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Cover photo: Mt Carlton cross-section, Fredrik Sahlström’s PhD thesis
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EGRU Facilities, Equipment and Analytical Capabilities
The first half of the year has been a busy time for EGRU, with its fair share of ups and downs. Like many in Townsville, a number of Geology staff and students were directly impacted by the flooding in February, with the recovery process still ongoing across the community. One good to come from this event, though, will be a better understanding of the hydrogeology of the Townsville region thanks to the PhD work of Caleb Puszkiewicz (See page 46 of this newsletter). A blow to the department in March was the resignation of Christa Placzek from her position of Senior Lecturer in Geochemistry. Christa has been a much-valued colleague in geology for the past 8 years and will be sorely missed by all of us, and we wish her all the best in her future career pursuits in the private sector.

On the good news front, the university has supported our push to replace not only the Geochemistry post, but also the Economic Geology position left vacant since Zhaoshan Chang departed JCU in early 2018. Both positions are permanent ongoing lectureships, and I’m pleased to report that a number of outstanding candidates have applied for both posts. We hope to have these two positions filled in the coming months, which will represent a significant leap in rebuilding capacity in JCU Geology and EGRU.

ERA (Excellence in Research Australia) ranking were also announced earlier in the year, with Geology and Geochemistry at JCU retaining scores of 5 and 4, respectively (out of a maximum of 5). These rankings are a performance measure of research publications, and are testament to the continued excellent research work coming not only from EGRU, but also across the range of geology and environmental geoscience disciplines at JCU.

While on the research front, we are excited to launch two new research initiatives this year: Firstly, a new collaboration with Dover Castle Metals Pty. Ltd to examine fascinating polymetallic (Sn, W, In, Ag, Pb, Zn, etc) mineralisation in and around the historic Dover Castle mine north of Herberton. This research project extends our recent focus on mineralisation in the Herberton region and ties in nicely with our upcoming Sn-W-critical metals conference in late June (more on this below). In June we will also begin a project to investigate the utility of Cu and Zn stable isotopes to fingerprint base metal mineralisation, with an initial focus on Mount Isa style Pb-Zn deposits. We are grateful to GSQ, Glencore-MIM and Anglo-American Exploration for their support for this project. Other new research projects include a new PhD project (Pieter Creus; see profile in this newsletter) to examine the structural geology of the Dugald River Deposit, and an ARC Discovery Project (with ANU) to investigate new methods for extracting REE from REE ore minerals.

We have passed the one-year milestones for our research projects focussed on the Mary Kathleen Domain, Mount Isa Inlier. These projects are sponsored by the Queensland Department of Natural Resources and Mines through the GSQ and include a detailed geological study of the Tick Hill gold mine, and studies of magma fertility and tectonic evolution on the Mary Kathleen Domain. Staff and students have presented results of these projects at a number of meetings across the state including the QEC Technical Forum in February in Brisbane, and the GSQ Technical Forums in Mount Isa (March) and Townsville (June).
We are continuing to build our links with China University of Geosciences, Wuhan, with another cohort of students signed up to attend our third-year mapping course in Mount Isa in July. We are hosting a number of PhD students and postdocs from Wuhan and Beijing as part of collaborative research efforts to understand various ore deposits across China. Details of these projects are also outlined in this newsletter. EGRU was also pleased to host a number of invited speakers in recent months, including the Haddon Forrester King Lecture by Prof. David Cooke (UTas) in November, a seminar on skarn mineralogy by Prof. Jade Star Lackey (Pomona College, California) in January, and Prof. Robert Linnen (Western University, Ontario) discussing Ta-Nb mineralisation in granites and pegmatites in April. We are also grateful to Noel White for providing an insightful talk on “Keeping Up or Getting Ahead? The Challenges and the Opportunities” at our EGRU annual meeting in December. In April, EGRU also jointly hosted (with the AIG and AusIMM) a special talk by Mark Berry on Geological Risk in Mining.

At the start of the year, the Department of Jobs and Small Business released a report on projections of employment growth by occupation, with geologists ranking twelfth best out of 474 professions. Jobs in geology are expected to grow by 21.6% over the next five years. With this in mind, the College of Science and Engineering has been actively marketing geology programs both regionally and internationally. Together with the university marketing team, Paul Dirks has been spreading the word about our degree programs across south-east and south Asia in coordinated marking trips in late 2018, and in April this year. These efforts are beginning to bear fruit with new student numbers in our undergraduate and Masters by coursework programs on the rise.

Our growing short-course/workshop offerings are seeing a healthy uptake from students and industry professionals alike. So far, for 2019, our courses have attracted 20 students and 76 industry participants, despite the partial washout of the core-logging workshop by the flooding events in February. We have an additional series of workshop modules coming up, focusing on Management in Mineral Exploration, as detailed in this issue on page 53.

Penultimately, to our Sn-W–Critical Metals and Associated Magmatic Systems conference, which will held in late June on the shores of Lake Tinaroo on the Atherton Tablelands. We have a very exciting line-up of local and international speakers covering broad aspects of ore geology, including the evolution and fertility of magmatic rocks, the chemistry and hydrothermal solubility of ore minerals, ore genesis processes, advanced exploration techniques, and case studies of ore deposits from across the globe. The oral program will be complemented by field trips to the Herberton region and Mt Carbine vein style W deposit, and so will showcase some of the fantastic geology of North Queensland. As a warm-up for the conference, check out the articles in this newsletter on critical metals in the Mount Carlton Mine by Fredrik Sahlström et al., and the article by John Nethery that reviews Permian mineralization events in the Chillagoe Region.

Also, a few days before the conference, we are hosting a workshop on Metal Isotopes in Mineral Exploration, which will be presented by Professor Ryan Mathur from Juniata College in Pennsylvania. This workshop is free for EGRU members.

Lastly, I would like to thank all of the EGRU membership for their ongoing support. Things are looking up for the rest of the year and thereafter, and we look forward to working with you in all things geology in the future.
Research Staff

Prof. Paul Dirks
Structural geology, geodynamics and the tectonic history of cratonic terrains and adjacent mobile belts, and associated mineralisation patterns.

Using petrology and geochemistry, including microanalysis of minerals for trace elements and isotopes, to understand the evolution of the Earth's crust and mantle, and the formation of metalliferous ore deposits.

A/Prof. Carl Spandler
Clastic sedimentology, sedimentary provenance, core logging, stratigraphy, U-Pb zircon geochronology, petroleum geology palaeontology, regional correlation.

A/Prof. Eric Roberts
Oceanography, geomorphology, sedimentology, geophysics, remote sensing and GIS

Dr James Daniell
Fluid-rock interaction processes in the lower crust and in hydrothermal mineralised systems, and thermodynamic modelling of carbon-oxygen-hydrogen systems.

Dr Jan Marten Huizenga
Structural geology and tectonics with a focus on field geology, structural controls on mineralised systems and the tectonic evolution of Proterozoic and Archean terranes.

Dr Ioan Sanislav
Economic geology, with a focus on tin and tungsten mineralisation, petrogenesis of granitic rocks, fertility of ore-related igneous rocks and genesis of “Critical Metal” ores.

Dr Yanbo Cheng
Vertebrate palaeontology; diversity, evolution and ecology of Mesozoic vertebrates.

Dr Espen Knutsen
Geochemistry and igneous petrology, supervision of geochemical/mineralogical processing laboratories and provision of specialised technical support for research projects.
Research Projects

NE Qld Magma Fertility: Cu-Au, Sn-W
NW Qld Magma Fertility
Rare Earths Project
Geita Gold Project
Adamantine Energy & Heritage Oil Project
Conglomerate Hosted Gold
Tick Hill Gold Deposit
Jurassic Arc? Reconstructing the Lost World of Eastern Australia
Porphyry Cu-Au Systems
Formation of Graphite Deposits in Sri Lanka
Identifying Hydrothermal Fluids in the Cloncurry District
Thermodynamic Modelling of Fluids in Hydrothermal Systems
The Role of Fluids in the Lower Crust
Seismic Stratigraphy and Petroleum Systems of the Mentelle Basin, Southwest WA
Establishing a Tectonic Framework for the Cretaceous Break-up of Eastern Gondwana
Stratigraphy and Sedimentary Basin Analysis of Qld's Jurassic to Cretaceous Basins
Jurassic-Cretaceous Tectonics, Paleogeography and Landscape Evolution, Central Africa
Dating hominin fossils in the East African Rift, Malawi
Seismic Stratigraphy of the Great Barrier Reef
Earthquake Hazard Mapping and Modelling to Support Qld Rail's Infrastructure
Structural Paragenesis of the Dugald River Zn-Pb-Ag Mine, Mount Isa Inlier
Groundwater – Ocean Interconnection
Sedimentary and Magmatic History of the Rukwa Rift Basin
Geochronology of Mineralisation Processes
Geology of the Tommy Creek Block, Mount Isa Inlier

Photos: L - Robbie Coleman, EGRU JCU; R - Hans Dirks, EGRU JCU
Mount Carlton High Sulphidation Epithermal Au-Ag-Cu Deposit

This issue of the EGRU newsletter features articles summarising EGRU research on the Mt Carlton high sulphidation epithermal Au-Ag-Cu deposit in northeastern Queensland, Australia. The research was carried out as part of Fredrik Sahlström’s PhD project, which was completed in 2018. The articles summarise three published papers resulting from this project. The research was funded by Evolution Mining and the Geological Survey of Queensland.

The Mount Carlton Deposit
Fredrik Sahlström, Paul Dirks, Zhaoshan Chang, Antonio Arribas, Isaac Corral, Matthew Obiri-Yeboah, and Chris Hall

1EGRU, JCU 2Department of Earth and Environmental Sciences, University of Michigan, USA. 3Evolution Mining, Mt. Carlton Operations

The following is a summary of research carried out as part of the first author’s PhD project. For the complete paper with details, data and a comprehensive discussion of results see: Sahlström, F, Dirks, P., Chang, Z., Arribas, A., Corral, I., Obiri-Yeboah, M., Hall., 2018. The Paleozoic Mount Carlton Deposit, Bowen Basin, Northeast Australia: Shallow High-Sulfidation Epithermal Au-Ag-Cu Mineralization Formed During Rifting. Economic Geology, v. 113, no. 8, pp. 1733–1767.

Introduction

High-sulphidation epithermal deposits are typically found in andesitic to dacitic volcanic arcs subjected to regional stress regimes ranging from mildly extensional to compressional (Sillitoe, 1993, 2010; Cooke and Simmons, 2000; Tosdal and Richards, 2001; Sillitoe and Hedenquist, 2003). These deposits are believed to form in magmatic-hydrothermal environments similar to those that occur beneath modern volcanic fumaroles and crater lakes (Hedenquist et al., 1993). They are mined predominantly for their Au content, while other metals (chiefly Ag and Cu) may be economically important in individual deposits (Arribas, 1995a; Singer, 1995).

Mineralisation in high-sulphidation deposits may occur in contact with, or only a few metres beneath, the paleosurface. But, more commonly, it is separated from the paleosurface by up to several hundred metres (Sillitoe, 2015). Mineralisation styles include hydrothermal breccias, veins, stockworks, and disseminations or replacements (Arribas, 1995a). High grade ore commonly occurs within cores of silicic alteration that locally exhibit a vuggy texture, and which typically are no more than a few tens of metres wide. These silicic cores have haloes of advanced argillic minerals that may have areal extents up to several square kilometres (Steven and Ratté, 1960; Stoffregen, 1987; Arribas, 1995a; Sillitoe, 1995).

High-sulphidation epithermal deposits typically have structurally controlled feeders, with the silicic-advanced argillic alteration possibly forming horizontal to subhorizontal lithocaps along specific horizons, such as unconformities and permeable rock layers (Arribas, 1995a; Sillitoe, 1999, 2010; Hedenquist et al., 2000; Chang et al., 2011).

These deposits and their associated lithocaps can be considered as the top parts of larger intrusion-driven hydrothermal mineralising systems, centred on porphyry intrusions that may be enriched in Cu, Au, and/or Mo (Arribas et al., 1995b; Hedenquist et al., 1998; Sillitoe, 2010; Chang et al., 2011).

In Queensland there is an abundance of mineral deposits related to Carboniferous and Permian magmatism that occurred inboard of an active continental margin (Henderson, 1980; Champion and Mackenzie, 1994; Blevin et al., 1996; Bain and Draper, 1997; Champion and Bultitude, 2013). Clusters of porphyry and epithermal Cu-Au deposits and prospects occur in the northern segment of the Bowen Basin in northeast Queensland (Fig. 1). Mineralisation in the northern Bowen Basin is mainly hosted in Early Permian volcanic rocks that were deposited within a back-arc rift environment (Donchak et al., 2013). The most significant, and the only deposit currently in production, is the Mt Carlton high-sulphidation deposit.
Mt Carlton was discovered in 2006 and the first concentrate was produced in 2013. The average Au grade at Mt Carlton (around 2.60 g/t – see footnote1), is comparable to medium-grade and unoxidised high-sulphidation deposits such as Lepanto, Rodalquilar, Chelopech, Chinkuashih, Pierina, and Pueblo Viejo.

Due to high erosion rates in most volcanic arcs, the preservation potential of high-sulphidation deposits in older terranes is generally poor (e.g., Kesler and Wilkinson, 2006). Mt. Carlton is, therefore, of particular interest as it is one of only few known economic, pre-Neogene, high-sulphidation deposits in the world. In this study, we document the geologic setting, hydrothermal alteration, mineralization, mineral chemistry, and 40Ar/39Ar geochronology of the Mt. Carlton deposit. This study contributes to the understanding of the characteristics, formation, preservation, and tectonic modification of shallow high-sulphidation deposits in extensional settings.

