge crowd of thousands of (mainly very young) people who turned out to take part in the Dinosaur Picnic at the Royal Tasmanian Botanical Gardens.

ConocoPhillips Science Experience

In April, PhD student Nathan Chapman took part in the ConocoPhillips Science Experience program and ran a Tasmanian Youth Science Forum in Burnie. Approximately 20 students from across the state (Burnie, Ulverstone and Hobart) took part and learned about nuclear radiation using a petrographic microscope, scintillometer, and various mineral and rock samples.



CODES PhD student Nathan Chapman enjoyed talking about geology to a group of students in Burnie, Tasmania, during the ConocoPhillips Science Experience in April 2018.

UTAS Paleontology Summer School Day Trip 2018

Our Rock Curator Izzy von Lichten, together with Dr Patrick Bender and Professor Patrick Quilty, led a summer school day trip in the Hobart area on 27 January for school students and the public covering the topic of the fossils of the Tasmanian Triassic. Participants took part in a field trip to Otago Bay in the morning and heard a series of lectures on the UTAS Sandy Bay campus in the afternoon.

Royal Society of Tasmania

Professor Patrick Quilty gave a two-hour lecture (including question time) to about 100 members and friends of the Northern Chapter of the Royal Society of Tasmania on 25 March. The topic was 'On some odd highlights of Tasmania's Antarctic history'. He also did an associated radio interview on ABC Northern Tasmania on 23 March.

Dr Karin Orth gave a presentation entitled 'Megavolcanic eruptions and the greatest mass extinctions of all time' to the Northern Chapter of the Royal Society of Tasmania on 24 June. The event, which attracted about 100 people, included members of the Society and the general public, and was held at the Queen Victoria Museum and Art Gallery.

Mineralogical Society

Dr Karin Orth gave a talk to the Mineralogical Society of Tasmania in November on minerals associated with the Coronation Hill deposit in the Northern Territory.

UTAS Open Day

Around 2,000 people visited UTAS for the Sandy Bay campus Open Day in August. Staff from CODES and the Discipline of Earth Sciences rallied again and provided interesting and interactive activities designed to showcase our work and set younger people thinking about taking up a science degree.

The Earth Sciences/CODES Open Day activities included appearances by our tame dinosaurs Rosie and Rex as a tie-in with the Dinosaur rEvolution exhibition at the Tasmanian Museum and Art Gallery, which had a huge amount of input from CODES.

Pint of Science

Pint of Science is a 'global science festival' that runs across 24 countries and is organised by a grass-roots community of scientists. In Australia a national festival is held each year with the aim of celebrating 'excellence in the Australian science and science engagement sectors'.

Events are run internationally in May; in 2018, Dr Anita Parbhakar-Fox contributed to this international event at the Republic Bar in Hobart with a presentation in the sold-out 'Waste not want not' session. Anita explained that tonnes of mine waste are produced

OPPOSITE PAGE: (TOP) More than 2,000 families turned out to take part in the Dinosaur Picnic at the Royal Tasmanian Botanical Gardens in November, an event organised by Professor Ross Large and Dr Karin Orth. (CENTRE) LEFT: The CODES Rock Curator Izzy von Lichten pictured with a large piece of blue celestite crystal, which was photographed to create the backdrop for an acclaimed Melbourne Opera production of Tristan and Isolde. RIGHT: Dr Rebecca Carey was invited by the 60 Minutes team to fly to Hawaii and be interviewed about the technical details of the Kilauea volcano eruption, which started in May. L-R: US National Guard soldier, Grace Tobin (producer for 60 Minutes), Liz Hayes (presenter/journalist for 60 Minutes), Rebecca Carey and (at front) the videographer for 60 Minutes. (BOTTOM) LEFT: A Chinese delegation from the University of Hefei, led by Professor Taofa Zhou from Hefei University of Technology, visited the Dinosaur rEvolution exhibition at the Tasmanian Museum and Art Gallery during December. Professor Ross Large (here wearing sunglasses) was instrumental in making the exhibition happen. RIGHT: CODES PhD student Tristan Wells talks to a class of primary school students in Bothwell as part of the Young Tassie Scientists program during April.





CODES/TMVC Senior Research Fellow Dr Anita Parbhakar-Fox spoke passionately to a capacity crowd at the Pint of Science event in Hobart, which was held at the Republic Bar in May.

annually and can introduce toxic metals into the environment. She invited the audience to join her on a virtual tour around Tasmania to see world-class examples of mine waste and learn about how these sites can be rehabilitated by exploring for 'green' metals as uncovered through her TMVC team's research.

Dinosaur Picnic

In November scientists from CODES – along with the two CODES dinosaur 'suits' – took part in the Dinosaur Picnic in the Royal Tasmanian Botanical Gardens, which was a joint effort between the Royal Society of Tasmania and the gardens. A massive crowd of over 2,000 families turned out to see the dinosaurs, Rosie and Rex. Educational activities were run during the event by Dr Karin Orth, Izzy von Lichtan, Dr Indrani Mukherjee and Professor Ross Large. The two dinosaur drivers, who were the centrepiece of the event, were Tobias Staal (PhD student) and Chris Large (MRT).

The event was held leading up to the Dinosaur rEvolution exhibition, held at the Tasmanian Museum and Art Gallery (see below).

The Rock Library

CODES Rock Library Curator Izzy von Lichtan was again involved in a substantial number of rock-related events and collaborations during 2018. Among them were:

Academy Gallery/ MONA FOMA Launceston

In January Izzy provided samples of minerals, together with a geological

background/context of volcanic eruptive products, for the exhibition called *SPEED: Mobility & Exchange*, which was held at the Queen Victoria Museum and Art Gallery at Inveresk and presented in partnership with the UTAS Collections Project and MONA FOMA Launceston. The exhibition ran from 13 January to 20 April. It considered all modes of communicative transport, from blood from the eye travelling through our body, to the broken-down car and the defunct computer system with hard drive no longer accessible.

Also in January, a large selection of fossils and rocks, together with rock descriptions, were provided by Izzy for the *Charles Darwin in Hobart* exhibition, a Joint Special Collections & Rare Collections/ Rock Library & Geological Museum exhibition held in the UTAS Morris Miller Library on the Sandy Bay campus from 19 January to 2 March.

Rock opera

In February the Melbourne Opera's production of Richard Wagner's *Tristan and Isolde* used a backdrop created through a collaboration between Izzy and filmmaker Keith Deverell. Deverell used Izzy's close-up photographs of the mineral celestite in a beautiful soft blue to produce the look of cave-like structures for use as the opera's backdrop.

The Tasmanian Fossils at TMAG, part of Dinosaur rEvolution

During the second half of the year Izzy was involved in preparing samples such as amphibians, fish, and a reptile for the exhibition that focused

on Tasmania's Lower Triassic to be displayed at TMAG in conjunction with *Dinosaur rEvolution*. Part of this exhibition included the first ever public display of the type specimen of *Tasmaniosaurus*, known as being one of the most complete Australian Triassic reptiles. Izzy also spent several weekends at TMAG as the resident geologist helping to interpret the Permian fossil boulders and answer any other geology question. See: <https://en.wikipedia.org/wiki/Tasmaniosaurus>

Dinosaur rEvolution: Secrets of Survival

An exciting outreach program in 2018 was CODES' involvement with the *Dinosaur rEvolution* exhibition produced by the Tasmanian firm Gondwana Studios, and held jointly with the Royal Society of Tasmania and the Tasmanian Museum and Art Gallery. The exhibition featured many of the recent fossil discoveries, especially from China and Mongolia, which demonstrate the evolution of one particular lineage of dinosaurs to birds. This was an expensive event to bring to Hobart and the Royal Society was successful in raising a total of \$100,000 sponsorship from a group of very generous supporters including Cripps Bakery, UTAS, RACV Hotel, The Old Woolstore, Events Tasmania and an anonymous donor. It has been particularly pleasing to see the number of families, young children and student groups who attended the exhibition. The event runs through to early May 2019.

The donation by UTAS was used to purchase two dinosaur suits – Rosie and Rex – that formed a major part of the exhibition, and other events leading up to the exhibition, such as the dinosaur picnic held at the Royal Tasmanian Botanical Gardens (see above).

School visits and trips

Among the outreach visits to schools and colleges by CODES and Earth Science staff and students were the following:

In **March** Dr Sasha Stepanov hosted three visits by students from Waimea Heights Primary School; they toured the Earth Sciences department.

In **April** CODES PhD student Tristan Wells gave a talk at Bothwell Primary

School as part of the Young Tassie Scientists program; he also did a radio interview in connection with this program.

On four days in **July** Associate Professor Sebastien Meffre and Earth Sciences staff conducted core sampling techniques and demonstrations on the River Derwent foreshore at Montrose with Elizabeth College students.

In **September** Dr Matthew Cracknell travelled to Rosebery High School and ran earth science-based activities with around 20 Grade 7/8 students and 15 Grade 9/10 students.

Over three days in **November** Associate Professor Sebastien Meffre, Dr Indrani Mukherjee, Dr Michael Roach and Dr Matthew Cracknell hosted approximately 90 Grade 8 Taroona High School students; the students toured the Earth Sciences department and took part in seismic exercises.

Also in **November**, Dr Matthew Cracknell and Dr Indrani Mukherjee hosted approximately 30 Ogilvie High Grade 8 students in the Earth Sciences department where they undertook seismic exercises and a tour. And three groups of students (around 100 altogether) from Grade 8 at Taroona High visited and took part in geological scientific activities and a tour of the Earth Sciences department.

Media

During 2018 CODES and Earth Sciences staff and students were involved in media activities across a number of platforms; below is a selection of the varied media activities undertaken:

In January Dr Rebecca Carey had a photo featured in the news section of the prestigious journal *Nature*. It was of the underwater Havre volcano, and was listed as one of that month's best science shots. See the image at: <https://www.nature.com/articles/d41586-018-01461-z>

- In May Dr Rebecca Carey appeared on the current affairs TV program *The Project* talking about the Kilauea volcano eruption in Hawaii.
- Three radio interviews were associated with Dr Karin Orth's Royal Society presentation: ABC's Launceston Drive Program (with



Dr Karin Orth appeared on the Today Show to talk about a dormant volcano in Victoria in August.

Piia Virsu), Radio City Launceston (with Tony Webb) and ABC Radio Hobart (with Chris Wisbey: 'Was Mt Wellington ever a volcano?'). Listen at: <http://www.abc.net.au/radio/hobart/programs/statewideweekends/karin-orth/9928854>.

- In June Professor Jocelyn McPhie did an ABC Radio Hobart interview about the June 2018 eruption of Fuego, Guatemala.
- In June Dr Rebecca Carey appeared on *Studio 10* talking about the Kilauea eruption.
- In July Tristan Wells did an interview for ABC Radio Hobart with Ryk Goddard on geology and the Young Tassie Scientists program.
- On 12 August a Nine Network *60 Minutes* television documentary was aired in which Dr Rebecca Carey was interviewed on location in Hawaii by Liz Hayes about scientific aspects of Hawaii's Mount Kilauea volcano crisis. Watch at: <https://www.9now.com.au/60-minutes/2018/extras/clips/clip-cjkqe2w03001q0rumnggyc538>
- Also in August, Dr Carey appeared on *Extra Minutes*, speaking with Liz Hayes in a *60 Minutes* interview about the dormant Melbourne volcano. Watch at: <https://www.9news.com.au/national/2018/08/14/13/11/volcanic-system-melbourne-eruption-unprepared?ocid=Social-9NewsM>
- In August Dr Karin Orth appeared on *The Today Show* talking about a dormant Victorian volcano.
- Karin Orth did three radio interviews on ABC Hobart radio's Evenings programme (Paul McIntyre interviewer) on the destructive force of volcanic eruptions: the Vesuvius 79 AD eruption that destroyed Pompeii (August); the Mount Pelee 1902 eruption that destroyed the city of St Pierre (October); and the 1980 Mount St Helens eruption in the US (December). These were aired in three 10-minute slots.
- In early November Karin Orth did an interview on collecting fossils for ABC Radio Hobart as part of the promotion for the Dinosaur Picnic at the Royal Botanic Gardens.

Social Media at CODES

CODES/Earth Sciences has an active presence on social media:



Earth Sciences Facebook page:
<https://www.facebook.com/EarthSciUTAS/>



TMVC Facebook page:
<https://www.facebook.com/tmvc.utas>



TMVC Twitter:
https://twitter.com/tmvc_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.

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 2018, the group of CODES' industry partners comprised of 10 Australian and international mining companies: Anglo American, Barrick, Evolution, First Quantum Minerals, Mount Isa Mines (Glencore), Newcrest Mining, Northparkes Mines (CMOC), Gold Fields, 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



CODES sponsors in the field: Mario Valdez from MMG (left) and Paul Agnew from Rio Tinto (centre) with TMVC PhD student Ayesha Ahmed at Yerington, Nevada, USA, for the 2018 AMIRA P1153 field meeting. They are examining magnetite and epidote in the distal alteration environment around the Ann Mason porphyry Cu deposit.



The first sponsors' review meeting for the AMIRA project P1202 'Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits' took place in November 2018. Here team members and sponsors are pictured outside the CODES offices in Hobart.

research directions. Gold and Platinum Partners are also offered a seat on the CODES Advisory Board, which meets annually to discuss the strategic direction of the Centre.

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 either the Silver (\$20K), Gold (\$40K) or Platinum (\$60K) level, depending on their planned level of involvement with the Centre.

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 three to four years. In 2018 it funded AMIRA P1153 'Applying the explorers' toolbox to discover porphyry and epithermal Cu, Au and Mo deposits', as well as AMIRA P1202 'Far-field and near-mine footprints: Finding and defining the next generation of Tier 1 ore deposits', both of which sit within the ARC TMVC Research Hub.

Research collaborations

In 2018, CODES further cemented its reputation for cultivating research collaborations with other Australian and international research organisations. Throughout the year, collaborative research was conducted with 101 international and 27 national organisations.



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.

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 2018, 194 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 2018.

► *Altered volcanic rocks: A guide to description and interpretation* (2005). Authors: C Gifkins, W Herrmann and R Large (19 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 copper-gold porphyry and epithermal gold deposits, and implications for exploration* (2011). Author: T Hoschke (15 copies).

► *Giant ore deposits: Characteristics, genesis and exploration*. CODES Special Publication 4 (2002). Editors: D Cooke and J Pongratz (4 copies).

► *New developments in Broken Hill type deposits*. CODES Special Publication 1 (1976). Editors: G Davidson and J Pongratz (1 copy).

► *The geology and origin of Australia's mineral deposits* (2000). Authors: M Solomon and D Groves (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: JB Gemmell and J Pongratz (2 copies).

► *Volcanic textures: A guide to the interpretation of textures in volcanic rocks* (1993). Authors: J McPhie, M Doyle and R Allen (49 copies).

The Master of Economic Geology short course 'Volcanology and Mineralisation in Volcanic Terrains' took place in March; 22 Masters students and two PhD students participated in field excursions to ancient subaerial and submarine volcanoes in New Zealand and Tasmania. Here participants are pictured at the iconic Bethells (Te Henga) Beach studying submarine volcanism from a Miocene arc.



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 21 events in these categories were held at various locations around the world, including Canada, China, New Zealand and the USA.

Total attendance by industry geologists, academic researchers and postgraduate students was 737, with 28 different presenters from CODES involved in delivering the lectures or leading the conferences or field trips.

2018 SHORT COURSES, WORKSHOPS, CONFERENCES AND FIELD TRIPS LED BY CODES

TITLE	PRESENTERS	NO.	LOCATION	DATE
Workshop on mineral chemistry at the Hefei University of Technology	Mike Baker	20	Hefei, China	20 January
Exploration Field Skills Mapping Camp (VIEPS)	Mike Baker, Evan Orovan, Robert Scott	13	CODES, MRT	February
Volcanology and Mineralisation in Volcanic Terrains (MEcon Geol short course)	Rebecca Carey , Isabelle Chambefort, David Cooke , Martin Jutzeler , Andrew McNeill, Andrew Rae, Julie Rowland, Robert Scott	24	Western Tasmania/ New Zealand	4–19 March
Ore Deposit Models (VIEPS)	Mike Baker, Stuart Bull, Angela Escolme, Ross Large, Brian McNulty, Evan Orovan, David Selley, Robert Scott, Lejun Zhang	10	CODES, Hobart	14–18 May
MDRU Geometallurgy practical short course	Ron Berry , Greg Dipple, Julie Hunt, Bern Klein	24	Vancouver, Canada	22–25 May
Practical Igneous Petrology (VIEPS)	Leonid Danyushevsky	20	CODES, Hobart	Late May
Exploration in Brownfield Terrains (MEcon Geol short course)	Matthew Cracknell, Nathan Fox, David Green , Scott Halley, Terry Hoschke, Ned Howard, Andrew McNeill, Michael Roach, Robert Scott , Steve Turner, Tony Webster	20	CODES, Hobart	11–22 June
AMIRA P1153 Yerington workshop	Ayesha Ahmed, Mike Baker, David Cooke, Kyle Eastman, Evan Orovan, Emily Smyk, Lejun Zhang	24	Reno, Nevada, USA	25 June
AMIRA P1153 Yerington field trip	Ayesha Ahmed, Mike Baker, David Cooke, Lejun Zhang	23	Yerington, Nevada, USA	26–29 June
Gordon Research Seminar (GRS): Mineralizing Processes Across All Scales	Ayesha Ahmed, Angela Escolme (Joint Chairs)	57	Waterville Valley, New Hampshire, USA	4–5 August
Gordon Research Conference on the Geochemistry of Mineral Deposits	Shaun Barker, David Cooke (Chair), Ross Large	130	Waterville Valley, New Hampshire, USA	5–10 August
Natural Hazards workshop	Sandra Astill, Rebecca Carey , Stuart Corney, Merylin Cross, Jennifer Styger	50	IMAS, Hobart	August
Environmental Geology Field Techniques (VIEPS)	Matthew Cracknell, Nathan Fox, Anita Parbhakar-Fox	5	CODES, Hobart/ western Tasmania	September
Garry Davidson Symposium	Rod Allen, Steve Bodon, Stuart Bull, David Cooke , Kathy Ehrig, Bruce Gemmell, David Green , Scott Halley, Margy Hawke, Terry Hoschke, Danny Huisman, David Huston, Sarah Jones, Paul Kitto, Ross Large , Neil Martin, Peter McGoldrick , Andrew McNeill, Michael Nugus, Nick Oliver, Karin Orth, Michael Roach, Robert Scott, David Selley , Penny Sinclair, Subira Sharma , Roger Skirrow, Peter Sorjonen-Ward, John Walshe, Tony Webster , Lesley Wyborn	130	CODES, Hobart	22–24 October
Ore Deposit Models and Exploration Strategies (MEcon Geol short course)	Ayesha Ahmed, Shaun Barker , Stuart Bull, Zhaoshan Chang, David Cooke, Evan Orovan, Robert Scott , Noel White, Lejun Zhang	46	CODES, Hobart	25 October– 2 November
AMIRA P1153 workshop	Mike Baker, David Cooke	10	Perth, WA	6 November
GSA Earth Science Student Symposium (GESSS-TAS)	Mark Curran, Jacqui Halpin, Peter McGoldrick	80	CODES, Hobart	16 November
Testing Evolutionary Stress Hypothesis research workshop	Ross Corkrey (TIA), Ross Large, Peter McGoldrick, Indrani Mukherjee , Anthony Poole, Tom Ross, Joe Wolfe	10	CODES, Hobart	22–23 November
Volcanic Processes, Products, Successions and Resources Short Course	Rebecca Carey , Ray Cas	25	Merimbula, NSW	2–8 December
Tasmania Geoscience Forum – Cenozoic submarine volcanism at Cape Grim (NW Tasmania)	Jodi Fox	8	Smithton, Tasmania	5 December
IODP Drilling workshop – submarine silicic calderas in the Kermadec	Martin Jutzeler	8	Washington DC, USA	8 December