1 Editor’s Note: As of December 2018 the deposit had produced almost 0.5 million ounces of gold, and had resources (measured, indicated + inferred) of 10.02 million tonnes @ 2.60 g/t Au and 0.34% Cu, for over 800 koz of Au (Evolution Mining web site, 16/05/2019: Mt Carlton Fact Sheet & Mineral Resource and Reserve Statement – Dec 2018.)

Regional Geology

The Bowen Basin is a NNW-trending, elongate, and asymmetrical sedimentary basin covering an area of around 200,000 km2 in eastern Queensland. It formed as part of the New England Orogen during the Early Permian to Middle Triassic and is the northern part of a larger basin system that also includes the Gunnedah and Sydney basins in New South Wales (Donchak et al., 2013). The Bowen Basin shows evidence of a complex and polyphase tectonic evolution, divided into back-arc extension, thermal relaxation, and foreland basin stages. The Bowen Basin was initiated in the Early Permian by extension of the back-arc continental crust inland of the Connors arc, causing rifting (Esterle et al., 2002; Korsch et al., 2009). This produced a series of isolated NNW-trending graben and half-graben basins, which were infilled by volcanic and sedimentary rocks (Murray, 1990; Hutton et al., 1999; Esterle et al., 2002; Korsch et al., 2009). The Lizzie Creek Volcanic Group was deposited during this time and comprises calc-alkaline, andesitic to rhyolitic volcanic rocks, and minor terrestrial sediments, which host most of the mineralization in the northern Bowen Basin (Paine et al., 1974; I. Corral, unpub. data, 2018). The back-
arc rifting stage was followed by a period of thermal relaxation and subsidence in the Middle Permian, which led to flooding of the Bowen Basin and deposition of marine and coastal plain sedimentary units (Malone et al., 1969; Esterle et al., 2002; Allen and Fielding, 2007; Korsch and Totterdell, 2009). The thermal relaxation stage was abruptly terminated in the Late Permian, due to the onset of the ~265 to 235 Ma Hunter-Bowen Orogeny (Donchak et al., 2013). This led to foreland loading, tectonic inversion, and development of a foreland basin. Terrestrial sediments deposited in the foreland basin make up the bulk of the Bowen Basin infill, and they contain several economically important coal deposits (Fielding et al., 1990; Fergusson, 1991; Holcombe et al., 1997; Esterle et al., 2002).

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 8: Flow-banded rhyolite (~200 m)</td>
<td>- Feldspar phric rhyolite with well-developed flow-banding</td>
</tr>
<tr>
<td>Unit 7: Volcano-sedimentary rocks (~150 m)</td>
<td>- Andesite-dacite volcaniclastic breccia</td>
</tr>
<tr>
<td></td>
<td>- Well to moderately sorted, subrounded fluvial conglomerate</td>
</tr>
<tr>
<td></td>
<td>- Water-laid graded sandstone-siltstone beds</td>
</tr>
<tr>
<td></td>
<td>- Coal-bearing laminated mudstone with dacite tuff interbeds</td>
</tr>
<tr>
<td></td>
<td>- Andesite-dacite porphyritic lava</td>
</tr>
<tr>
<td>Unit 6: Fragmental andesite (~50 m)</td>
<td>- Fragmental andesite containing rounded boulders</td>
</tr>
<tr>
<td>Unit 5: Volcaniclastic dacite (~150 m)</td>
<td>5A. Massive dacite with fragments and boulders of dacitic and andesitic material in a coarse quartz-feldspar phric groundmass</td>
</tr>
<tr>
<td></td>
<td>5B. Polymict subrounded volcanic conglomerate (A39 only)</td>
</tr>
<tr>
<td></td>
<td>5A. Polymict dacite ignimbrite with sandy groundmass (A39 only)</td>
</tr>
<tr>
<td>Unit 4: (Rhyo)dacite tuffs and sediments (~100 m)</td>
<td>4B. Massively bedded dacite tuffs (V2 only)</td>
</tr>
<tr>
<td></td>
<td>4A. Well-bedded fragmental rhyodacite lapilli tuffs with interbedded carbonaceous lacustrine sediments</td>
</tr>
<tr>
<td>Unit 3: Rhyodacite porphyry (~200 m)</td>
<td>- Massive quartz-feldspar phric rhyodacite</td>
</tr>
<tr>
<td></td>
<td>- Flow-banded quartz-feldspar phric rhyodacite</td>
</tr>
<tr>
<td></td>
<td>- Monomict autolithic quartz-feldspar phric rhyodacite breccia</td>
</tr>
<tr>
<td>Unit 2: Andesite porphyry (~300 m)</td>
<td>- Fine-grained feldspar-pyroxene + hornblende phric andesite</td>
</tr>
<tr>
<td></td>
<td>- Monomict autolithic andesite breccia</td>
</tr>
<tr>
<td>Unit 1: Granite basement (unknown thickness)</td>
<td>- Fine- to medium-grained equigranular monzogranite</td>
</tr>
</tbody>
</table>

Figure 2. Stratigraphic column for the area near the Mt Carlton mine.
Geology of the Mt. Carlton Deposit

Stratigraphy
The stratigraphy in the area of the Mt Carlton mine is illustrated in Figure 2. The basement unit (unit 1) is a fine- to medium-grained monzogranite belonging to the Permo-Carboniferous Urannah batholith. This basement unit is overlain by a volcanosedimentary sequence belonging to the Permian Lizzie Creek Volcanic Group. Near the Mt. Carlton mine, the basal unit of the Lizzie Creek sequence is a ~300-m thick andesite unit (unit 2); this is overlain by up to 200 m of massive and locally flow banded quartz-feldspar phryic rhyodacite (Fig. 3A), and minor monomict autobreccia quartz-feldspar phryic rhyodacite breccia, referred to as unit 3. Unit 3 is affected by silicic and quartz-alunite alteration and hosts mineralisation in the Mt Carlton V2 pit.

The altered and mineralised breccia of unit 3 is overlain by an up to 100-m-thick unit of dacitic to rhyodacitic tuffs and sediments (unit 4). Unit 4 has been subdivided into a lower unit (unit 4A) and an upper unit (unit 4B). Unit 4A comprises well-bedded, fragmental rhyodacite lapilli tuffs with interbedded carbonaceous lacustrine sediments, locally containing fossilised wood (Fig. 3B). This unit occurs in both the V2 and A39 pits and hosts mineralisation in the A39 pit. Unit 4B overlies unit 4A in the V2 pit and comprises massively bedded dacitic tuffs.

Overlying unit 4 is a unit, up to 150 m thick, that contains dacitic and andesitic volcaniclastic rocks (unit 5). These rocks show variable facies throughout the two pits (V2 and A39) and include dacitic ignimbrite (unit 5A), coarse volcanic conglomerate (unit 5B), and fragmental dacite breccia (unit 5C).

Unit 6, which conformably overlies unit 5 in the area near the open pits, is an up to 50-m-thick unit of fragmental andesite that locally contains rounded boulders (Fig. 4).

Unit 7 is an up to 150-m-thick sequence of volcanosedimentary rocks that overlies unit 6 (Fig. 4) comprising andesitic to dacitic volcaniclastic breccias and volcanic sediments. Porphyritic andesitic to dacitic lavas occur locally within unit 7 and occur in the northwest wall of the A39 pit (Figs. 4, 5, 7).

The youngest stratigraphic unit in the Mt. Carlton area, unit 8, comprises flow-banded rhyolites that conformably overlie units 1 to 7 throughout the district (Coughlin, 1995). Unit 8 is exposed as a semi-horizontal sheet along the hilltops to the south of the open pits.

In the north wall of the V2 pit, unit 3 is crosscut by a younger dacitic to rhyodacitic volcanic vent (~25 m wide). This unit, here called unit 9, exhibits at least two distinct vent facies, including porphyritic, rhyodacitic lava with well developed columnar jointing in the centre and weakly layered, boulder-rich, tuffaceous, dacitic rocks along the margins.

Deformation Sequence
A deformation sequence for the Mt. Carlton deposit was established by structural mapping of the open pits and regional outcrops, coupled with analysis of drill core structural data. The Mt. Carlton deposit has undergone seven stages of extensional deformation and dike emplacement (herein called D1–D7); no evidence for compressional deformation has been observed. The spatial distribution of stratigraphic units, hydrothermal alteration, and mineralisation at Mt. Carlton is intimately linked to this deformation sequence, which can be summarised as follows:
D₁  Rifting and associated high angle normal faulting in response to both E-W and N-S extension. D₁ rifting was initiated during the deposition of unit 2, was most intense during the deposition of units 3 and 4, and was waning during the deposition of the younger stratigraphic units (units 5–8). D₁ normal faults exposed in the pits facilitated displacements on the order of tens of metres and include synsedimentary growth faults that were active during the deposition of volcanic sediments in localized half-graben and graben basins. Locally, the half-grabens are infilled with Lizzie Creek volcanic rocks and are bounded by D₁ faults that also host mineralization. Hydrothermal enargite, pyrite, and dickite that grew along such faults define mineral lineations that record a normal component of shear. Hydrothermal alteration and epithermal mineralisation, thus, occurred partly contemporaneously with rifting and deposition of volcanic sediments during the earlier stages of D₁, with rifting and sedimentation outlasting mineralisation.

D₂  Continued E-W extension, with development of 1- to 5-m-wide, low-angle (and locally layer-parallel) fault zones and associated, high-angle antithetic normal faults (Fig. 4). Within the pit area, the D₂ low-angle faults accommodated a top-to-the-east displacement along a broadly E-W axis, and they have truncated the stratigraphy, the hydrothermal alteration halo, and the ore zones (Figs. 5, 6F, 7). Major through-going D₂ structures, with potential displacements of hundreds of metres, appear to be restricted to the younger stratigraphic units (i.e., unit 6 and above) that blanket the regional horst-and-graben topography created during D₁.

The volcanic vent, unit 9, crosscuts D₂ faults in the V2 pit.

D₃  High-angle normal faulting in response to N-S extension, with partial reactivation of D₁ and D₂ faults. Based on the regional distribution of lithological units in the area (with basement granite to the north and a progressively thicker volcanosedimentary pile to the south), the overall sense of movement related to D₃ faults around the V2 and A39 pits was probably south-down, resulting in a shallow, southerly tilt of the layering.

D₄  Block rotation of kilometre scale lithological domains across steep, NNW-trending normal faults and ENE-trending cross faults. A NNW-trending D₄ normal fault cuts across the entire stratigraphic pile and passes between the V2 and A39 pits. This has caused segmentation of the stratigraphy and the ore zones within the Mt. Carlton deposit, as well as a reorientation of primary layering and mineralization. Bedding planes in the northeast fault block, which includes the V2 pit, have remained near horizontal after the D₄ event. In contrast, bedding planes in the southwest fault block, which includes the A39 pit, have been rotated in a west-southwest direction by ~32°.

D₅  Emplacement of basaltic dikes along high-angle D₁, D₃, and D₄ faults and, to a lesser degree, along low-angle D₂ faults.

D₆  Strike-slip faulting along the margins of D₅ dikes. The movement was dominantly dextral, but
sinistral movement has also been observed, indicating a long and multi-staged history of unknown age. The amount of displacement in the pit area during D₆ events was minor (less than 20 m).

D₇ Emplacement of WNW trending basaltic dikes.

Alteration

The alteration at Mt. Carlton was studied by drill core logging, open-pit mapping, transmitted polarised light microscopy, short-wave infrared (SWIR) spectroscopy, and powder X-ray diffraction (XRD).

Silicic alteration zone

Silicic alteration occurs as multiple cores (~10–100 m wide) that formed in and around D₁ high-angle structures in units 3 and 4A (Fig. 8). The silicic alteration zones are characterized by almost complete replacement of the original rock by microcrystalline quartz, with almost total destruction of the primary textures. The texture is predominantly massive, with local vuggy and breccia textures (Fig 5A). The silicic alteration zones contain small amounts of alunite, pyrite, dickite, kaolinite, aluminum-phosphate-sulfate (APS) minerals, and pyrophyllite (Fig. 6).

Quartz-alunite alteration zone

A zone of quartz-alunite alteration defines a ~100 to 300m wide envelope to the silicic alteration zones in units 3 and 4A, with a gradational transition between the two zones (Fig. 8). Quartz-alunite alteration is not as pervasive as the silicic alteration and primary rock textures are generally preserved. It consists of a groundmass of microcrystalline quartz with disseminated alunite and local pyrite, dickite, and kaolinite and, more rarely, barite and rutile (Figs. 5C, 6).

Quartz-dickite-kaolinite alteration zone

A zone of quartz-dickite-kaolinite alteration forms a laterally extensive (>1-km-wide) halo to the silicic and quartz-alunite alteration zones in units 3 and 4A (Fig. 8). Primary volcanic and sedimentary textures are typically preserved.

Illite-montmorillonite alteration zone

The zoned alteration halo developed in unit 3 and unit 4A (silicic → quartz-alunite → quartz-dickite-kaolinite) shows sharp transitions with respect to mineralogy across sheared (D₂) contacts to the units overlying and underlying it, which include units 2, 5, and 6 and parts of unit 4 (Fig. 8). Illite-montmorillonite alteration, with local red hematite dusting, is pervasive in rocks above and below the fault-bounded ore zones (Fig. 5E). These peripheral rocks are very friable and poorly preserved, due to the swelling properties of the clay minerals.

Chlorite-illite alteration zone

The illite-montmorillonite alteration zone transitions downwards to a chlorite-illite alteration zone. This transition is sharp and is again controlled by a D₂ fault along the contact between unit 2 and the granite basement. Chlorite-illite alteration occurs as green veinlets that crosscut the primary granitic texture (Fig. 5F). Chlorite and illite have also replaced preexisting feldspar, hornblende, and biotite crystals.

Timing of the alteration assemblages

The zoned alteration halo present within unit 3 and unit 4A (silicic → quartz-alunite → quartz-dickite-kaolinite) is interpreted to be directly linked to the mineralising hydrothermal event at Mt. Carlton, based on its close spatial relationship with mineralisation, and also based on comparisons to other high sulphidation deposits (e.g., Steven and Ratté, 1960; Stoffregen, 1987; Arribas, 1995a; Hedenquist et al., 2000). In contrast, the illite-montmorillonite alteration is partly developed in units that were deposited after mineralisation (Fig. 8) and shows no obvious zonation. Therefore, we interpret this alteration assemblage to have developed regionally during D₂ deformation. Chlorite-illite alteration of the granite basement was most likely related to the mineralising hydrothermal event. This is based on the presence of chlorite-illite altered granite clasts in conglomerates within unit 7, which predates D₂ deformation.

The presence of pyrite together with kaolinite in unit 9 implies a hypogene origin for kaolinite alteration. Because unit 9 crosscuts both the primary hydrothermal alteration halo and D₂ faults in unit 3, a later hydrothermal alteration event (likely occurring concomitantly with the emplacement of the volcanic vent itself) is inferred to have overprinted the earlier alteration halo in unit 3. This late-stage alteration appears to be confined to within and proximal to unit 9

Mineralisation

The ore geometry, metal zonation, and mineral paragenesis at Mt. Carlton was studied by open-pit mapping, drill core logging, modelling of drill core assay data using Leapfrog, whole-rock geochemical analyses, reflected polarized light microscopy, and reconnaissance scanning electron microscopy with an energy dispersive scanning system (SEM-EDS).

Ore geometry and metal zonation

On a local scale (1–10 m), proximal Au-Cu mineralisation in the V2 pit occurs in moderately to steeply (~60°–90°) dipping D₁ fracture networks within the rhyodacite porphyry (unit 3). The mineralised fractures have a predominantly NE to NNE trend,
Figure 5. Photographs of selected hydrothermal alteration assemblages at Mt. Carlton. (A) Silicic alteration with a vuggy texture, reflecting the leaching effects of highly acidic fluids. The vugs are partly infilled with dickite, kaolinite, and pyrophyllite. (B) Banded alunite vein developed within a silicic alteration zone. After deposition of alunite, the vein was reopened to form two stage 2A enargite veins. The composite vein was then overprinted by stage 3 dickite. (C) Quartz-alunite-pyrite alteration developed in a quartz-feldspar phric ryodacite (unit 3). Alunite has mainly replaced preexisting feldspar crystals, while the pyrite occurs as disseminations. (D) Quartz-dickite-kaolinite alteration developed in a quartz-feldspar phric ryodacite (unit 3). The clay minerals have replaced preexisting feldspars. (E) Illite-montmorillonite alteration developed in a volcaniclastic dacite (unit 4B). (F) Veinlets of chlorite and illite crosscutting the granite basement rocks (unit 1). Mineral abbreviations (Kretz, 1983): Alu = alunite, Chl = chlorite, Dck = dickite, Eng = enargite, Ill = illite, Kln = kaolinite, Mnt = Montmorillonite, Prl = pyrophyllite, Py = pyrite, Qtz = quartz.
The phases highlighted in green are minerals investigated in the critical element study that has been summarised for the following article.

with NW- to E-trending fractures being secondary. Hydrothermal breccias infilled with ore minerals are locally developed along intersection lines between mineralised fractures.

At a scale of hundreds of meters, three distinct ore zones can be identified in the V2 pit (the Western, Eastern, and Link ore zones). These ore zones line up in an en echelon fashion along a broadly E trending corridor, and all have grade envelopes that trend SW. The Eastern and Link ore zones terminate in the V2 pit, while the Western ore zone extends to the SW and can be traced into the A39 pit across a D4 fault. Along strike of the ∼600 m of known mineralisation, the Western ore zone shows a distinct metal zonation, from proximal to distal, of Au-Cu → Cu-Zn-Pb-Ag → Ag-Pb-(Cu) → Ag (Figs. 7, 8). Distal Ag mineralisation is concentrated in the A39 pit, where it occurs in the volcanolacustrine sediments (unit 4A) that overlie the rhyodacite porphyry. Pit mapping, in combination with the analysis of structural and stratigraphic data in drill core, reveal that mineralisation in A39 occurs in a stratabound position oriented parallel to primary sedimentary layering. Furthermore, mineralisation in A39 is distributed parallel to the lineation defined by the intersection between the sedimentary bedding planes in unit 4A and the mineralised feeder structures.
in the underlying unit 3.

The high-grade ore and associated hydrothermal alteration halo within the Western ore zone has been dismembered by an NNW-trending D₄ normal fault that is positioned between the two open pits. Due to the rotation of the southwest fault block that contains A39, the originally subhorizontal Ag ore in A39 now plunges to the SW (Fig. 7). The feeder system in V2 occurs essentially in its original, steep orientation, since the rotation of the northeast fault block was negligible.

**Paragenetic sequence**

The zoned hydrothermal alteration assemblages in units 3 and 4A (stage 1; Fig. 6) are crosscut by three stages of epithermal mineralisation (stages 2A-C). The ores were, in turn, overprinted by a late stage of dickite and pyrite void fill (stage 3). Following D₂ deformation and associated alteration (stage 4), a final stage of supergene oxidation (stage 5) locally overprinted the mineralised rocks. Because the paragenetic sequence is identical in V2 and A39, we infer that the now segmented Western ore zone originally formed as a single hydrothermal system. Both stage 2A and stage 2B mineralisation contain high-grade Au (locally >600 ppm) and Ag, as well as variable amounts of base metals (e.g., Cu, Zn, and Pb) and rare metals (e.g., Ge, Ga, In, Te, Se, Sn). The deposit-scale metal zonation shown in Figure 7 is caused in part by the temporal zonation of metals through stages 2A to C (Fig. 6), and in part by the spatial zonation of metals within each individual stage.

**Stage 2A: Cu-Au-Ag mineralisation**

Stage 2A was the initial and most voluminous mineralisation event at Mt. Carlton and developed in all three ore zones. It produced a high-sulphidation-state ore mineral assemblage dominated by massive enargite, and mineralisation was associated with silicic alteration of the wall rocks (Fig. 6). The first minerals to crystallise in the stage 2A assemblage were tetrahedrite-group minerals. The tetrahedrite-group minerals and silver minerals were, in turn, overprinted by the main enargite assemblage, which includes pyrite and luzonite and, to a lesser degree, electrum, sphalerite, galena, chalcopyrite, bornite, and argyrodite (Ag₈GeS₆; Fig. 6). Barite is a common gangue mineral in the stage 2A assemblage, and it is predominantly concentrated in the distal parts of the deposit (A39 pit). This is similar to barite documented at the Lepanto high-sulphidation deposit (Mankayan, Philippines; Gonzalez, 1959).
Stage 2B: Zn-Pb-Au-Ag mineralisation
Stage 2B ore mainly occurs in veins that cut across stage 2A mineralisation, predominantly within the Western ore zone. The textures of stage 2B veins range from massive to colloform, and the mineral assemblages are dominated by Fe-poor sphalerite. Subordinate minerals include galena and pyrite and, to a lesser degree, electrum, tetrahedrite-group minerals, chalcopyrite, bornite, an uncharacterised Zn-In mineral (ideally CuZn\textsubscript{0.9}[In,Ga]S\textsubscript{4}; Sahlström et al., 2017b), and barite (Fig. 6).

Stage 2C: Cu-Au-Ag mineralisation
Stage 2C was a minor event that overprinted stage 2B mineralisation. Evidence for it has only been observed at a microscopic scale within the Western ore zone. The mineral assemblage is dominated by massive tennantite.

Stage 3: Hydrothermal void fill
A late stage of dickite and pyrite is widely distributed at Mt. Carlton and has been observed within all three ore zones. The dickite and pyrite generally occur as massive veins or as void fill that overprinted stage 2A, 2B, and 2C mineralisation (Fig. 6).

Stage 5: Supergene oxidation
Minor supergene oxidation affected the upper ~50 m of the present-day deposit, with an irregular distribution. Secondary covellite, chalcocite, and malachite are locally developed on Cu-bearing minerals such as enargite, luzonite, and bornite, particularly along fractures in the minerals. Supergene oxidation is limited at Mt. Carlton (~1–5 % of total ore), and the vast majority of the metals are hosted in primary and refractory ores.

Sedimentary ore textures
The structurally controlled veins and hydrothermal breccias that host proximal Au-Cu mineralisation in the V2 pit are texturally distinct from the distal, stratabound Ag mineralisation that occurs in the A39 pit and in
Mount Carlton Deposit cont’d

the southwest corner of the V2 pit. A selection of ore textures from A39 are shown in Figure 9. In Figure 9A, a D1-related fracture that first developed within a silicic altered rhyodacite tuff (unit 4A) has been infilled with hydrothermal sediments made up of finely laminated quartz. Fine particles of pyrite occur within the siliceous sediments, which are interlayered with massive layers of stage 3 dickite and pyrite. Soft-sediment deformation textures were produced as breccia fragments of the wall rock dropped into the open fracture zone as it was being infilled.

Figure 9B shows a similar fracture within unit 4A that has been infilled with a complex sequence of detrital sediments. The sediments preserve graded bedding and comprise beds of finely laminated siltstone, as well as coarser sandstone beds that are made up of igneous quartz crystals, rhyodacite fragments, and pyrite. Several steep, synsedimentary normal faults can be observed within the laminated siltstone in the lower part of the fracture opening. Soft-sediment deformation textures were produced by coarse fragments of the rhyodacite wall rock that dropped into the open fracture during infill. The sedimentary sequence was at one point infiltrated by a hydrothermal fluid, and the paleofluid channel can be seen cutting across the laminated sediments in the lower part of the fracture cavity. The

Figure 9. Photographs of sedimentary ore textures from the A39 pit at Mt Carlton. (A) A fracture cavity developed within a silicic altered rhyodacite tuff (unit 4A) has been infilled with hydrothermal sediments made up of finely laminated quartz, which occur interlayered with massive Stage 3 dickite and pyrite. Note the soft-sediment deformation textures caused by wall rock clasts that dropped into the sediments as the open fracture was being infilled. (B) Detrital sediments infilling a fracture within Unit 4A. The sediments show a graded bedding, and comprise finely laminated siltstone beds and pyrite-rich sandstone beds. Syn-sedimentary normal faults and soft-sediment deformation textures are visible within the laminated siltstone in the lower part of the fracture cavity. A hydrothermal fluid has infiltrated and disturbed the sediments (indicated in stippled lines). Note the quartz and pyrite crystals that have dropped down through the fluid channel and accumulated at the bottom of the open fracture. Younger sediments deposited within the fracture have progressively draped the topography that was produced by the fluid. (C) Disseminated Stage 2A enargite mineralization infilling a fracture cavity has been covered by and remobilized into siliceous sediments, prior to being crosscut by Stage 3 dickite pyrite veinlets. (D) Spherules made up of concentric rings of fibrous and radial Stage 3 pyrite and dickite, which occur as discrete layers within a volcano-lacustrine sediment (Unit 4A). Mineral abbreviations (Kretz, 1983): Dck – dickite; Eng – enargite; Py – pyrite.
hydrothermal fluid migrated vertically through the sediments, likely within one of the steep normal faults, and then dispersed laterally when it intersected a thick layer of sandstone. The fluid disturbed this sandstone layer as well as the overlying siltstone beds, which created a distinct topography within the fracture. Some quartz and pyrite crystals in the sandstone layer can be seen to have dropped down through the fluid channel and accumulated at the base of the open fracture. Subsequently, younger beds of siltstone and sandstone progressively draped the topography that was created by the hydrothermal fluid, as the open cavity along the fracture was infilled with sediment.

The fracture shown in Figure 9C contains three distinct sedimentary domains. The basal infill within the fracture is predominantly made up of stage 2A enargite mineralisation, along with minor amounts of quartz. The enargite-rich layer is overlain by light-coloured siliceous sediments, which exhibit intricate cross-laminations. Soft-sediment deformation textures are visible along the contact between the two layers. The laminated siliceous sediments, in turn, overlap by darker coloured quartz sediments that lack laminations. Clasts of enargite ore have been remobilised into these sediments, and the entire sedimentary sequence was subsequently crosscut and brecciated by younger veinlets of stage 3 dickite and pyrite.

Figure 9D shows coarse-grained spherules, made up of concentric rings of fibrous and radial stage 3 pyrite and dickite, which form layers within a volcanolacustrine sediment (unit 4A). Equivalent but finer-grained pyrite-dickite spherules have been observed occurring as infill within restricted open spaces in fractures.

Overall, the four examples shown in Figure 9 highlight how metal deposition in A39 occurred partly contemporaneously with sedimentation and deformation. The significance of these sedimentary textures with respect to the potential of the hydrothermal system to reach the paleosurface at the time of mineralisation is discussed below.

**Alunite & Aluminium-Phosphate-Sulphate (APS) Minerals**

Disseminated alunite at Mt. Carlton occurs as platy euhedral crystals up to ~300 μm long, typically in aggregates. Some alunite grains from V2 contain cores of APS minerals, which was not observed in alunite grains from A39. The vein alunite shows a distinct saw-tooth compositional banding parallel to the vein orientation in BSE images, mainly due to variations in Na and K content.

Analyses of both disseminated and vein alunite gave compositions within the alunite-natroalunite solid solution (trigonal KAl₃[SO₄]₂[OH]₆ - NaAl₃[SO₄]₂[OH]₆, and they are low in Ca (Ca/[K + Na + Ca] < 0.1). Many analyses are dominated by K, with only a minority of the analyses plotting in the natroalunite field.

Since WDS analysis of alunite-group minerals requires a large beam size (e.g., 15 μm; Deyell et al., 2005b), we were not able to analyze APS minerals directly, and the analytical data indicate a trend from alunite/natroalunite toward compositions within the woodhouseite-svanbergite solid solution (trigonal CaAl₃[SO₄][PO₄][OH]₆ - SrAl₃[SO₄][PO₄][OH]₆), with woodhouseite dominating over svanbergite.