Performance indicators

PERFORMANCE MEASURES IN 2014 – 2018 STRATEGIC PLAN

	TARGET	2018
Research Findings (CODES and Earth Sciences)		
Publications in international journals	50pa	82
Percentage of publications in high-quality international journals	74%	74%
Reports to industry collaborators	80pa	194
Special Issues and/or research monographs	1 per 2 years	1
Invitations to give keynote conference presentations	10pa	9
Papers at national/international meetings	70pa	74
Research Training and Professional Education		
Percentage of HDR students attracted from interstate	25%	18%
Percentage of HDR students attracted from overseas	65%	43%
Number of Honours students in CODES' programs	15	23
Number of HDR students in CODES' programs	50	56
Percentage of students in projects linked with industry	80%	69%
Professional short courses/workshops for industry	4pa	21
International, National and Regional Links and Networks		
CODES' national or international conferences/workshops	1 per 2 years	1
Registrants at CODES' conferences/workshops	600pa	737
End-user Links		
Frequency of meetings with industry representatives	15pa	25+
National Benefit		
CODES' research has input into a major mineral discovery	1 per 5 years	9 in 29 years

OPPOSITE PAGE: Spectacular sea cliffs
formed by columnar jointed Jurassic dolerite
at Cape Hauy on the Tasman Peninsula.



Finances

2018 income

Total CODES income was \$7.0 million (see Table 1). This was derived principally from UTAS (28%), the combined income sources of the ARC TMVC Research Hub (28%), and industry (19%) (see Figure 1). The main income streams over time are compared in Figure 2, showing a slight increase in overall income to CODES in 2018 when compared to 2017 despite a decrease in ARC funding.

Summary of the main income streams to CODES in 2018:

- **Host institution support:** Funding from UTAS in 2018 was \$1.9 million, up compared to the figure for 2017, mostly due to an increase in PhD scholarship funding (living and tuition fees) 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 \$2.0 million in 2018, comprising of funding from the ARC (\$408k), industry Partner Organisations (\$1.2 million), Host Institution (\$128k), and other sources including Additional Funder Projects (\$240k).

- **Industry income:** Industry funding of \$1.3 million comprises funding related to Industry Partner support, industry funded student projects, and other research projects. This figure does not include industry-based support for the ARC TMVC Research Hub (see above).

2019 income estimates

There is expected to be a reduction in overall funding to CODES with the final ARC funding to the TMVC having been received in 2018 (although the majority of Partner and UTAS funding will continue until the end of 2019). Industry and Other funding to CODES is expected to remain strong with the commencement of several new multi-year one-on-one projects in 2018. UTAS support is also expected to remain steady into 2019.



TABLE 1: CASH INCOME FINANCIAL STATEMENT 2018

ARC Transforming the Mining Value Chain Research Hub	
ARC Industrial Transformation Research Project	408,359
Partner Organisations	1,198,263
– <i>AMIRA International</i>	791,743
– <i>BHP</i>	176,000
– <i>Newcrest Mining</i>	230,520
Host Institution	127,738
Additional Funder Projects	200,571
Miscellaneous	39,806
	1,974,738
ARC Grants	
Linkage Grants	136,206
	136,206
Other Commonwealth Government	
Specific Projects	420,506
Miscellaneous	159
	420,665
State Government	
Specific Projects	25,000
	25,000
Industry/private	
CODES Industry Partners	350,000
Cooperative Research Centre Projects	399,184
Directly Funded Research Projects	410,000
Directly Funded Student Projects	150,712
Miscellaneous	32,707
	1,342,603
Contracts/consultancies/revenue raising	
Short Courses	101,174
Symposiums	41,040
Book Sales	10,115
Miscellaneous (incl. Analytical Services)	859,266
	1,011,595
University of Tasmania – host institution support	
Operating Grant	870,341
Scholarships and Tuition Fee Waivers	855,822
Strategic Projects	192,751
	1,918,914
Other income sources/interest	
Society of Economic Geologists – Student Scholarships	6,492
Student Support	96,136
Specific Projects	23,240
Miscellaneous	11,713
	137,581
Total annual income	6,967,301