**Discussion**

**Deposit classification**

The alteration mineralogy (e.g., alunite, dickite, kaolinite, pyrophyllite, APS minerals) as well as the alteration zonation (silicic core → quartz-alunite → quartz-dickite-kaolinite) at Mt. Carlton are consistent with highly acidic hydrothermal fluids leaching the volcanic host rocks, with decreasing intensity away from the fluid conduits. These features are characteristic of high-sulphidation deposits worldwide (e.g., Steven and Ratté, 1960; Stoffregen, 1987; Arribas, 1995a). The high sulphidation-state ore mineral assemblage dominated by enargite further supports the interpretation that Mt. Carlton is a high-sulphidation epithermal deposit (e.g., Hedenquist, 1987; Sillitoe, 1993; Hedenquist and Lowenstern, 1994; Arribas, 1995a; Einaudi et al., 2003). This identification has implications for exploration in the district, as Mt. Carlton is likely to have formed as part of a larger magmatic-hydrothermal mineralising system, centred on an underlying porphyry intrusion that could be mineralised with Cu, Au, and/or Mo (Arribas et al., 1995b; Hedenquist et al., 1998; Sillitoe, 2010; Chang et al., 2011).

**Age of the Mt. Carlton deposit**

The U-Pb zircon ages of the volcanic rocks that host mineralization (unit 3, 281 ± 4 to 277 ± 3 Ma; I. Corral, unpub. data, 2018) and of those that crosscut mineralization (unit 9; 266 ± 3 Ma; I. Corral, unpub. data, 2018) provide upper and lower constraints on the age of the Mt. Carlton deposit. Alunite formed during hydrothermal alteration at Mt. Carlton was dated using ⁴⁰Ar/³⁹Ar geochronology, and the age range from five out of the six dated alunite separates (284 ± 7 to 277 ± 7 Ma) overlaps within error with the U-Pb zircon age of unit 3. These results suggest that hydrothermal alteration and epithermal mineralization at Mt. Carlton occurred shortly (no more than 7 m.y.) after the formation of the volcanic host rocks. This is a common feature in
many documented high sulphidation deposits (Arribas, 1995a) and confirms the geologic observations that link the formation of the Mt. Carlton deposit to the Early Permian back-arc rifting stage in the Bowen Basin. The youngest outlier alunite age at ~265 Ma overlaps within error with the U-Pb zircon age of unit 9, and these two dated samples were collected close to each other (<100 m apart). This may suggest that the emplacement of unit 9 represented a later heating event that formed or reset alunite locally, possibly along veinlets that are not visible in the strongly altered rocks (e.g., Arribas et al., 2011).

Origin of alunite and implications for exploration
For exploration purposes, it is important to determine the origin of advanced argillic alteration in epithermal deposits, as the spatial relationship between precious and base metal mineralisation and advanced argillic assemblages varies with the origin of the alteration (Sillitoe, 1993; Hedenquist et al., 2000). As the key mineral for understanding the origin of advanced argillic alteration, a distinction should be made between alunite formed from hypogene vapoours and from vapour condensates (magmatic-steam alunite and magmatic hydrothermal alunite, respectively), and alunite formed from near-surface geothermal and secondary oxidation processes (steam-heated alunite and supergene alunite, respectively; Rye et al., 1992).

The disseminated alunite at Mt Carlton exhibits coarse grain size, platy crystal habit, local Na enrichment, and inner cores of APS minerals, which point toward a magmatic-hydrothermal origin (Stoffregen and Alpers, 1987; Rye et al., 1992; Aoki et al., 1993; Arribas et al., 1995a; Itaya et al., 1996; Deyell et al., 2005a, b; Rye, 2005). Alunite of steam-heated and supergene origins, in contrast, tends to occur as porcellaneous masses of fine-grained rhombohedral (pseudocubic) crystals that lack enrichment in Na (Stoffregen and Alpers, 1987; Sahlström et al., 2016). The mostly K dominated compositions of Mt. Carlton alunite, therefore, could indicate relatively low formation temperatures, implying that the Mt. Carlton lithocap formed distal to the causative intrusion. The spatial zonation in the Na content of alunite at Mt. Carlton suggests that the formation temperatures were higher in the V2 pit compared to the A39 pit.

Interpreted environment of mineralisation
The sedimentary ore textures observed in the A39 pit at Mt. Carlton (Fig. 9) are similar to those described from other high-sulphidation deposits, including Rodalquilar, Spain (Arribas et al., 1995a), Akaia, Japan (Arribas, 1995b), Martabe, Indonesia (Sutopo, 2013), Golden Wonder mine, Colorado (Kalliokoski and Rehn, 1987), Los Porfirios, Chile (A. Arribas, unpub. data, 2005), and Mulatos, Mexico (J. Hedenquist, pers. commun., 2017). At the Rodalquilar deposit, acidic hydrothermal fluids have dissolved the volcanic host rocks along steeply dipping fractures, which produced isolated cavities at depth (Arribas et al., 1995a). Such dissolution cavities, which locally can be more than 1 m wide, have subsequently been infilled with subhorizontally layered sediments made up of chalcedony, quartz, and Au-rich sulphides. The siliceous sediments at Rodalquilar locally exhibit intricate cross-laminations and slumping textures, and they are commonly thicker on the bottom than on the sides of the cavities, due to gravitational infilling (Arribas et al., 1995a). These morphological features suggest that the sediments were precipitated from a hydrothermal fluid as amorphous silica, which are inferred to have interacted with the volcanic host rocks to produce the laterally extensive alteration halo surrounding the Mt. Carlton deposit (e.g., Rye et al., 1992; Rye, 2005; Hedenquist and Taran, 2013). Pulses of rapidly ascending magmatic steam from the degassing magma sporadically punctuated the deposit, producing veins of magmatic-steam alunite (e.g., Rye et al., 1992; Rye, 2005). At Mt. Carlton, magmatic-steam alunite is largely confined to the high-grade D₉ feeder structures. Magmatic steam alunite has only been documented in a limited number of high-sulphidation deposits globally (Rye, 2005). However, when present, this alteration feature could be a good exploration indicator for close proximity to the paleolfuid conduits and potential epithermal mineralisation.

The Na content in magmatic-hydrothermal alunite may locally be dependent on variability in the Na content of the host rocks that are being altered (Deyell and Dipple, 2005). However, in most cases where the host rocks are compositionally similar, an increasing Na content in alunite can be linked to higher temperatures of deposition (Stoffregen and Cygan, 1990; Deyell and Dipple, 2005; Chang et al., 2011). The mostly K dominated compositions of Mt. Carlton alunite, therefore, could indicate relatively low formation temperatures, implying that the Mt. Carlton lithocap formed distal to the causative intrusion. The spatial zonation in the Na content of alunite at Mt. Carlton suggests that the formation temperatures were higher in the V2 pit compared to the A39 pit.
later recrystallized to chaledony and quartz (Fournier, 1985; Arribas et al., 1995a). Furthermore, a basal layer of igneous quartz phenocrysts was observed in some of the larger cavities. Such quartz layers were interpreted to have formed after the complete dissolution of all rock components except quartz, which accumulated at the bottom of the cavity (Arribas et al., 1995a). At the Los Porfiros deposit, dissolution cavities are partially infilled with sedimentary layers of quartz intercalated with barite, and silica speleothems (flowstones) were deposited locally along the cavity walls (A. Arribas, unpub. data, 2005). Sedimentary infill in similar cavities at the Akaïwa deposit comprises laminated quartz as well as discrete layers of barite and other hydrothermal minerals (e.g., alunite, kaolinite, dickite, and sulphides; Arribas, 1995b). These cavities were interpreted as pipes that composed the roots of overlying crater lakes (Arribas, 1995b).

At Mt. Carlton, mineralised sediments occur as infill within open spaces such as cavities along fractures (Fig. 9A-C), but they have also been observed in the volcanolacustrine sequence (unit 4A; Fig. 9D) extending at the scale of the A39 pit. The finely laminated siliceous sediments observed at Mt. Carlton (Fig. 9A, C) are similar to the chemical sediments that accumulate in acidic lacustrine environments, such as crater lakes (Sillitoe, 2015). The spherulitic pyrite at Mt. Carlton (Fig. 9D) bears a strong resemblance to that documented in ore deposits forming in and around hydrothermal vents (e.g., Larher et al., 1981; Tufar, 1991; Vearncombe et al., 1995; Scotney et al., 2005; Xu and Scott, 2005; Badrzadeh et al., 2011). In the seafloor environment, spherulitic pyrite is believed to form by rapid crystallisation with undercooling, as hot metalliferous vent fluids discharge into cold ambient seawater (Xu and Scott, 2005). The synsedimentary normal faults and breccia-related soft-sediment deformation textures observed within some infilled fracture cavities at Mt. Carlton (Fig. 9A, B) indicate that sedimentation took place during active rifting. Furthermore, the detrital nature of sediments, the graded bedding, and the draping over pre-existing topography observed within some fracture fills (Fig. 9B) are inconsistent with sediments having been deposited into isolated cavities at depth (e.g., Rodalquilar; Arribas et al., 1995a). We infer that fractures such as the one shown in Figure 9B must have been open to the paleosurface, which would have allowed detrital sediments to slump into the fractures and deposit from suspension.

Based on the rift-related tectonostratigraphic setting identified at Mt. Carlton, combined with the ore textures observed, the environment of mineralisation is interpreted to have included structurally controlled feeder zones of veins and hydrothermal breccias that developed within the deeper rhyodacite porphyry (represented by rocks of the V2 pit). The feeder zones focused ore fluids into an overlying volcanolacustrine sedimentary sequence, which most likely was deposited in lakes developed within localized rift basins (represented by rocks of the A39 pit). In this interpretation, the fluids locally breached the paleosurface and discharged into the lakes at the same time as the volcanolacustrine sediments were deposited, producing the observed stratabound mineralisation, laminated siliceous sediments, spherulitic pyrite, and associated synsedimentary ore textures. Sediments were sporadically slumped into the fractures that composed the structural roots of the rift basins, where interaction with the ascending ore fluids produced similar textures within open spaces at depth.

**Tectonic setting and implications for exploration**

Due to the shallow environment of formation and the high erosion rates in most volcanic arcs, the preservation potential of high-sulphidation deposits is generally poor, such that most known deposits are of Tertiary age or younger (Arribas, 1995a). The Paleozoic age and the exceptional preservation (including what is interpreted as mineralised paleosurface and near-surface features) of Mt. Carlton is, therefore, remarkable.

Throughout the Paleozoic and Mesozoic, the eastern margin of Australia was extensional for long durations of time, caused by rollback of the subducting plate and repeated eastward migration of the subduction system. As a result, the basement rocks in the overriding plate were extended, and back-arc basins (e.g., the Drummond Basin and the Bowen Basin) developed on top of the extending basement (e.g., Donchak et al., 2013). The structural observations at Mt. Carlton indicate that the mineralisation formed along the axis of the northern Bowen Basin during the onset of the Early Permian back-arc rifting stage, consistent with the 40Ar/39Ar dating results. Prolonged extension in the Bowen Basin provided rapid burial of the Mt. Carlton deposit beneath post mineralisation volcanosedimentary cover. Preservation of epithermal paleosurface features tends to be geographically confined to either extensional (commonly back-arc) regions characterized by semi-arid climates and relatively low erosion rates (e.g., the Great Basin, Mexican Altiplano, Deseado Massif, and Drummond Basin) or the highly arid central Andes (Sillitoe, 2015). The preservation of the Mt. Carlton deposit is thus strongly linked to the extensional setting in which it formed.

Post mineralisation extension, most notably during D2 and D3, has caused significant tectonic modification.
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of the Mt. Carlton deposit, including rotation and segmentation of the stratigraphy and the ore zones. This deformation also has important implications for exploration for linked porphyry mineralization in the area. Assuming a similar scenario as documented at the coupled Far Southeast porphyry and Lepanto high-sulphidation deposits at Mankayan, Philippines (Arribas et al., 1995b; Hedenquist et al., 1998; Chang et al., 2011), the mineralised feeders at Mt. Carlton should theoretically extend to the causative intrusion. Based on the present-day shape of the ore zones, with mineralisation occurring in predominantly NE to NNE trending fractures, and the vectors defined by the metal zonation (distal Ag-Pb-Zn to proximal Au-Cu, from SW to NE; Fig. 7), alunite composition (increasing Na content to the northeast), and ore textures (shallow stratabound ore in the SW, mineralised feeders in the northeast) within the Mt. Carlton deposit, the simplest assumption would be that more proximal mineralization should occur to the northeast of the current V2 pit. However, drilling and induced polarization (IP) geophysical surveys conducted at Mt. Carlton have so far been unsuccessful in detecting any high-grade exploration vectors in the area. Assuming a similar scenario as documented at the coupled Far Southeast porphyry and Lepanto high-sulphidation deposits at Mankayan, Philippines (Sillitoe and Lorson, 1994). The deeper parts of the feeder system as well as potential linked porphyry mineralization should, therefore, be displaced relative to the currently mined Mt. Carlton deposit. Based on the kinematics of D2 faults observed in the open pits, this displacement is expected to be to the west of Mt. Carlton. Since mineralization occurs in the deeper parts of the stratigraphy, where D2 faults are poorly developed, the amount of such displacement is most likely relatively small (e.g., on the order of tens to hundreds of meters). NNW-trending D2 normal faults, similar to the one that passes between the two open pits, also occur to the NE of the V2 pit and to the SW of the A39 pit, respectively. The potentially major displacement across such structures and associated block rotation add an extra layer of complexity to the development of exploration vectors in the Mt. Carlton district.

Concluding Remarks

The study of the Mt. Carlton deposit highlights that shallow level high-sulphidation epithermal mineralisation can be preserved in Paleozoic settings under appropriate geodynamic conditions. We suggest that extensional segments of volcanic arcs, such as back-arc rifts, are particularly prospective for this type of mineralisation. The study also highlights the need to understand the post mineralisation tectonic modification of the porphyry-epithermal system in extensional settings and concerns exploration in the northern Bowen Basin and similar geologic terranes elsewhere.

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Introduction

Germanium (Ge), gallium (Ga) and indium (In) have become increasingly sought after in recent years. This is largely due to their growing usage in various high-tech and green-tech applications, such as smartphones (Ga, In), optoelectronics (Ge, Ga, In), fibre optics (Ge) and solar cells (Ge, Ga, In) (Schwartz-Schampera et al., 2002; Frenzel et al., 2016a,b; Guberman, D., 2017; Jaskula, B., 2017; Tolcin, 2017). These elements are commonly classified as critical raw materials due to their increasing economic importance combined with current supply security risks (Erdmann & Graedel, 2011).

The three elements can be concentrated in a variety of hydrothermal ore deposits, including volcanic hosted massive sulphide ( VHMS) deposits, Mississippi Valley-type (MVT) deposits, carbonate-hosted polymetallic deposits of Tsumeb-type (exemplified by Tsumeb in Namibia, Kipushi in D.R. Congo and the Apex Mine in Utah; e.g., Höll et al., 2007), syngenetic or early diagenetic sedimentary exhalative (SEDEX) deposits, epithermal deposits, polymetallic (±Sn) vein or stockwork deposits linked to granites, and skarn deposits (Schwartz-Schampera et al., 2002; Höll et al., 2007; Paradis, 2015). Although Ge, Ga and In may form minerals in which they are a major component, they are also incorporated as trace components into various minerals (Schwartz-Schampera et al., 2002; Höll et al., 2007; Bernstein, 1985; Cook and Ciobanu, 2015). There are no hydrothermal ore deposits that are mined primarily for Ge, Ga and In. Rather, these elements are recovered as by-products from extractive operations for other commodities, chiefly from the processing of sphalerite ores (Schwartz-Schampera et al., 2002; Frenzel et al., 2014, 2016a,b; Ishihara et al., 2006; Cook et al., 2011). Sphalerite enrichment in Ge and Ga is generally favoured in low-temperature magmatic-hydrothermal systems, often related to felsic intrusions (Cook and Ciobanu, 2015; Shimizu and Morishita, 2012; Murakami and Ishihara, 2013).

In this study, we use electron probe microanalysis (EPMA) and laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) to determine the concentrations and distribution of Ge, Ga and In and related elements in key minerals formed throughout the paragenetic sequence at the Mt Carlton high sulphidation (HS) Au-Ag-Cu deposit (see previous article in this issue for a summary of the Mt Carlton geology and mineralisation; for a comprehensive description see Sahlström et al., 2018). Samples from a selection of global HS and porphyry deposits are analysed for reference, and the results are compared with published case studies. The main aim of the study is to improve the understanding of the mineralogical distribution of Ge, Ga and In in HS deposits. This information is a pre-requisite for the evaluation of HS deposits as potential sources for these elements, and for the development of efficient ore processing methods during recovery.

Stratigraphy and Deformation Sequence at Mt Carlton

The Mt Carlton deposit occurs in the northern Bowen Basin, a NW-trending elongate sedimentary basin located in eastern Queensland, Australia. The basin formed during the Early Permian to Middle Triassic, and shows evidence for a complex and polyphase tectonic evolution (Donchak et al., 2013). The basement in the northern Bowen Basin consists of fine- to medium-grained I-type granitoids belonging to the Urannah Batholith. At Mt Carlton, the granite basement (Unit 1) is overlain by a volcano-sedimentary sequence belonging to the Early Permian Lizzie Creek Volcanic Group. The Lizzie Creek sequence consists of (from bottom to top): fine-grained porphyritic andesite (Unit 2), massive and locally flowbanded porphyritic rhyodacite (Unit 3), well-bedded fragmental rhyodacite lapilli tuffs with interbedded carbonaceous lacustrine sediments (Unit 4A), massively bedded dacite tuffs (Unit 4B), fragmental to agglomeritic dacite (Unit 5), fragmental to agglomeritic andesite and minor andesite lava (Unit 6), water-laid sediments with local coal seams (Unit 7), and a flowbanded rhyolite unit (Unit 8) forming the top of the sequence (Sahlström et al., 2018; stratigraphic column included as Fig. 2 in the preceding
article in this issue). Mineralisation at Mt Carlton is hosted partly in the massive rhyodacite porphyry (Unit 3) and partly in the overlying volcano-lacustrine sediments (Unit 4A).

The Mt Carlton deposit has experienced several stages of extensional deformation (Sahlström et al., 2018; summary included in preceding article). Hydrothermal alteration and epithermal mineralisation occurred during a stage of rifting with associated high-angle normal faulting in response to both E-W and N-S extension (D1). Mineralisation was controlled by steep normal faults and fracture networks related to the rifting, and occurred partly contemporaneously with volcanism and deposition of volcanic sediments into local graben and half graben basins. Continued E-W extension after mineralisation provided rapid burial of the Mt Carlton deposit beneath volcano-sedimentary cover. It also caused the development of a series of low-angle (and locally layer-parallel) detachment faults which have rotated and displaced the stratigraphic sequence and the ore zones at Mt Carlton. High-angle normal faulting in response to N-S extension and emplacement of E-W trending basaltic dykes into the normal faults was followed by dominantly dextral strike-slip faulting along the dyke margins. A final stage involved emplacement of WNW-trending basaltic dykes.

Hydrothermal Alteration

Mineralisation at Mt Carlton is hosted in a sequence of volcanic and sedimentary rocks. The host rocks are extensively hydrothermally altered, and the paragenetic alteration sequence is presented as Figure 6 in the preceding article in this issue. Stage 1A of the paragenetic sequence comprises a suite of magmatic-hydrothermal alteration assemblages that are zoned outward, away from fluid conduits, as follows: silicic (massive + vuggy + hydrothermal breccia) → quartz-alunite (Fig. 1A) → quartz-dickite-kaolinite. This alteration halo envelops mineralization in Units 3 and 4A. The silicic cores locally contain veins and void fill made up of magmatic-steam alunite (Stage 1B; Fig. 1B). Stage 1A alteration in the granite basement comprises chlorite and illite occurring in veinlets and as replacements of pre-existing phenocrysts of feldspar, biotite and hornblende.

Hydrothermal Mineralisation and Void Fill

Three major ore zones at Mt Carlton (Eastern, Western and Link zones) are aligned in an en echelon fashion along an E-W trending corridor (see Fig. 7 in preceding article). The Eastern and Link ore zones terminate in the V2 pit, whereas the Western ore zone continues along ~600 m strike length SW into the A39 pit. Proximal Au-Cu mineralisation in the V2 pit occurs in networks of steep veins, fractures and hydrothermal breccia bodies in the rhyodacite porphyry (Unit 3). From proximal and deep to distal and shallow (at the time of formation), the Western ore zone shows a metal zonation of: Au-Cu → Cu-Zn-Pb-Ag → Ag-Pb-(Cu) → Ag. Distal Ag mineralization in the A39 pit occurs in the overlying volcano-lacustrine sediments (Unit 4A), in a stratiform position parallel to primary sedimentary layering (Sahlström et al., 2018).

Epithermal mineralisation at Mt Carlton developed in three stages (Stages 2A–C; Fig. 6 preceding article)

Stage 2A (the most voluminous event)

A high-sulphidation state mineral assemblage dominated by enargite. The assemblage also contains variable amounts of pyrite, luzonite, fahlores, electrum, chalcopyrite, bornite, sphalerite, galena, argyrodite, pearceite-polybasite group minerals, an uncharacterised analogue to aguilarite and cervelleite (ideally Ag₄TeSe₂), and barite (Figs 1B–F). Stage 2A mineralization is associated with silicic alteration (quartz ± alunite) of the wall rocks (Fig. 1C).

Whole rock analyses of Stage 2A ore samples from the V2 pit showed average concentrations of 61 ppm Ge (up to 246 ppm), 34 ppm Ga (up to 66 ppm) and 56 ppm In (up to 151 ppm In), while samples from the A39 pit yielded average concentrations of 109 ppm Ge (up to 342 ppm), 24 ppm Ga (up to 45 ppm) and 11 ppm In (up to 19 ppm) (Sahlström et al., 2018).

Stage 2B

An intermediate-sulphidation state mineral assemblage dominated by sphalerite, that crosscuts Stage 1A. The Stage 2B assemblage also contains variable amounts of galena, pyrite, electrum, fahlores, chalcopyrite, bornite and barite (Fig. 1D). Sahlström et al. (2017) recently documented the presence of a mineral with compositions close to CuZn(In,Ga)S₄, which occurs as fine (~1 µm thick) colloform bands inside the Stage 2B sphalerite (Table 1; see the following article in this issue). This mineral corresponds to a Ga-rich variety of the uncharacterized Zn-In mineral (ideally CuZn(In,S)₄] first described from the Toyoha deposit in Japan (Ohta, 1989), and later from the Mt Pleasant deposit in Canada (Sinclair et al., 2006).

Stage 2B ore samples from the V2 pit showed average whole rock concentrations of 167 ppm Ge (up to 265 ppm), 284 ppm Ga (up to 396 ppm) and 255 ppm In (up to 408 ppm), while average concentrations of 7 ppm Ge (up to 13 ppm), 108 ppm Ga (up to 151 ppm) and 201 ppm In (up to 468 ppm) were observed for samples from the A39 pit (Sahlström et al., 2018).
Figure 1. Photographs of alteration and mineralisation assemblages from Mt Carlton. (A) Quartz-alunite-pyrite alteration (Stage 1A) developed in a quartz-feldspar phryic rhyodacite. Magmatic-hydrothermal alunite occurs as disseminations and as replacements of pre-existing feldspars. (B) Plumose alunite vein of magmatic-steam origin (Stage 1B). After deposition of alunite, the vein was re-opened along the central line to form an enargite vein (Stage 2A). The composite vein was then overprinted by dickite (Stage 3). (C) Silicic hydrothermal breccia cemented by Stage 2A enargite-pyrite ore. (D) Silicic altered rhyodacite crosscut by a fine enargite-cemented hydrothermal breccia (Stage 2A). The enargite breccia is crosscut by a sphalerite-pyrite-galena vein containing specules of electrum(Stage 2B). The sphalerite vein is in turn locally overprinted by tennantite (Stage 2C). (E) Stage 2A enargite veinlet with a halo of barite. (F) Disseminated Stage 2A enargite mineralisation crosscut by a Stage 3 dickite-pyrite vein. Mineral abbreviations: Alu—alunite; Brt—barite; Dck—dickite; Elc—electrum; Eng—enargite; Gn—galena; Py—pyrite; Qtz—quartz; Sp—sphalerite; Tn—tennantite.
Stage 2C
This is a minor intermediate-sulphidation event, dominated by tennantite, that overprinted Stage 2B mineralization and has only been observed at the microscopic scale.

Stage 3
A late stage of dickite and pyrite (Fig. 1F) occurring in veins and as massive void fill overprinting Stage 2 mineralization.

Stage 4
Pervasive illite-montmorillonite ± red hematite alteration with local syn-tectonic gypsum veins, that developed regionally during the D2 deformation event.

Stage 5
The final paragenetic stage at Mt Carlton involves minor supergene oxidation in the upper ~50 m of the deposit. This has caused local development of secondary covellite, chalcocite and malachite on Cu-bearing minerals such as enargite, luzonite and bornite, particularly along fractures within the minerals.

Results
The samples for this study were collected from drill cores and in situ from outcrops in the open pits at Mt Carlton, and prepared as polished thin and thick sections. This study focuses on key minerals formed throughout the paragenetic sequence at Mt Carlton, including minerals formed during Stage 1 acid sulphate alteration (alunite), Stage 2A high-sulphidation mineralisation (enargite, argyrodite, sphalerite, pyrite and barite), Stage 2B intermediate-sulphidation mineralization (sphalerite, pyrite and galena) and Stage 3 hydrothermal void fill (dickite) (Table 1). Analytical measurements were generally conducted on multiple samples to obtain a range of representative results and, when possible, samples from both the V2 pit (proximal) and the A39 pit (distal) were included.

Alunite
Trace element data was obtained for magmatic-hydrothermal alunite (Stage 1A; Fig. 1A) and magmatic-steam alunite (Stage 1B; Fig. 1B) from the V2 pit at Mt Carlton. Both types of alunite exhibit moderate to locally high concentrations of Ga. The average Ga concentrations are 32 ppm (up to 109 ppm) in magmatic-hydrothermal alunite and 72 ppm (up to 339 ppm) in magmatic-steam alunite. Gallium shows smooth downhole signals in alunite, suggesting it is hosted in solid solution, and the trends of Ga concentrations closely match those of Al. Indeed, incorporation of Ga into minerals of the alunite supergroup is generally attributed to direct substitution of Ga$^{3+}$ into the site normally occupied by Al$^{3+}$ or Fe$^{3+}$ (Tananaev et al., 1967; Jambor et al., 1996; Jambor, 1999; Dutrizac and Chen, 2000). The concentrations of Ge and In in alunite were consistently below 10 ppm and 2 ppm, respectively. Overall, magmatic-hydrothermal and magmatic-steam alunite display similar trace element signatures.

Argyrodite
Argyrodite, the mineral in which Ge was first detected (Weisbach, 1886), occurs in the Stage 2A ores as up to ~100 µm anhedral crystals intergrown with barite and enargite. The presence of argyrodite appears to be restricted to the distal, Ag-rich parts of the deposit (A39 pit). Spot analyses of two grains showed one grain to have a composition close to argyrodite sensu stricto, while the other grain corresponds to a Se-rich analogue of argyrodite [ideally Ag$_8$GeSe$_2$S$_4$]. The average Ge concentration in argyrodite is 5.76 wt % (up to 6.95 wt %).