Figure 1
Total Cash Income 2018

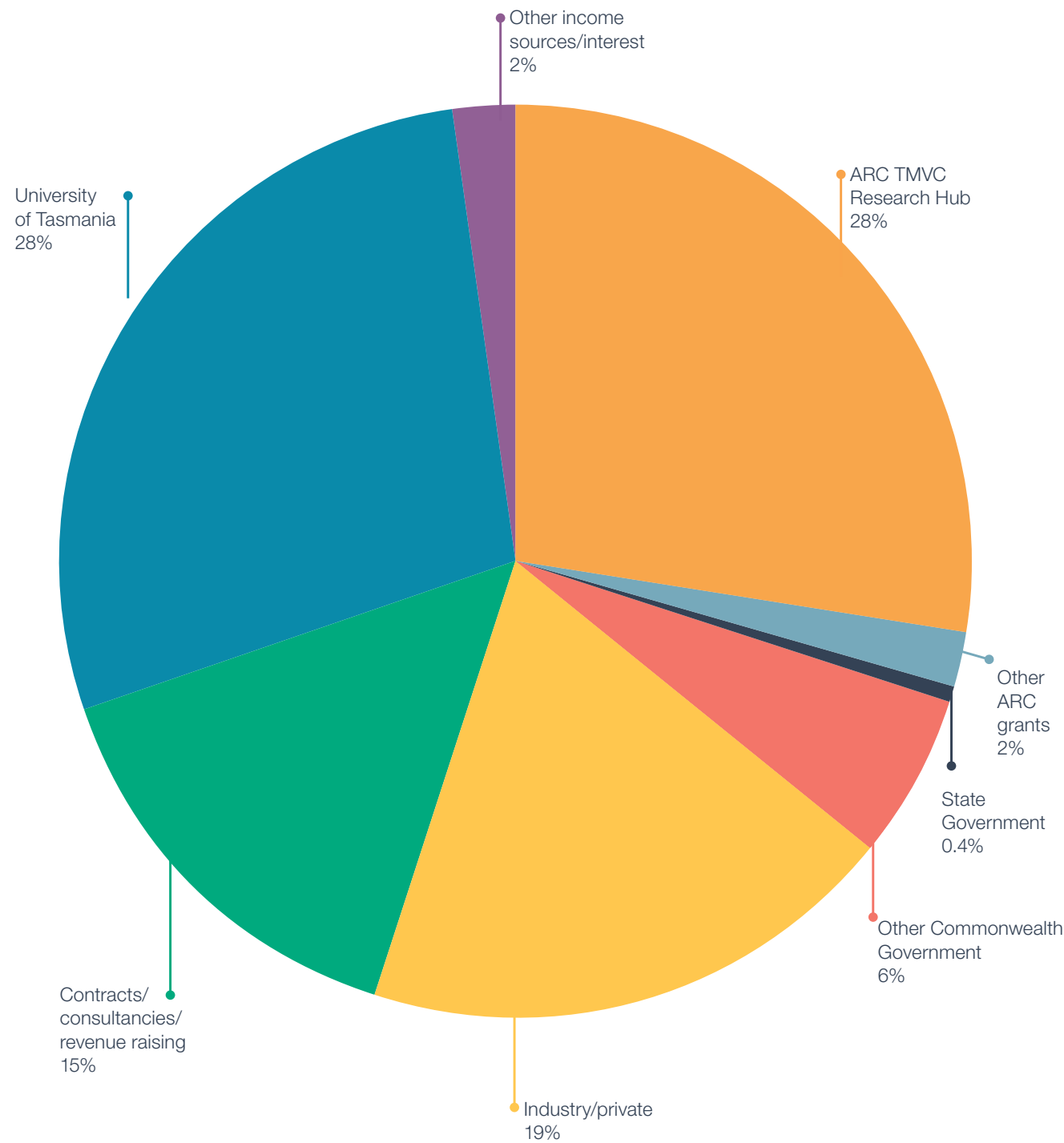
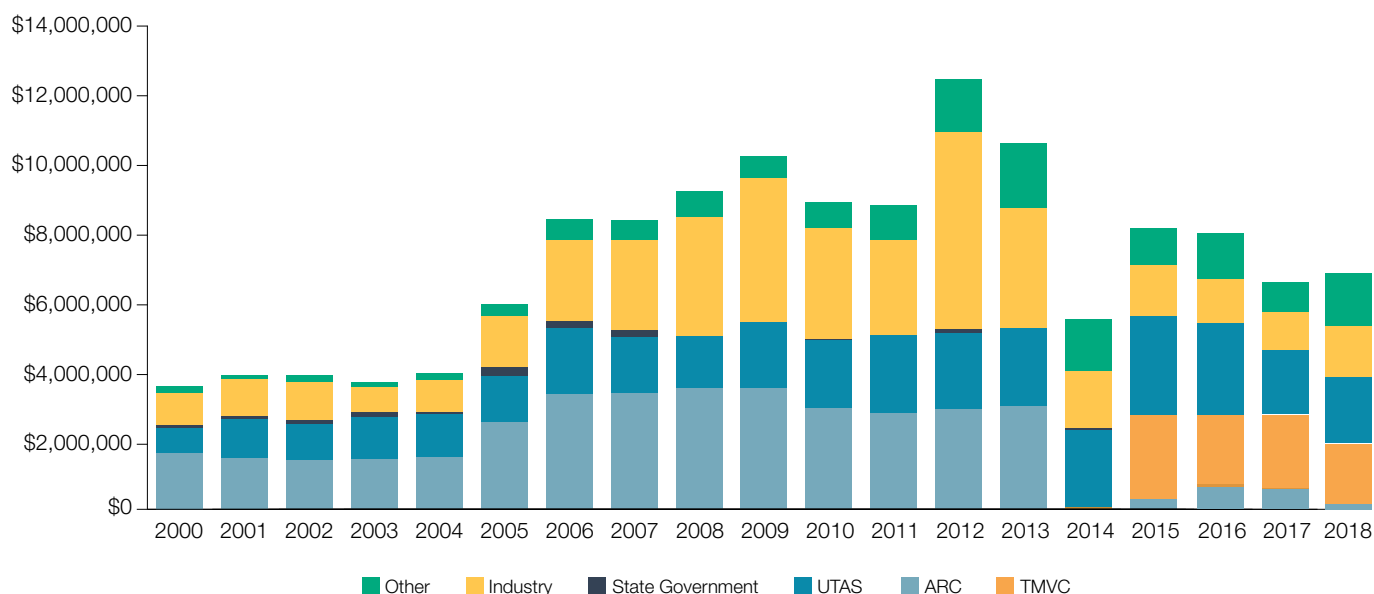


Figure 2

Comparison of CODES main income streams 2000–2018



Notes to, and forming part of, the financial statements for 2018

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 2018, or centrally administered for CODES RHD students (as in the case of scholarships and tuition fee waivers).



2018 publications

Outputs related to the TMVC Research Hub are marked with an asterisk.

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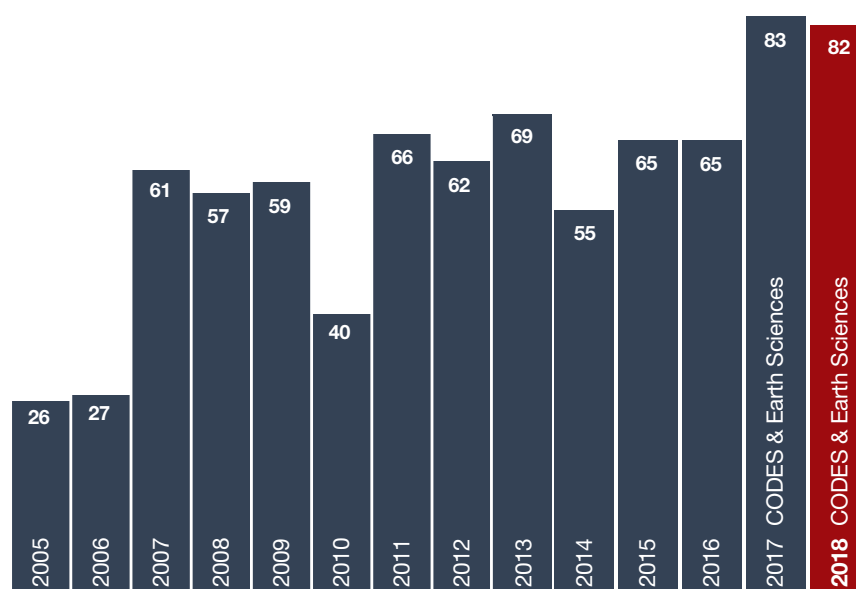
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View of the Andes, Peru, taken during a fieldwork trip to South America in December 2018.

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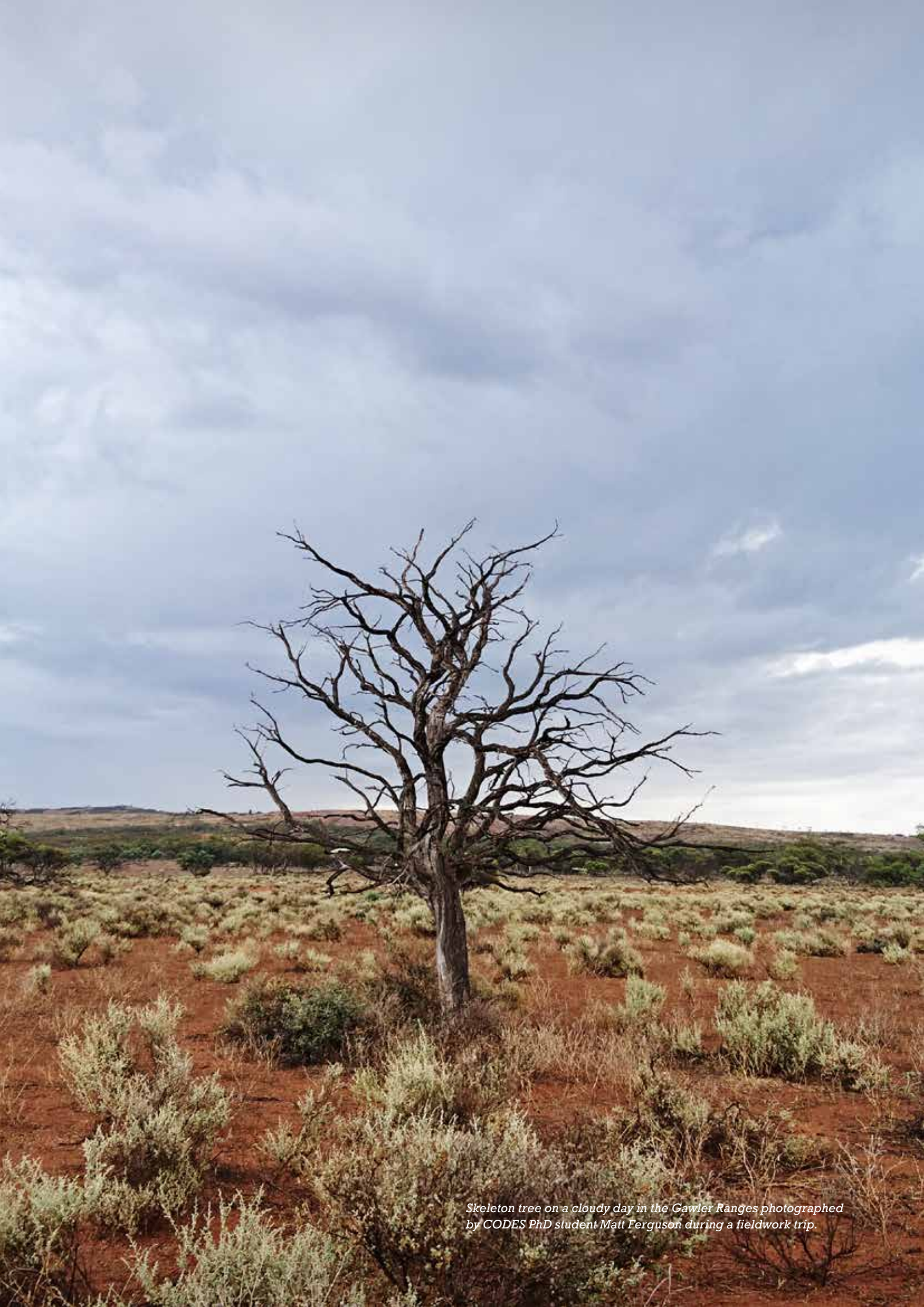
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Skeleton tree on a cloudy day in the Gawler Ranges photographed by CODES PhD student Matt Ferguson during a fieldwork trip.

Research reports to industry/government agencies (194)

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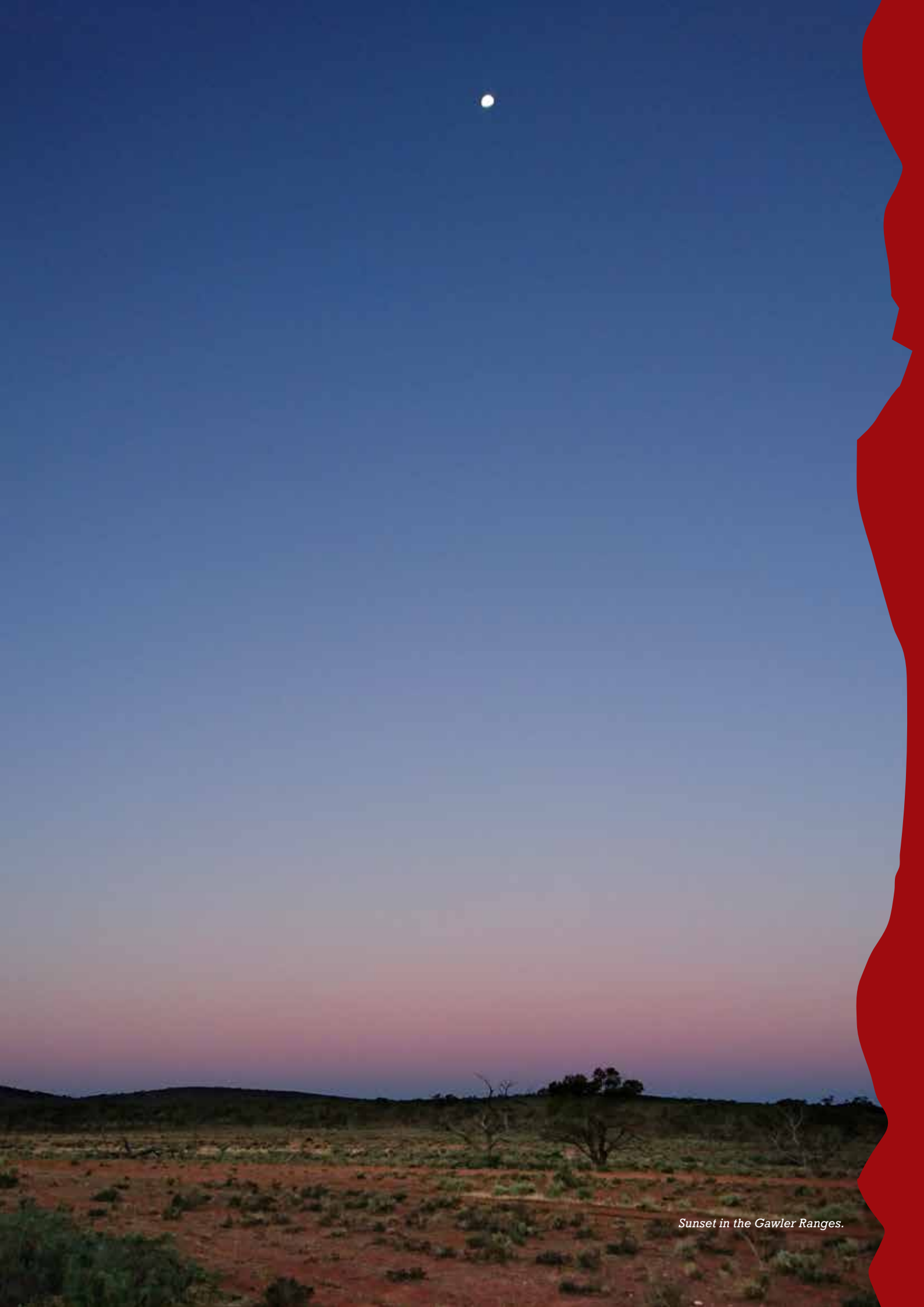
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*Masters student Victor Torres at the Soldedad Breccia
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- Thompson, J., and Danyushevsky, L., 2018, P651: U-Pb zircon geochronology: Report to Archer Exploration, 4 p.
- Thompson, J., Lounejeva Baturina, E., and Danyushevsky, L., 2018, P620: U-Pb apatite geochronology: Report to BHP Chile, 5 p.
- Thompson, J., Lounejeva Baturina, E., and Danyushevsky, L., 2018, P650: U-Pb apatite geochronology: Report to BHP Chile, 4 p.
- Thompson, J., Meffre, S., Olin, P., and Danyushevsky, L., 2018, P657: Pb isotopic analysis of galena in one sample: Report to Rio Tinto, 4 p.
- * Thompson, J., Thompson, J., Cooke, D.R., Baker, M., Danyushevsky, L., and Wilkinson, C., 2018, Calcite U-Pb dating method development: AMIRA P1202 Sponsors Meeting 2, Hobart, Australia, 28–29 November 2018, p. 383–400.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P623: U-Pb zircon geochronology: Report to Stavely Minerals, 5 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P624: U-Pb zircon geochronology and trace elements: Report to QPX, 4 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P625: U-Pb zircon geochronology: Report to Friendly Mining Consulting LLC, 4 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P629: U-Pb zircon geochronology: Report to First Quantum Minerals, 8 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P638: U-Pb zircon geochronology: Report to Barrick Gold, 4 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P645: U-Pb zircon geochronology (Batches 1 and 2): Report to Gold Fields, 7 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P646: U-Pb zircon geochronology: Report to Barrick USA, 6 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P648: U-Pb zircon geochronology: Report to Emsac Ecuador, 6 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P649: U-Pb zircon geochronology: Report to Teck Chile, 5 p.
- Thompson, J., Zhukova, I., and Danyushevsky, L., 2018, P654: U-Pb zircon geochronology and trace elements: Report to Newcrest, 6 p.
- Tolley, J., Olin, P., and Danyushevsky, L., 2018, P589: Gold content of pyrite and arsenopyrite in central composite, gravity concentrate, 8 p.
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- Tolley, J., Olin, P., and Danyushevsky, L., 2018, P642: Gold content of pyrite in six samples, 10 p.
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- * White, N., Zhang, L., Cooke, D.R., and Orovan, E., 2018, Exploring lithocaps: new concepts, new approaches: AMIRA P1153 Sponsors Meeting 7, Hobart, Australia, 6–7 June 2018, p. 1,065–1,103.
- * Zhang, L., 2018, Geochemical and mineralogical vectors to ore at Bilihe-Hadamiao district, Inner Mongolia, China: Report to Peking University and Inner Mongolia Mining Technology Research Institute, 22 p.
- * Zhang, L., Bartlett, J., Escolme, A., and Cooke, D.R., 2018, Tjueh Bukit, East Java, Indonesia: AMIRA P1202 Sponsors Meeting 1, Hobart, Australia, 8 June 2018, p. 192–210.
- * Zhang, L., Cooke, D.R., Orovan, E., White, N., Baker, M., Chen, H., Wilkinson, J.J., Baig, A., Taylor, J., Smyk, E., Thompson, J., Derome, N., Hollings, P., Chang, Z., Jimenez, C., Thompson, J., Belousov, I., Goemann, K., Hong, W., and Chen, J., 2018, Quartz: a tool for vectoring and fertility assessments in magmatic-hydrothermal ore deposits: AMIRA P1153 Sponsors Meeting 7, Hobart, Australia, 6–7 June 2018, p. 843–907.
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- * Zhang, L., Orovan, E., Eastman, K., Rodrigues, A., White, N.C., and Cooke, D.R., 2018, Buckskin lithocap, Yerington, Nevada: AMIRA P1202 Sponsors Meeting 2, Hobart, Australia, 28–29 November 2018, p. 38–62.
- * Zhang, L., Orovan, E., White, N., and Cooke, D.R., 2018, Buckskin lithocap, Yerington, Nevada: a vertical profile of a lithocap: AMIRA P1153 Sponsors Meeting 7, Hobart, Australia, 6–7 June 2018, p. 458–493.
- * Zhang, L., Orovan, E., White, N., and Cooke, D.R., 2018, Yerington lithocap, Nevada: AMIRA P1202 Sponsors Meeting 1, Hobart, Australia, 8 June 2018, p. 152–163.
- * Zhang, L., Orovan, E., White, N., Cooke, D.R., Trujillo, J., and Andia, R., 2018, La Zanja district, Peru: AMIRA P1153 active exploration site: AMIRA P1153 Sponsors Meeting 7, Hobart, Australia, 6–7 June 2018, p. 59–66.
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Sunset in the Gawler Ranges.