Enargite
Enargite is the principal mineral in the Stage 2A ores at Mt Carlton. Enargite occurs as masses of anhedral to subhedral crystals that host most of the subordinate minerals (Fig. 1C). Trace element data was obtained

Table 1. Critical element-bearing minerals identified at the Mt Carlton deposit.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Class</th>
<th>Crystal System</th>
<th>Ideal Formula</th>
<th>Paragenesis</th>
<th>Contained Elements</th>
<th>Reference</th>
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<tr>
<td>Alunite</td>
<td>Sulphate</td>
<td>Trigonal</td>
<td>KAl$_3$(SO$_4$)$_2$(OH)$_5$</td>
<td>1A and 1B</td>
<td>Ga</td>
<td>this study</td>
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<tr>
<td>Argyrodite</td>
<td>Sulphide</td>
<td>Orthorhombic</td>
<td>Ag$_8$Ge$_6$S$_6$</td>
<td>2A</td>
<td>Ge</td>
<td>this study</td>
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<tr>
<td>Enargite</td>
<td>Sulphosalt</td>
<td>Orthorhombic</td>
<td>Cu$_3$As$_4$S$_4$</td>
<td>2A</td>
<td>Ge (In, Ga)</td>
<td>this study</td>
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<td>Isometric</td>
<td>ZnS</td>
<td>2A and 2B</td>
<td>In, Ga, Ge</td>
<td>this study</td>
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<td>Uncharacterised</td>
<td>CuZn$_2$InS$_4$</td>
<td>2B</td>
<td>In, Ga</td>
<td>**</td>
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<tr>
<td>Dickite</td>
<td>Silicate</td>
<td>Monoclinic</td>
<td>Al$_3$Si$_2$O$_4$(OH)$_4$</td>
<td>3</td>
<td>Ga</td>
<td>this study</td>
</tr>
</tbody>
</table>

**Reference: Sahlström et al., 2017; summary article in this issue.
for enargite from both the V2 and A39 pits. Mt Carlton enargite shows moderate to high enrichment in Ge, with average concentrations of 86 ppm in V2 samples (up to 330 ppm) and 612 ppm in A39 samples (up to 2189 ppm). Both In (average 14 ppm in V2, 7.7 ppm in A39) and Ga (average 6.0 ppm in V2, 5.2 ppm in A39) are generally low, but significant concentrations are present locally (e.g., up to 155 ppm In and 37 ppm Ga in V2).

A comparison of trace elements that occur in Mt Carlton enargites with average concentrations above 100 ppm, indicates the V2 enargites are relatively enriched in Sb, Bi and Sn. Both Bi and Sn are elements indicative of higher temperature conditions (De Ronde et al., 2011) and both are commonly present in HS deposits (e.g., Pierina in Peru and Rodalquilar in Spain; Arribas, 1995). Samples from A39 are in turn relatively enriched in Zn, Ag, Ge and Pb. The concentrations of Te, Se and Fe are similar in samples from V2 and A39. Gold has average concentrations of 12 ppm in V2 (up to 62 ppm) and 0.2 ppm in A39 (up to 1.4 ppm).

Previous studies of the Far Southeast-Lepanto porphyry-epithermal system (Mankayan, Philippines) have revealed a spatial variability in the trace element composition of enargite (Gonzalez, 1959; Deyell and Hedenquist, 2011). Enargite collected close to the Far Southeast porphyry deposit was enriched in Au-Te, enargite collected from the center of the Lepanto HS deposit was enriched in Ag-Fe-Pb, and enargite collected from the most distal ores was enriched in Zn (±Cd) (Deyell and Hedenquist, 2011). From proximal to distal, the Sn content in enargite was progressively decreasing (Gonzalez, 1959). The trace element signatures for enargite from Mt Carlton in part corroborate the trends observed at Far Southeast-Lepanto, suggesting that this method may have some potential as a vectoring tool for exploration in the porphyry-epithermal environment. Furthermore, at the Rodalquilar HS deposit, the presence of anomalous Sn concentrations (high enough to form Sn-bearing minerals such as cassiterite (wood tin), colusite or rodalquilarite; (Arribas et al., 1995)) was considered to be a prospective guide to high Au grade mineralised structures (Martin-Vivaldi et al., 1971).

**Barite**

Barite is present in Stage 2A ores as up to ~0.5 cm anhedral to subhedral crystals intergrown with the enargite assemblage. More rarely it occurs as halos to enargite veinlets (Fig. 1F). Barite is most abundant in the distal and shallow parts of the Mt Carlton deposit (A39 pit; Sahlström et al., 2018). The LA-ICP-MS analyses of barite from the A39 pit yielded concentrations of Ge, Ga and In consistently below 2 ppm. However, the barite has high concentrations of Pb (average 1.3 wt %) and Sr (average 2406 ppm). This reflects a solid solution toward hokutolite ((Ba,Pb,Sr)SO₄), a plumbian variety of barite reported from some acidic hot springs (e.g., the Tamagawa Hot Spring in Japan and the Peitou Hot Spring in Taiwan). The identification of Pb-rich barite at Mt Carlton has some significance for exploration, as this mineral potentially is responsible for the distal Pb geochemical anomaly observed at the deposit (Sahlström et al., 2018).

**Pyrite**

Pyrite occurs in Stage 2A ores as up to ~1 cm subhedral crystals intergrown mainly with massive enargite and luzonite (Fig. 1C). Stage 2B pyrite occurs as subhedral pyrite crystals, up to ~0.5 cm, mainly intergrown with sphalerite and galena. Pyrite grains from Stage 2A and Stage 2B consistently show low concentrations of Ge, Ga and In (below 5 ppm). Both stages of pyrite exhibit similar enrichment in Cu (average >700 ppm), but Stage 2A pyrite shows a relative enrichment in Co, Ni, Zn and Ag (average 100–500 ppm), while Stage 2B pyrite is richer in As (average 2443 ppm, up to 1.2 wt %) and Pb (average 314 ppm).

The Stage 2B pyrite is also significantly enriched in Au (average 56 ppm and up to 367 ppm) relative to Stage 2A pyrite (average 2.4 ppm and up to 11 ppm). This is consistent with previously made observations of high incorporation of Au in arsenian pyrite (Reich et al., 2005).

**Sphalerite**

Sphalerite is present in small quantities in the Stage 2A ores. It occurs intergrown with enargite and luzonite as up to ~150 µm dark brown to black subhedral crystals. Sphalerite is the principal mineral in the Stage 2B ores, where it has a massive to colloform texture, and varies from almost transparent to dark brown (Fig. 1D). Stage 2A sphalerite shows average concentrations of 77 ppm Ge (up to 143 ppm), 677 ppm Ga (up to 1181 ppm) and 469 ppm In (up to 571 ppm). Stage 2B sphalerite from V2 yielded average concentrations of 206 ppm Ge (up to 611 ppm), 444 ppm Ga (up to 2829 ppm) and 369 ppm In (up to 2169 ppm). In contrast, Stage 2B sphalerite from A39 shows significantly lower average concentrations of these elements, including 5.1 ppm Ge (up to 8.5 ppm), 260 ppm Ga (up to 476 ppm) and 20 ppm In (up to 40 ppm).

Both Stage 2A and Stage 2B sphalerite are highly enriched in Cu, Cd and Pb (average > 1000 ppm). The Cu content in Stage 2B sphalerite decreases from proximal (average 2013 ppm Cu in V2) to distal (average 486 ppm Cu in A39), which is consistent with the deposit scale metal zonation.
Other elements with average concentrations in excess of 100 ppm in sphalerite include As, Ag and Sb (both stages), Se and Te (Stage 2A), and Fe and Hg (Stage 2B). Concentrations of Au are locally significant: up to 21 ppm in Stage 2A sphalerite and up to 75 ppm in Stage 2B sphalerite.

Germanium, Ga and In all show smooth downhole profiles in sphalerite, confirming that they are predominantly hosted in solid solution in this mineral (Cook et al., 2009).

**Ga enrichment in Al-bearing sulphates and silicates**

This study highlights how Ga may be present in moderate to high concentrations in Al-bearing hydrothermal sulphates and silicates such as alunite and dickite, due to substitution of Ga³⁺ into the structural sites normally occupied by Al³⁺ in these minerals. Equivalent substitutions (Ga³⁺ ↔ Fe³⁺) should be possible in Fe³⁺-analogue to such minerals. Exceptionally high Ga contents in minerals of the alunite supergroup have previously been documented in the oxidized zones of Tsumeb-type polymetallic deposits. The Tsumeb deposit in Namibia locally contains supergene galloledudantite (PbGa₃(AsO₄)(SO₄)(OH)₆; Jambor et al., 1996) and galloplumbogummite (Pb(Ga,Al)₃(PO₄)₂(OH)₆; Mills et al., 2009). Similar ores at the Apex Mine in Utah contain supergene jarosite (the Fe³⁺-analogue to alunite; KFe₆(SO₄)₃(OH)₆) with up to 7000 ppm Ga (Dutrizac et al., 1986; Bernstein, 1986). At the Apex Mine, the world’s only deposit ever considered as a primary Ga and Ge producer, jarosite is one of the principal Ga carriers (Dutrizac et al., 1986; Bernstein, 1986).

Compared to the above examples, the Ga concentrations in alunite and dickite at Mt Carlton are distinctly lower. However, they are comparable to those of worldwide bauxite deposits (average 57 ppm Ga; Schulte and Foley, 2014), the main source of the global Ga supply (Frenzel et al., 2016). Similar Ga enrichment to that at Mt Carlton has previously been documented in whole rock samples from the advanced argillic alteration zone at the Paradise Peak HS deposit in Nevada (up to 120 ppm Ga; Rytuba et al., 2003). The similarities between X-ray absorption spectra of these samples and those of gallium sulphate suggest the Ga there is predominantly hosted in alunite (Rytuba et al., 2003). Alunite is a primary ore mineral for Al, K and S in exceptionally alunite-rich HS deposits similar to those at Alunite Ridge in Utah (Cunningham et al., 1984) and Red Mountain in Colorado (Bove et al., 1990), several of which have been exploited historically. The added possibility of recovering Ga as a by-product could spark a renewed interest in such occurrences. Furthermore, there could be potential for recovery of Ga from alunite present in the gangue in HS deposits that are primarily mined for their precious and/or base metal contents. Methods for extracting Ga from alunite concentrate have been developed in Japan (e.g., Asahi Chemical Industry, 1965), and more recently in China (e.g., Zijin Mining Group, 2012).

1) Ga enrichment in Al-bearing hydrothermal sulphates and silicates,
2) Ge ± In-Ga enrichment in high-sulphidation enargite ores, and
3) In-Ga ± Ge enrichment in intermediate-sulphidation sphalerite ores.
**Ge ± In-Ga mineralisation in high-sulphidation enargite ores**

The presence of argyrodite at Mt Carlton is not unique for HS deposits, and a variety of independent Ge sulphide minerals have previously been documented in HS deposits elsewhere. Deposits from the Cretaceous Panagyurishte district of Bulgaria (including the Chelopech, Radka, Krassen and Elshitsa HS deposits) locally contain germanite (Cu9Fe2Ge2S16), renierite ([Cu3(Zn,Fe)GeS3]2+, germanocolusite (Cu13V(Ge,As)3S16), briartite (Cu3(Zn,Fe)GeS3) and Ge-bearing arsenosulvanite (Cu4(As,V,Ge)S5) (Terziev, 1966, 1968; Kovalenker et al., 1986; Petrunov, 1995; Bonev et al., 2002; Bogdanov et al., 2004). Neogene epithermal mineralization in the South Apuseni Mountains in Romania (including the Bucium, București–Rovina, Băița Crăciunești and Părăul lui Avram occurrences) contain argyrodite and/or germanite associated with enargite (Támas et al., 2006, and references therein). The Capillitas deposit (Catamarca province, Argentina) comprises a number of mainly intermediate-sulphidation epithermal veins, some of which show high-sulphidation affinities (Putz et al., 2009). Oxidized enargite-bearing ores in the mine dumps from the La Rosario vein exhibit a supergene mineral assemblage that contains several original species of Ge sulfides, including putzite (Cu3Ag6GeS13), catamarcaite (Cu9GeWS4) and omariniite [Cu9Fe2ZnGe2S12], with zinccobriartite also being present in trace amounts (Paar et al., 2004; Putz et al., 2002, 2007, 2009; Paar and Putz, 2005; Bindi et al., 2017).

Based on the LA-ICP-MS analyses of enargite from seven HS deposits and one porphyry deposit conducted in this study, moderate Ge concentrations (10–100 ppm) seem to be common in enargite in these systems. Higher Ge concentrations in enargite (e.g., 100–3000 ppm) are potentially restricted to a smaller number of deposits (e.g., Mt Carlton, La Mejicana, Cerro Quema and Chelopech).

Sphalerite is typically a volumetrically minor component of high-sulphidation enargite ores (Arribas, 1995). Sphalerite is probably the preferred host for In and Ga in this assemblage, however, moderate enrichment of these elements may also be present in sulphosalts minerals.

At Mt Carlton, the presence of argyrodite and the high Ge content of enargite are predominantly confined to the distal and shallow, Ag-rich parts of the deposit. This may suggest that mixing of the ore fluid with cooler meteoric waters, and a high activity of Ag, were important controls on this type of Ge mineralization. High-sulphidation enargite ores are generally voluminous in most HS deposits and, thus, represent a potential source of Ge, in addition to their commonly exploited Au, Ag and Cu contents. The gossans of some HS deposits (e.g., the La Rosario vein), Tsumeb-type deposits (e.g., Tsumeb and Apex Mine) and polymetallic vein deposits (e.g., San Roque and Pingüino, Argentina; Dill et al., 2013; Lopez et al., 2015) are known to be enriched in critical elements, which can be attributed to the general immobility of Ge, Ga and In during weathering (Bernstein, 1985, 1986; Lopez et al., 2015; Wood and Samson, 2006).