Appendices

CODES postgraduate students 2018

BACHELOR OF SCIENCE (HONOURS) (23)

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Tomas Andrews ^	Scott, Bull	3	Pyrite trace element geochemistry and sedimentology of the Barney Creek Formation, Rosie Creek Sub-basin, NT	MMG
Rebekah Cornelius *^	Parbhakar-Fox, Cooke, Fox	2	Geoenvironmental characterisation of the Lill-Laverbergt Cu-porphyry deposit, Northern Sweden	Boliden Mineral, ARC TMVC
Hannah Couper *^	Escolme, Cooke	2	Geological and geometallurgical characterisation of the high Au, low Cu domain at Newcrest's Telfer Cu-Au mine	ARC TMVC, Newcrest Mining
Hamish Cowie	Scott, Steadman	1	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
Sarah Gilmour *^	Parbhakar-Fox, Fox, Olin	2	Mineralogical and geochemical characterisation of historical slag: evaluating environmental impacts and economic significance	ARC TMVC, MRT, AusIMM, MMG, CMT, GSA
Stewart Jackson ^	Lotter (IMS), Gal	6	Finite difference wavefield modelling for mine seismology	Institute of Mine Seismology
Darcy James	Meffre, Bottrill (MRT)	3	Mineralogy, geochronology and whole rock geochemistry of basement to the Tasmanian Basin.	Mineral Resources Tasmania
Colin Jones *^	Orovan, Cooke	1	The magmatic hydrothermal transition at Bluestone Bay, Freycinet Peninsula, Tasmania	ARC TMVC, UTAS Foundation
Ben Kowaluk *^	Zhang, Baker	1	Geology, geochemistry and genesis of the Hadamiao Au-Cu porphyry prospect, Inner Mongolia, China	Inner Mongolia Mining Technolgy Research Institute, Peking University, ARC TMVC
Bridie Le'Gallais ^	Danyushevsky, Meffre, Everard (MRT), Cumming (MRT)	4	Olivine cumulates from the Whyte River Complex in Western Tasmania	MRT
Richard (Sigmund) Lloyd §	Meffre, Steadman	1, 3	Comparison of the mineralogy and geochemistry of altered rocks in the Woodlawn and Oberon areas, NSW	ARC Linkage, Heron Resources
Tim McDonald	Cracknell, Roach	6	Geophysical investigation of buried karst landscape, Railton, Tasmania	
Robert McLaine *^	Parbhakar-Fox, Fox	2	Determining bioaccessibility risks at the historic Aberfoyle tailings site, North East Tasmania: Opportunities for effective rehabilitation	ARC TMVC, MRT
Ryan McMann ^	Cas, Olin	4	A syn-depositional sill intrusive model for the Golden Mile Dolerite, Kalgoorlie, WA	GSWA
Fatin Amni Mohamed Amin *^	Zhang, Orovan	1	Advanced argillic alteration at Glen Lyell and Western Tharsis deposits, Mt. Lyell district, Western Tasmania: Implications for the genesis of Cu-Au mineralization and district exploration	ARC TMVC, MRT, CMT
Rhiannan Mundana ^	Whittaker (IMAS), Carey, Johnson	4	The geological evolution of the Cascade Seamount, Tasman Sea	UTAS, IMAS, MNF, GSA
Emmet O'Keefe *^	Orovan, Zhang	1	Genesis of the Trial Harbour Fe-Mg skarn	ARC TMVC, UTAS Foundation

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BACHELOR OF SCIENCE (HONOURS) (23) cont.

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Ben Ridgers ^	Meffre, Bottrill (MRT), Steadman	1, 3	Pb isotopic characterisation of ore deposits and prospects from NE Tasmania	ARC Linkage, New South Resources, MRT
Riquan Ropli ^	Meffre, Steadman, Duncan (GSVic)	1, 3, 4	Age and paragenesis of the Hill 800 prospect, Victoria	ARC Linkage, GS Victoria
Xin Ni Seow *^	Baker, Orovan	1	Geology and genesis of the Prince Darwin prospect, Western Tasmania	ARC TMVC, MRT, Corona
Mark Sinfield ^	Webster, Scott	3	The litho-structural controls on the origin of mineralisation at Carbonate Ridge, Broken Hill, NSW	Perilya
Matthew Vincent *	Zhang, Baker	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

MASTER OF ECONOMIC GEOLOGY (54)

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Michael Adams			coursework only	
Robert Ayres			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	Geochemical classification of ore fluids, Costerfield Sb-Au deposit, Victoria	Mandalay Resources
Brianna Clark			coursework only	
Jesse Clark			coursework only	
Sarah Cochrane			coursework only	
Roseanna Dale			coursework only	
Lieth de Selincourt			coursework only	
Alison Dines			coursework only	
Laura Dowling			coursework only	
David Eddy			coursework only	
Paul Edmonds			coursework only	
Benjamin Ferguson			coursework only	
Franco Ferreyra	Cooke		TBC	
Arga Firmansyah	Cooke	1	Geology and mineralisation of the Trenggalek district, East Java, Indonesia	PT Pamapersada Nusantara
Daniel Foulds			coursework only	
David Groombridge^			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
Kyle Hodges			coursework only	
Kyle Hughes	Meffre	1, 3	Paragenesis of the Dobroyde Deposit, central NSW	ARC Linkage

* Affiliated with the ARC TMVC Research Hub # Degree completed, not yet graduated ^ Graduated § Withdrawn

MASTER OF ECONOMIC GEOLOGY (54) cont.

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
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	
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	
Thomas Langley ^			coursework only	
Esther Little			coursework only	
Walter Lozano Garcia Naranjo			coursework only	
David Mallon			coursework only	
Todd McGilvray			coursework only	
Paul Merriner			coursework only	
Dominic Murphy			coursework only	
Menford Ngara			coursework only	
Alister Orton			coursework only	
Nicholas Poznik			coursework only	
Thomas Ralston ^			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
Christopher Shanley^			coursework only	
John Stacpoole			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 EXPLORATION GEOSCIENCE (1)

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Peerapong Sritangsirikul	Meffre	3	Tectonic evolution and ore deposit prospectivity of the Rockley Volcanics, NSW Australia	Thai Royal Government Scholarship

MASTER OF SCIENCE (1)

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Eyob Andemeskel ^	Selley, Carey	3, 4	Litho-chemo-stratigraphic, structural and mineral prospectivity aspects of the Rosebery Group, an enigmatic Cambrian volcano-sedimentary succession in western Tasmania	MMG, CODES

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DOCTOR OF PHILOSOPHY (54)

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
Ayesha Ahmed *	Cooke, Baker, Orovan	1	The effect of pressure/depth on propylitic alteration mineral chemistry in the porphyry environment	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
Alexander Cherry #	V.Kamenetsky, McPhie, Ehrig (BHP)	3, 4	Petrology, provenance and composition of bedded sedimentary facies in the Olympic Dam deposit	UTAS, ARC Linkage, SEG, BHP
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	Origin, geochemistry, stratigraphic and structural setting of the Archean Invincible gold deposit, St Ives gold camp, Yilgarn Craton, Western Australia	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, UTAS
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	Submarine basaltic intraplate volcanism	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
Cassady Harraden^	Meffre, Berry, Cracknell	2	Geotechnical and geometallurgical assessment by Corescan and complementary microanalytical techniques	UTAS, ARC TMVC, Newcrest Mining, Corescan
Rachel Harrison **	Cooke, Zhang	1	The Tumpangpitu porphyry gold-copper-molybdenum and high-sulfidation epithermal gold-silver deposit, Tjjuh Bukit, southeast Java, Indonesia	UTAS, SEG, ARC TMVC
Jacob Heathcote	Scott, G.Davidson	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
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

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DOCTOR OF PHILOSOPHY (54) cont.

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Shawn Hood *	Cracknell, Reading	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
Amery Jackson §	Fox	2	Geometallurgical controls on grade by size fractionation in gold systems with applications to Grade Engineering	CRC ORE
Laura Jackson *	Parbhakar-Fox, 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
Colin Jones *	Orovan, Cooke, Meffre	4	Petrogenesis of Devonian granites, eastern Tasmania	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, 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
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
Claire McMahon §	G.Davidson, Danyushevsky	1	Distribution of, and controls upon, pyrite trace element content of hydrothermal alteration zones at Hercules VHMS ore deposit, Tasmania and NICO IOCG ore deposit, Northwest Territories, Canada	ARC
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
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, Bassom (Mathematics)	6	A model-based approach to the interpretation of seismicity associated with mass mining	Institute of Mine Seismology
Peter Morse	Reading, Lueg (Computing)	6	Interactive visualisation for data inference in the geosciences	UTAS, CODES, ARC TMVC
Annah Moyo *	Parbhakar-Fox, Cooke	2	Controlling acid and metalliferous drainage at legacy sites in Tasmania using industrial waste materials	UTAS, Mineral Resources Tasmania, ARC TMVC
Nanda Yusentri Mrabawani *	Danyushevsky, Meffre	5	Laser Ablation applied to mineral characterisation	ARC TMVC, UTAS
Indrani Mukherjee ^	Large, Halpin (IMAS), Meffre	1, 3	Pyrite trace element chemistry of black shales of the "boring billion" period	UTAS, SEG, AMIRA, CODES
Sibele Cristina do Nascimento *	Parbhakar-Fox, Cracknell, Cooke	2	Geoenvironmental characterisation of historic mine tailings: Evaluating opportunities for reprocessing	ARC TMVC, UTAS

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DOCTOR OF PHILOSOPHY (54) cont.