**In-Ga ± Ge mineralisation in intermediate-sulphidation sphalerite ores**

Indium and Ga display a similar distribution in the intermediate-sulphidation sphalerite ores at Mt Carlton. Both elements are primarily hosted in sphalerite and in the “Zn-In mineral”. The highest concentrations of In and Ga in sphalerite occur in the proximal, Cu-rich parts of the deposit. Indeed, a high Cu activity in the ore fluid is a strong control on In enrichment and, to a lesser degree, Ga enrichment in sphalerite (Frenzel et al., 2016), as it allows for extensive incorporation of these elements in coupled substitution with Cu.

Germanium also appears to be hosted predominantly in sphalerite in the Stage 2B ores at Mt Carlton. In-Ga ± Ge enrichment in intermediate sulphidation sphalerite ores similar to those at Mt Carlton have been documented elsewhere. The most prominent example is the world-class Toyoha IS deposit in Japan. Toyoha was the world’s largest In producer in the 1990s—early 2000s, containing 33,700 kt of ore with an average In grade of 138 ppm (Ishihara et al, 2006). Similar to Mt Carlton, the main carriers of In at Toyoha are In-bearing sphalerite ores (up to 7 wt % In, 3.6 wt % Cu and 273 ppm Ga; Shimizu and Morishita, 2012; Cook et al., 2009) and the “Zn-In mineral” (Ohta, 1989). Other In-bearing minerals at Toyoha include roquesite (Cu(InS2), stannite-kësterite (Cu2FeSnS4–Cu2ZnSnS4), and wurtzite exhibit high concentrations of In (up to 3.5 wt %), Ga (up to 1.6 wt %) and Ge (up to 800 ppm) (Driesner and Pintea, 1994; Skarpelis, 1995; Melfos and Voudouris, 2012). The Roşia Montana IS deposit in Romania locally contains alburnite (Ag8GeTe2S4), sakuraiite ([Cu9ZnFe-In,Sn]-S), laforetite (AgInS2) and chalcopyrite (Ohta, 1989). The Ge content of Toyoha sphalerite is low (1–4 ppm; Cook et al., 2009).

The Agios Philippos HS deposit in Thrace, Greece, contains a stage of Zn-Pb-rich intermediate-sulphidation ore rich in sphalerite and wurtzite (the hexagonal polymorph of sphalerite). Here, sphalerite and wurtzite exhibit high concentrations of In (up to 3.5 wt %), Ga (up to 1.6 wt %) and Ge (up to 800 ppm) (Driesner and Pintea, 1994; Skarpelis, 1995; Melfos and Voudouris, 2012). The Roşia Montana IS deposit in Romania locally contains alburnite (Ag9GeTe34), the Te-rich analogue of argyrodite (Támas et al., 2006; 2014), as well as sphalerite with up to 73 ppm Ge, 366 ppm Ga, 38 ppm In and 1906 ppm Cu (Cook et al., 2009). The Nueva Esperanza HS vein at the Capillitas
deposit in Argentina is the type locality of the rare Ga-In mineral ishiharaite ((Cu, Ga, Fe, In, Zn)S). This mineral is associated with a late intermediate-sulphidation assemblage containing In-bearing sphalerite and tennantite, as well as pyrite, chalcopyrite and galena (Márquez-Zavalia et al., 2014). A additional example is the Palai-Islica IS deposit in Spain, where sphalerite is variably enriched in Ge (up to 0.42 wt %), Ga (up to 0.16 wt %), In (up to 0.43 wt %) and Cu (up to 1.72 wt %) (Carrillo-Rosúa et al., 2008).

There is, thus, a noteworthy potential for In-Ga ± Ge enrichment in (Cu-rich) intermediate sulphidation sphalerite ores in the epithermal environment. This mineralisation style may be present in both HS deposits (e.g., Mt Carlton, Agios Philippou, Nueva Esperanza vein) and IS deposits (e.g., Toyoha, Roşia Montana and Palai-Islica). When sphalerite in such deposits is volumetrically significant enough to be processed, the possibility of extracting critical elements as by-products could increase the value of these ores.

**Concluding Remarks and Future Developments**

In summary, the evidence from this study and from the literature highlights the potential for various styles of Ge, Ga and In mineralisation in high-sulphidation epithermal deposits, as well as in the closely related intermediate-sulphidation epithermal deposits. This is something that is seldom considered during exploration and mining in these environments. In addition to their well-known resources of precious and base metals, the potential for critical elements could increase the prospectivity of these deposits.

In addition to magmatic-hydrothermal processes, carbonaceous sedimentary rocks could potentially be important for the concentration of Ge, Ga and In in HS deposits (see the original publication for further discussion).

Holistic mineralogical studies of similar deposits, including more trace element data for common ore and alteration minerals, can help improve our understanding of the distribution of Ge, Ga and In in the epithermal environment. Data are particularly limited for deposits affected by supergene processes. To improve exploration for these commodities, a better understanding of the source(s) as well as the mechanisms of enrichment, transport and deposition of Ge, Ga and In in epithermal systems is also needed. We find the potential link between critical element enrichment and carbonaceous sedimentary rocks particularly interesting and deserving of more detailed investigation.

**References**


Ge, Ga, In at Mt Carlton cont'd


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Indium has become increasingly sought-after in recent years due to its importance in various high-tech applications (Schwarz-Schampera and Herzig, 2002). The vast majority of the world’s In is recovered as a by-product from the processing of sphalerite ores (Schwarz-Schampera and Herzig, 2002; Alfantazi and Moskalyk, 2003; Cook et al., 2011a). Indium occurs in the sphalerite structure, where it may reach concentrations of several weight percent (Schwarz-Schampera and Herzig, 2002; Ishihara et al., 2006; Ishihara and Endo, 2007; Cook et al., 2009), and shows a strong correlation with Cu in sphalerite. In many cases, sphalerite with high-grade In shows complex compositional zonation with respect to In (Pattrick et al., 1993; Cook et al., 2009, 2011a; Shimizu and Morishita, 2012), and new techniques to study the presence and distribution of In can therefore be of interest for both scientific and technological purposes.

In this study we use hyperspectral Cathodoluminescence (CL) mapping, combined with X-ray element mapping and spot analyses, to characterise the composition and CL properties of In-bearing sphalerite from the Mt Carlton deposit in northeast Queensland.

Method

Cathodoluminescence is an optical and electromagnetic phenomenon whereby a luminescent material is excited by an electron gun that emits photons with wavelengths ranging from ultraviolet to infrared. A particular advantage of CL is that it can reveal cryptic crystallisation textures and zoning patterns in a variety of minerals, features that may not be distinguishable using other microscopy techniques (e.g., Kuhlemann and Herring, 2002; Ishihara et al., 2006; Ishihara and Endo, 2007; Cook et al., 2009), and shows a strong correlation with Cu in sphalerite. In many cases, sphalerite with high-grade In shows complex compositional zonation with respect to In (Pattrick et al., 1993; Cook et al., 2009, 2011a; Shimizu and Morishita, 2012), and new techniques to study the presence and distribution of In can therefore be of interest for both scientific and technological purposes.

In this study we use hyperspectral Cathodoluminescence (CL) mapping, combined with X-ray element mapping and spot analyses, to characterise the composition and CL properties of In-bearing sphalerite from the Mt Carlton deposit in northeast Queensland.

Sphalerite

The sphalerite samples for this study were collected from the Mt Carlton high-sulphidation epithermal deposit (Sahlström et al., 2015, 2016; Howard et al., 2015). The Mt Carlton setting and geology is summarised in the first article in this issue of EGRU News.

Mineralisation at Mt Carlton dominantly occurs as structurally controlled lodes within silicic and advanced argillic alteration (Sahlström et al., 2015, 2016; Howard et al., 2015). The Mt Carlton setting and geology is summarised in the first article in this issue of EGRU News.
Indium-bearing sphalerite from Mt Carlton cont’d

2016, 2018; Howard et al., 2015). Most of the Au, Ag and Cu is hosted in high-sulphidation ore dominated by enargite (Stage A), which is crosscut by two later stages dominated by sphalerite (Stage B) and tennantite (Stage C; Sahlström et al., 2018). Sphalerite in Stage B occurs in veins with subordinate galena, pyrite, electrum, fahlores, chalcopyñte, bornite and barite (Fig. 1). The sphaleñte is generally light brown, indicating a low Fe content, with delicate (~1 μm wide) colloform bands which show dark brown colours in transmitted light microscopy (Fig. 2). In reflected light these bands are largely indistinguishable from the surrounding sphalerite, but locally have a slightly higher reflectance. In back-scattered electron (BSE) images these colloform bands are very bright (Fig. 3A). Energy dispersive X-ray spectroscopy (EDS) indicated high concentrations (wt%-level) of In within the bands. The highly localised presence of In, combined with the low Fe content, make these samples ideal for the study of the CL response of In in sphalerite.

Results

Wavelength Dispersive Element (WDS) mapping showed much stronger signals from In, Cu and Ga in the colloform bands with a bright BSE response (Fig. 3A-D). The counts of In and Cu show a strong correlation for most of the pixels within the mapped area, while a broad correlation is observed for Ga and Cu. The local tendency toward high Cu associated with low In and Ga, observed for some pixels is, at least in part, due to the presence of submicroscopic Cu sulphides within fractures (Fig. 3B).

Results from the WDS spot analyses were complicated by the fact that the width of the In-rich bands (~1 μm) is similar to the spot size of the microprobe, and most analyses probably contain a minor component of the surrounding sphalerite. The average metal content of the bands, based on 14 measurements, are 16.65 wt% In (up to 19.59 wt%), 12.27 wt% Cu (up to 14.55 wt%), 0.98 wt% Ga (up to 1.48 wt%) and 0.17 wt% Fe (up to 1.29 wt%). Cadmium, Ag and Ge are below the detection limit of ~250 ppm, apart from one Cd analysis of 0.03 wt%. Based on these results, we interpret the CL emissions of these colloform bands are caused by the elements with high concentrations, namely In and Cu, and to a lesser degree Ga, within the sphalerite structure.

The CL spectra of the material in the In–Cu–(Ga)-enriched bands have a high-intensity peak in the visible light; the wavelength position of this peak varies between ~500 and ~600 nm. This wavelength interval was used to image the distribution of the In–Cu–(Ga)-enriched material in the hyperspectral CL maps, which show the spatial distribution of the lower-wavelength emissions (500–550 nm; Fig. 4A) and the higher-wavelength emissions (550–600 nm; Fig. 4B). The results indicate that the higherwavelength emissions are mainly restricted to the rim of the indium-bearing zone. The CL maps also show the distribution of a broad, low-intensity CL emission in the near-infrared light (between ~825–950nm). This signal delineates a colloform growth zone in the sphalerite, and potentially represents an intrinsic CL emission.

Discussion

The element mapping results from this study emphasise a strong spatial and statistical correlation between In and Cu (Fig. 2B, 2C, 2D) which confirms the well-
established coupled substitution of $2\text{Zn}^{2+} \leftrightarrow \text{Cu}^+ + \text{In}^{3+}$ (Johan, 1988; Schwarz-Schampera and Herzig, 2002; Cook et al., 2009, 2011b, 2012; Shimizu and Morishita, 2012; Murakami and Ishihara, 2013). The LA-ICP-MS studies of Cook et al. (2009) and Bonnet et al. (2014) found a broad correlation between Ga and Cu, suggesting the similar coupled substitution of $2\text{Zn}^{2+} \leftrightarrow \text{Cu}^+ + \text{Ga}^{3+}$. Our element maps show a close spatial association of Ga and Cu (Fig. 3B, 3D), which corroborates this substitution. The incorporation of
In, Cu and Ga into Mt Carlton sphalerite can thus be summarised as $2\text{Zn}^{2+} \leftrightarrow \text{Cu}^+ + (\text{In},\text{Ga})^{3+}$.

Sphalerite exhibits an extensive, but incomplete, solid solution series with roquesite (tetragonal CuInS$_2$; e.g., Jonsson et al., 2013). The In-rich sphalerite in this study has a roquesite component (also including Ga) that varies between 31 and 43 mole%. This solid solution could explain the highly elevated concentrations of In in Mt Carlton sphalerite. Synthetic CuZn$_3$In$_4$S$_8$ has cubic sphalerite structure (Parthé et al. 1969; Kissin and Owens, 1986). Natural CuZn$_3$In$_4$S$_8$, however, occasionally displays a weak anisotropism (Ohta, 1989), which suggests that significant distortion of the sphalerite structure occurs due to incorporation of In and Cu, which would explain the strong CL activation. This study has shown that hyperspectral CL mapping provides a powerful and efficient tool to study the presence and distribution of In in luminescing (i.e. Fe-poor) sphalérites. This method can be applied to samples of In mineralization from other areas. It can also be used to study other CL activator elements of scientific and/or economic interest in sphalerite.

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Early Permian epithermal events in the Chillagoe district, northeast Queensland

John Nethery, Nedex Pty Ltd.

The following is a contribution from Chillagoe-based geologist and EGRU member, John Nethery.

Introduction

The 1982 discovery of Anastasia, a pristine high sulphidation epithermal gold system related to an autobrecciated rhyolite dome and milled breccia diatreme, alerted the author to the presence of this style of mineralisation in the general Chillagoe district (Nethery, 1998). In 1992 an assessment of targets and priority ranking exercise in the immediate Chillagoe district highlighted a widespread overprinting epithermal event, late in the paragenetic sequence of the known hypothermal to mesothermal porphyry – skarn – breccia systems such as Red Dome, Mungana, Harpers, and other targets (Nethery et al., 1994; Nethery & Barr, 1998; Barr, 1998). Diatremes had been previously inferred but were thought to relate to Silurian Chillagoe Formation volcanism (Broadhurst, 1952). This brief paper focuses on images of the preserved evidence of this widespread event, with brief notes describing each location.