STUDENT	SUPERVISORS	RESEARCH PROGRAM	PROJECT	SUPPORT
Thomas Ostersen	Reading, Cracknell	6	Geoelectric 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), Roach, Cracknell	3, 6	Plate tectonic modelling of the Early Palaeozoic evolution of South Eastern Australia	ARC Linkage, UTAS
Subira Sharma ^	G.Davidson, Cooke	1	Evaluation of the links between Merlin-style Mo-Re mineralisation and magmatism in the Cloncurry fold belt, Queensland: Implications for exploration	UTAS, Chinova Resources
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
Tobias Staal	Reading, Whittaker (IMAS), Halpin (IMAS)	6	Seismic and geological constraints on the lithospheric structure of Antarctica	Antarctic Gateway Partnership
Nathan Steeves ^	Gemmell, Large, Hannington (UOttawa)	1, 4	Ore genesis of the Greens Creek VHMS Deposit, Alaska: Implications for mining, milling and exploration	Hecla Mining, UTAS
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, 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 ₂ 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 (Reunion): 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	Geochemistry and cathodoluminescence of magmatic apatite and zircon as vectors to mineralised centres within the Lachlan Fold Belt	ARC Linkage, UTAS, CODES, NorthParkes

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Masters students on the Red Crater of Tongariro volcano, New Zealand, pictured during the 'Volcanology and Mineralisation in Volcanic Terrains' short course, March 2018.

Major externally funded research projects[^]

ARC INDUSTRIAL TRANSFORMATION RESEARCH HUB GRANTS 2018

INVESTIGATORS	PROJECT	FUNDING BODY	PERIOD	ARC FUNDING FOR 2018	PARTNER FUNDING FOR 2018	UTAS FUNDING FOR 2018	MISC FUNDING FOR 2018
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	\$408,359	\$1,198,263	\$127,738	\$39,806

ADDITIONAL FUNDER PROJECTS WITHIN THE ARC TMVC RESEARCH HUB 2018

INVESTIGATORS	PROJECT	FUNDING BODY	PERIOD	FUNDING FOR 2018
Cooke, White, Zhang, Gemmell, Testa	Geological and geochemical vectors to low sulfidation epithermal gold mineralization, Cerro Negro district, Deseado Massif, Argentina	Oro Plata SA	2017–2019	\$114,607
Cooke, Parbhakar-Fox, Moyo (student)	Controlling acid and metalliferous drainage at legacy sites in Tasmania using industrial waste materials	Mineral Resources Tasmania	2017–2020	\$36,346
Parbhakar-Fox, Cornelius (student)	Establishing effective mineralogical and geochemical techniques for geoenvironmental characterisation: Laver, Sweden	Boliden Mineral AB	2017–2018	\$18,256
Parbhakar-Fox	Savage River: Kinetic trials of waste rock materials; Long Plains, Tasmania	Grange Resources	2015–2018	\$12,986
Zhang, Baker, Vincent (student)	The application of visible near infrared (vis-NIR) and short wavelength infrared (SWIR) spectral analysis in exploration for Mount Cassidy porphyry prospect, Rockhampton district, eastern Australia	Signature Gold	2018	\$8,769
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	2015–2018	\$4,000
Orovan, Zhang, O'Keefe (student)	Genesis of the Trial Harbour Fe-Mg skarn	UTAS Foundation	2018	\$2,200
Baker, Orovan, Seow (student)	Geology and genesis of the Prince Darwin prospect, Western Tasmania	Mineral Resources Tasmania	2018	\$2,000
Zhang	Geochemical and mineralogical vectors to the ore at Bilihe-Hadamiao district, Inner Mongolia, China	Peking University	2017–2018	**
		Inner Mongolia Mining Technology Research Institute	2017–2018	**
Parbhakar-Fox, Fox, McLaine (student)	Integrated kinetic testing for best practice mine waste characterisation	Australian Academy of Technology and Engineering	2017–2018	‡‡

[^] projects with greater than \$2,000 external funding per year ** all project funding received, project still active

‡‡ full project funding received in one year

Pulau Merah porphyry Cu-Au island in Tujuh Bukit district, East Java, Indonesia.

ARC LINKAGE GRANTS 2018

INVESTIGATORS	PROJECT	FUNDING BODY	PERIOD	ARC FUNDING FOR 2018	PARTNER FUNDING FOR 2018
Kamenetsky, McPhie, Meffre, Maas (Umelb), Ehrig (BHP)	The supergiant Olympic Dam U-Cu-Au-REE ore deposit: towards a new genetic model	ARC, BHP	2014–2018	**	**
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	\$136,206	\$115,000

ARC DISCOVERY GRANTS 2018

INVESTIGATORS	PROJECT	PERIOD	ARC FUNDING FOR 2018
Reading, Koper (Utah)	Are ocean storms impacting Australia becoming more severe?	2015–2018	**

ARC DISCOVERY EARLY CAREER RESEARCHER AWARDS 2018

INVESTIGATORS	PROJECT	PERIOD	ARC FUNDING FOR 2018	UTAS FUNDING FOR 2018
Carey	The role of hydrostatic pressure in modulating submarine silicic eruptions	2015–2019	**	\$51,596

CRC PROJECTS 2018

INVESTIGATORS	PROJECT	PERIOD	CRC FUNDING FOR 2018	UTAS FUNDING FOR 2018
Cooke, Gemmell	CRC ORE II Participant funding	2015–2021	\$0	\$100,000
Fox, Gemmell	CRC ORE II – Predictive geometallurgy controls on grade by size	2016–2019	\$399,184	\$0

INDUSTRY AND OTHER EXTERNALLY FUNDED RESEARCH GRANTS 2018

INVESTIGATORS	PROJECT	FUNDING BODY	PERIOD	FUNDING FOR 2018
Barker, Steadman, Cooke	Mineral geochemistry vectoring: Uncovering Northwest Queensland's hidden potential	Geological Survey of Queensland	2018–2020	\$375,500
Cooke, Meffre, Jutzeler, Carey	4D geological modelling of the Cowal district, NSW	Evolution Mining	2018–2021	\$200,000
Large, Mukherjee	Application of a technology driven approach to defining targets for Cu-Co deposits associated within the Neoproterozoic Tapley Hill Formation, South Australia	Drummond Gold	2018	\$110,000
Gemmell, Cooke, Davidson (student)	Geology and genesis of the San Sebastian vein system, Durango, Mexico	Hecla Mining Company	2017–2020	\$48,000
Cooke, Zhang, Xiao (visitor)	Porphyry and skarn mineralisation in China	Hefei University of Technology	2015–2018	\$38,560
Gemmell, Fox, McNulty (student)	Geology and genesis of the mineral deposits of the Myra Falls VHMS District, Canada	Nyrstar Myra Falls	2015–2018	\$25,000
Cooke, Torres (student)	Geology, genesis and exploration implications of Cu-Au mineralised tourmaline breccia pipes at Soledad, central Peru	Chakana Copper	2017–2019	\$23,100
Li (visitor)	Zircon U-Pb dating for granite and trace element compositions of sulfides from the deposits on the northern and southern margins of the North China Craton: implications for orogenic belt evolution and mineralisation	Peking University	2018	\$22,240
Parbhakar-Fox	Cobalt recovery from mine tailings using bioleaching: Environmental and economic benefits	Dept of Primary Industries, Parks, Water & Environment	2018	\$15,000
		Grange Resources	2018	\$5,000
Bull, Selley, G.Davidson	Controls on copper mineralising processes in the McArthur Basin, NT, and its implications for the metallogeny of extensional basins	Northern Territory Geological Survey	2016–2018	\$16,281
Scott, Bull, Andrews (student)	Pyrite trace element geochemistry and sedimentology of the Barney Creek Formation, Rosie Creek Sub-basin, NT	MMG	2018	\$16,028
Scott, Steadman, Cowie (student)	Architecture of intrusion related mineralisation at Ora Banda, Eastern Goldfields, Western Australia	Evolution Mining	2018–2019	\$12,584
Jutzeler, Carey	Eruption styles and periodicity of the silicic Sumisu caldera, Izu-Bonin-Mariana Arc	IODP (via Australian National University)	2018–2020	\$10,000
Stepanov, Bottrill (MRT), Hong, Denholm (student)	The trace element chemistry and U-Pb geochronology of Tasmanian cassiterite	UTAS Foundation	2018	\$5,000
		Mineral Resources Tasmania	2018	\$5,000
Escolme, Rojas Lopez (student)	Origin, characteristics and age of mineralization of the Ollachea orogenic gold deposit, Puno Region, southeastern Peru: Implications for exploration	Society of Economic Geologists	2018	\$6,492
		PRONABEC	2018	\$2,000
Danyushevsky, Tolley	Development of fundamental aspects of laser-ablation analysis applied to geological problems	Laurin Technic	2015–2019	**
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	2015–2018	**
Reading, Meyer (student)	Mine seismology using model-based processing	Institute of Mine Seismology	2017–2019	**
Scott, Cas, Douch (student)	The geology and geological controls on gold mineralisation at the Invincible deposit, St Ives Gold Mine, Kambalda, WA	St Ives Gold	2015–2018	**

^ projects with greater than \$2,000 external funding per year ** all project funding received, project still active

‡‡ full project funding received in one year

OPPOSITE PAGE: TMVC PhD student Kyle Eastman (left) and undergraduate Earth Sciences student Imbi Simpson with pseudoclasts of mafic pyroclastic material in the Devonian Boyd Complex, southern New South Wales.



Visitors 2018

INDUSTRY VISITORS TO CODES IN 2018

NAME	COMPANY
Paul Agnew	Rio Tinto
Rodney Allen	Volcanic Resources
Zaid Al-Mowaled	Ma'aden Company (Saudi Arabia)
Abdulrhman Al-Muhaya	Ma'aden Company (Saudi Arabia)
Anita Andrew	Australian Journal of Earth Sciences
Debora Araujo	Rio Tinto
Ingemar Arellano	Freeport-McMoRan (Canada)
Julian Bartlett	Merdeka Copper-Gold
Bob Beeson	Beeson Geoscience Pty Ltd
Susan Belford	Consultant
Jeff Bigelow	Newmont
Steve Bodon	CSA Global
Dave Braxton	Anglo American
Rex Brommecker	Evolution Mining
Alex Brown	Glencore-MIM
Tim Callaghan	Consultant
Keith Cameron-Smith	Grange Resources
John Carswell	Carswell and Associates
Ian Cook	Map to Mine
Ken Cross	Consultant
Sefton Darby	KPMG
Andrew Davies	Teck Resources
Brett Davis	Orefind
Kim Denwer	MMG
Glen Diemar	New South Resources
Mary Doherty	Newmont
Rowena Duckworth	Mintex Petrological Solutions
Wess Edgar	Kirkland Lake Gold
Kathy Ehrig	BHP
Alex Farrar	First Quantum
David First	Freeport-McMoRan Exploration Australia
Daniel Foulds	Kirkland Lake Gold
Kim Frankcombe	Consultant Geophysicist
Rizal Fraval	Rio Tinto
Alina Gaibor	BHP
Sam Garrett	Pacific Trends Resources
Simon Gatehouse	BHP
Andrea Gerson	Blue Minerals Consultancy
Scott Halley	Mineral Mapping
Cassady Harraden	CoreScan
Mary Harris	Newcrest Mining
Rex Harris	Thermo
Kate Hine	Mitre Geophysics
Terry Hoschke	Newcrest/Alterrex
Jonathon Hoyer	North Parkes
Ned Howard	Evolution Mining

NAME	COMPANY
Danny Huisman	South 32
Christain Ihlenfeld	Anglo American
Martin I'ons	Cobalt Qld Pty Ltd
Tim Ireland	First Quantum/CODES associate
Jose Luis Jara	QPX
Sarah Jones	Gold Fields
Ben Jones	VDL Geological
Sam Kemp	Sample Data
Punit Kumar	Rio Tinto
Chris Lay	ASI
Joshua Leigh	First Quantum/Freeport-McMoran
Vanessa Lickfold	BHP
Angela Lorrigan	Diversified Minerals
Neil Martin	BML (UK)
Jonathan McLoughlin	MMG
Bruce McQuitty	Carawine Resources
Edward Morris	Diversified Minerals Pty Ltd
Ashley Norris	ASI
Mike Nugus	AngloGold Ashanti
Dana Olafson	Fortescue Metals Group
Nick Oliver	Consultant
Grant 'Rocky' Osborne	Geosborne Pty Ltd
Tom Pearson	Chinova Resources
Sasha Pontual	AusSpec
Cameron Quinn	Fortescue Metals Group
Peter Rea	Glencore-MIM
Chris Reed	Teck Resources
Andrew Ryan	QPX
Tony Saric	Exploration geologist
Martin Scott	Fortescue Metals Group
Ivan Semenov	Rio Tinto
Adele Seymon	AMIRA International
Trevor Shaw	Glencore-MIM
Rob Sievwright	First Quantum
Penny Sinclair	Vimy Resources
Roger Smart	Blue Minerals Consultancy
Gary Snow	Gold Fields Australia
McLean Trott	First Quantum
Mario Valdez	MMG
Patrick Verbeek	Traka Resources Ltd
Tony Webster	South 32
Mike Whitbread	Rio Tinto
Noel White	Consultant
Greg Wilkie	CRC ORE
Sarah Williamson	ASI
Kunshya Zimba	FQM, Zambia

NATIONAL ACADEMIC AND GOVERNMENT VISITORS IN 2018

NAME	INSTITUTION
Laurent Ailleres	Monash University
Stephen Barnes	CSIRO Mineral Resources
Ralph Bottrill	Mineral Resources Tasmania
Marcello Blaxell	University of Canberra
Ross Corkrey	University of Tasmania
David Clases	University of Technology Sydney
Alie Cowood	University of Canberra
Mark Duffett	Mineral Resources Tasmania
David Green	Mineral Resources Tasmania
Paul Heithersay	Department for Energy and Mining, South Australia
Mark Hemer	CSIRO
Mark Hunt	Head of School of Natural Sciences, UTAS
David Huston	Geoscience Australia
Tania Lado Insua	Office of Research Services, UTAS
Chris Large	Mineral Resources Tasmania
Trevor Lewis	Chemistry, UTAS

NAME	INSTITUTION
Vladimir Lisitsin	Geological Survey of Queensland
Andrew McNeill	Mineral Resources Tasmania
Brenda Mooney	Chemistry, UTAS
Leah Moore	University of Canberra
Jacob Mulder	Monash University
Robert Musgrave	Geological Survey of New South Wales
Jennifer Parnell	Mineral Resources Tasmania
Brett Paull	Director ACROSS, UTAS
Tim Rawlings	University of Melbourne
Anya Reading	Physics, UTAS
Angela Rodrigues	Monash University
Roger Skirrow	Geoscience Australia
Miles Smith	School of Natural Sciences, UTAS
Penny Stringer	Student Experience, UTAS
John Walshe	CSIRO
Lesley Wyborn	Australian National University

INTERNATIONAL ACADEMIC AND GOVERNMENT VISITORS IN 2018

NAME	INSTITUTION
Ben Andrew	University of Waikato, New Zealand
Ali Bani	University of Guilan, Iran
Shaun Barker	University of Waikato, New Zealand
Zhaoshan Chang	Colorado School of Mines, USA
Emily Crowder	Aberdeen University, UK
Chris Eastoe	University of Arizona, USA
Yongwei Gao	Xi'an Centre of Geological Survey, China
Dieter Garbe-Schönberg	Kiel University, Germany
Xianzheng Guo (student)	China University of Geosciences, Wuhan, China
Katharina Hochmuth (student)	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany
Peter Hollings (student)	Lakehead University, Canada
Nikita Kepezhinskis (student)	University of Florida, USA
Joe Lacsce (student)	University of Oslo, Sweden
Xuanxuan Li (student)	Hefei University of Technology, China
Anders McCarthy (student)	University of Bristol, UK
Liqing Nie (student)	Hefei University of Technology, China
Kira Olsen (student)	Columbia University, New York, USA
Ant Poole (student)	University of Auckland, New Zealand
Bing Qian	Xi'an Centre of Geological Survey, China
Dan Rasmussen (student)	Columbia University, New York, USA

NAME	INSTITUTION
Mark Smyk	Ontario Geological Survey, Canada
Quanxiang Song	Ministry of Natural Resources, China (with 18 other visitors)
Peter Sorjonen-Ward	Geological Survey of Finland (GTK)
Adam Soule	Woods Hole Oceanographic Institution, USA
Shiqiang Su (student)	Institute of Geology and Geophysics, CAS
Keyan Tan	National Research Centre of Geoanalysis of CAGS, (Chinese Academy of Geological Sciences), China
Doug Wiens	Department of Earth and Planetary Sciences, Washington University, USA
Jo Wolfe	Harvard University, USA
Song Wu	China University of Geosciences, China
Guo Xianzheng (student)	China University of Geosciences (Wuhan)
Qi Yabin	National Research Centre of Geoanalysis of CAGS (Chinese Academy of Geological Sciences), China
Lin Yang (student)	China University of Geosciences, Beijing
Liqiang Yang	China University of Geosciences, Beijing
Zhiyuan Zhang (student)	Chinese Academy of Geological Sciences, China
Mingyu Zhang (student)	Chinese Academy of Geological Sciences, China
Richen Zhong	University of Sciences, Beijing, China
Limin Zhou	National Research Centre of Geoanalysis of CAGS, (Chinese Academy of Geological Sciences)
Tao Zhu	Xi'an Centre of Geological Survey, China



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TOP LEFT: Masters students Roseanna Dale, Daniel Foulds, Thomas Ralston and John Higgins outside a lava tube, Bethells Beach, New Zealand, during the 'Volcanology and Mineralisation in Volcanic Terrains' MEconGeol short course. Course leaders David Cooke and Rebecca Carey are standing in the tube itself. TOP RIGHT: Masters student Carlos Diaz (right) conducting fieldwork in the Cascabel porphyry Cu-Au district, Ecuador, in December 2018 with Leonardo Aguilar, a SolGold geologist who is also working on the Cascabel project. BOTTOM: Participants of the field trip for the International Conference on Metallogeny of the Middle Lower Yangtze Metallogenic Belt, China, reviewing the open pit geology at the Xinqiao Cu-Au-S deposit, Tongling district, China.