The sites described in the following sections, and shown on Figure 1, are mines and prospects, many of which have been surface sampled and drilled. Although considered to be related to the O’Brien’s Creek Supersuite, Anastasia is also shown (12). The Kennedy Igneous Province in the immediate Chillagoe district comprises four magmatic supersuites, defined by age and whole rock geochemical characterisation (Donchak & Bultitude, 1994). The Late Carboniferous supersuites are of I-type affinity, and span rhyolitic to andesitic compositions, whilst those of Early Permian age are of A-type affinity and are rhyolitic and granitic. The initial O’Brien’s Creek Supersuite (326-303 Ma, Mean 315Ma) comprises fractionated reduced I-type plutons and extrusive

Figure 1. Chillagoe district simplified geology with the locations of epithermal mines and prospects referred to in the text: (1) Arachnid; (2) Mungana; (3) Red Dome; (4) Griffith’s Hill; (5) Morrison’s; (6) Redcap; (7) Harpers; (8) May Queen; (9) Fluorspar; (10) Dargalong; (11) Red Hill; (12) Anastasia.
rocks, with associated tin, tungsten, molybdenum and the main gold mineralisation (Georges and Nethery, 2009). The Ootann Supersuite (306-299 Ma, Mean 300Ma) comprises fractionated reduced to oxidised I-type plutons and associated tungsten, molybdenum, bismuth, copper, lead, zinc and minor gold mineralisation. The Almaden Supersuite (310-292 Ma, Mean 300Ma) comprises fractionated reduced to oxidised I-type plutons and associated tungsten, molybdenum, bismuth, copper, lead, zinc mineralisation. The final Lags Supersuite (300-280 Ma, Mean 290Ma) comprises A-type plutons and volcanics and minor base metal sulphides and sulphosalts, uranium, fluorine, and minor gold mineralisation (Donchak & Bultitude, 1994).

An Early Permian palaeosurface is preserved over an area of at least 50km by 20km in the district. Remnants of sinters, hot springs, near surface brecciated low-sulphidation veins, silica flooded mud-pools and diatreme related hydrothermal eruption breccias are preserved along dilational fault systems related to the onset of Lags Supersuite Volcanism, as described on the schematic cross-sections (Fig. 2).

Some of these features are hosted by Almaden Supersuite granitoid plutons unroofed by erosion, indicating a large time gap between pluton emplacement and the near surface epithermal event. Preservation of this palaeosurface was due to burial soon after formation by the Featherbed Volcanics outflow ignimbrite facies. Complete erosional stripping of the ignimbrite outflow facies occurred prior to onset of deposition of the Carpentarian Basin in the late Jurassic.

Amongst the prospects and mines shown on Figure 1, three major sets of low sulphidation quartz + adularia veins are known:

Arachnid (1) is a linear 2.2 km long low-sulphidation brecciated vein with minor outcropping sinter cappings up to 30m wide. Milled hydrothermal eruption breccias (Figure 3) commonly formed bulbous diatreme vents to +100m diameter. A 250m by 30m autobrecciated, flow-banded, vesicular rhyolite plug intrudes the vein.

Dargalong (10) is a low-sulphidation vein system, hosted by Proterozoic metamorphics, which extends over a length of some 5 km and commonly comprises
massive chalcedony and fluorite, with rare colloform veining. Vein widths are generally 1m to 2m.

Fluorspar (9) is hosted by an Almaden Supersuite pluton. It comprises a swarm of mixed chalcedonic and colloform fluorite-bearing veins, with minor high grade gold, in kaolinitic pipes at faulted structural intersections. Small parcels of ore averaging up to 9 ounces per ton were recorded.

Mungana (2) has minor low-sulphidation veins at depth that have been intersected in cored drillholes, but which lack significant gold.

The most common examples of preserved Permian palaeosurface features with epithermal characteristics are partly eroded diatremes which have remnants of sinters, fumeroles, near surface brecciated low-sulphidation veins, silica flooded mud-pools and hydrothermal eruption breccias. These are focused on dilational fault systems and are elongate inverted wedge and cone shaped. The oxidised sections have been shown by mining at Red Dome (3) and Mungana (2), and by drilling elsewhere, to extend to several hundred metres depth to a transitional zone with sulphidic diatreme material.

An alteration assemblage comprising crystalline kaolinite, alunite group minerals, and vuggy residual silica, indicative of advanced argillic alteration, overprint the hypothermal-mesothermal porphyry and sulphide – skarn systems late in the Mungana alteration and mineralisation paragenesis. Coarse hydrothermal eruption breccia (Fig. 5), localised sub-horizontally bedded sulphide muds (Fig. 4), and fluidisation textures, characterise the texture of the upper sulphide mineralisation. This upper sulphide mineralisation is characterised by a mineralisation assemblage comprising sphalerite + chalcopyrite + galena + tennantite ± tetrahedrite ± chalcocite ± covellite - sulphasalt(Barr 1998).
At Red Dome (3) and adjacent Griffith's Hill (4) a hydrothermal eruption breccia wedge extends for over a kilometre and is superimposed on the porphyry and skarn deposit and retrograde chloritic breccia. At 300m depth in the northwest corner of the Red Dome pit the oxidised breccia contained a mega-clast of sulphide – sulphosalt matrix breccia, a sample of which is shown in Figure 6. This wedge of oxidised breccia was previously thought to have formed by solution (karstic) collapse. The eruption breccia features were recognised in 1992, and phreatic brecciation was proposed (Nethery, Barr and Woodbury, 1994). The most explicit evidence of the age of these breccias is the occurrence of well preserved sub-horizontal slickensides, as evidence for post-formational strike slip faulting. The Griffith's Hill eruption breccia is, in part, very fine grained and chalcedony flooded and, in part, is coarsely laminated with drop clasts (Figure 7).

The chalcedonic mud-pool at Griffith's Hill is also the site for rare, crudely layered, fragmented silica sinter clasts in silicified mud (Figure 8).

Redcap (6) is another example of a fault-aligned elongate inverted wedge shaped hydrothermal eruption breccia, partly silicified and partly chaotic non-silicified, which bulged out to a 100m diameter eroded diatreme at the intersection of the Redcap Thrust with an oblique fault (Figure 9).

The historic Morrison's mine (5) was developed within the Redcap Thrust-aligned breccia and a high proportion of the waste dump is autobrecciated clay altered flow-banded rhyolite with infill of very fine grained pyrite and marcasite (Fig. 10). Similar rhyolite intrudes eruption breccia at Arachnid, Girofla and Griffith's Hill which, by inference, are Lag's Supersuite intrusives.

The Redcap setting highlights the Late Carboniferous to Early Permian history. The Redcap Volcanics are inferred to be O'Brien's Supersuite as eutaxitic layering demonstrates a kilometre-scale asymmetric syncline, and Chillagoe Formation is thrust over the folded volcanics on the southwest dipping Redcap Thrust. Two kilometres along strike to the northwest, the thrust is “stitched” by the 300Ma Almaden Supersuite Belgravia Granodiorite (Lehrmann, 2012). In the immediate Redcap area the thrust is occupied by late hydrothermal eruption breccia and (?)Lags Supersuite rhyolite.

Harpers (8) is another area of complex geological history where a diatreme eruption breccia vent is imposed on an earlier skarn that, nearby, is intruded by a partly porphyritic leucocratic microgranite (O’Brien’s Supersuite?); adjoining the entire edifice on
Figure 9. Redcap - chaotic diatreme breccia.

Figure 10. Morrison’s - Autobrecciated argillic altered flow-banded rhyolite with a matrix of very fine pyrite and marcasite.

Figure 11. Harper’s - fumerole vents (rough and cut face) in mud-pool eruption breccia.
two sides are Almaden Supersuite coarse equigranular granodiorites. Harper’s silicified mud-pool diatreme breccia is notable for the preservation of cone-in-cone fumerolic vents (Fig. 10).

May Queen (8) is a remnant low sulphidation chalcedonic vein and siliceous banded sinter (fig. 12), located along a steep faulted boundary between an Almaden Supersuite granodiorite and Chillagoe Formation sediments. Brecciated silica sinter is also known from the opposite end of the mineral field at Arachnid.

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Figure 12. May Queen - laminated and partly slump folded silica sinter with eruptive clasts.
Hydrogeologic response to recent extreme rainfall in Townsville

Caleb Puszkiewicz, PhD Candidate
JCU Earth and Environmental Science

The Townsville region experienced record-breaking rainfall in early 2019, with 1333mm of rain falling during a two-week period; this contrasts with an average yearly rainfall total of 1143mm (Bureau of Meteorology data). These record-setting rains led to a series of tragic flooding events on the surface. Understanding the groundwater recharge response to such events is important to understanding both groundwater resources in Townsville, which has been on various levels of water restrictions since 2015, and to understanding water storage during such extreme events. As part of a plan for water independence, JCU-Townsville uses groundwater for irrigation across the campus. The water levels in two bores are monitored for sustainable management and ongoing research.

In response to the record rainfall, the groundwater level of BW2 increased 4m to 3.5 meters below the surface (mbs), and BW3 rose 1.8m to 5mbs.

Data from each bore shows a variation in response to the 602mm of rain the first 6 days (27 January-1 February), and the remaining 557mm received over the next 7 days. BW3 shows an overall steady increase of 1.8m through the period, while BW2 varies, displaying a quick rise before levelling out and declining. This variation is attributed to the additional aquifer layer that BW3 draws from, whereas BW2 only draws from one.

Caleb Puszkiewicz is an international student from America and has been studying at JCU since 2013. He became interested in groundwater during lectures in a hydrology class, taken as part of his undergraduate studies at JCU-Townsville. Completing his Bachelor of Geology in 2016 and recognizing the growing need for hydrogeologists, he moved into the Honours program and began a hydrogeological assessment of the campus’ groundwater system for the JCU Estate Directorates Office. Caleb achieved a First Class for his Honours thesis and was subsequently awarded a JCU PhD scholarship to continue his research. His PhD research has expanded outward from JCU onto the Townsville coastal plain, working with the local Council to assess the quality and sustainability of groundwater systems in the presence of climate change and assessing the variability of rainfall in the region to aid in planning. Caleb is scheduled to complete his PhD research in 2022.

The key aspect is that the level of BW2 was nearly at its maximum on 2 February, the day prior to the highest recorded daily rainfall of 245mm. Notably, this rain event does not significantly represent itself in the data, with the water level reaching 3.5mbs on 4 February and then declining over the next two days before rising slightly again; the rise in the daily averages of 7-8 February is attributed to the 110mm of rainfall on 6 February. Altogether, this indicates that the shallow aquifer system was nearly at saturation (3.6mbs) after 600mm of rainfall in 6 days. After which, heavy rainfall does not appear to significantly affect the groundwater level and suggesting that additional rainfall left the catchment as surface runoff. While saturation could be viewed as ideal from a groundwater resource perspective, this can lead to significantly higher erosion rates as rainfall accumulates and drains from the landscape as surface runoff, contributing to flooding along the Ross River.
Frederick Bird  
EGRU Honours Scholarship 2019

I would like to thank EGRU for assisting me in my honours year with this scholarship. My honours project will be focused on geochemical mineral exploration, specifically gold mineralisation in Archaean greenstone systems. This topic will require a lot of data analysis and computer work, so my scholarship will help me pay for computer equipment, software, and printing.

My journey through university up to this point has been a little different to most. I grew up in Cooktown (historical gold-mining country), and finished school in Cairns. After taking a gap-year I decided to pursue a career in law and accounting. I completed my degree and worked in private industry in taxation accounting until I decided I wanted a change and got a job in the then Department of Natural Resources and Mines (DNRM), in the Queensland Government.

I worked in a variety of roles; starting in mining tenures administration and Native Title, before moving onto the role of Mining Registrar for the Charters Towers Mining Region. It probably didn't help that much of my role at the time was driving and hiking through North Queensland, looking at mining tenure and the wonderful rocks that made up this part of the world because before I knew it, I was enrolled in a bachelor of geology here at JCU, studying part-time while I continued working.

Studies were temporarily put on hold while I worked a policy advisor for the Honourable Doctor Anthony Lynham MP, the Minister for DNRM, where I was able to be involved with all things mining and put my previous degrees and learning to work. Despite the challenges and enjoyment of the role, I was inevitably drawn back to complete my geology studies.

Now that I have completed three years and I am now in my honours year, I know I have made the right choice in returning to university. Studying geology here at JCU has not only taught me a lot about geology, it gave me practical skills that have enabled me to earn internship positions with both Evolution Mining at their Mt Rawdon gold operation, and Glencore Coal Assets at their Oaky underground coal mine. Having these experiences, and the solid foundation of geological knowledge from JCU has instilled within me the confidence in myself to pursue an honours year this year and to look forward to my career in geology.

I would like to thank JCU and EGRU for all of the support I have received over my studies.

Scholarships & Awards

Frederick Bird  
Sandvik JCU Award  
for Bachelor of Geology Degree  
Best Overall and Continuing Student 2018

Frederick receiving his Sandvik award from Len Maluga, Technical Sales Representative, Sandvik Mining and Construction

Ross Chandler  
2018 JCU University Medal  
For outstanding academic achievement in both coursework studies and research undertaken at undergraduate level
Scholarships & Awards

Joshua Spence

AusIMM Ian Morley Thesis Award 2018

In Queensland, the Ian Morley Prize is awarded for the two best theses in Geosciences and in Mining or Extractive Metallurgy. A panel of industry professionals assesses the theses submitted by UQ, QUT and JCU. The adjudicators are all senior, highly respected professionals who are active in the industry. In 2018 each of the eligible Universities nominated a thesis in Earth Sciences. All three of the Theses submitted were of a very high standard, however, in the opinion of the adjudicators, one stood out as being an exceptional piece of work.

The 2018 Prizewinner in Earth Sciences, receiving a prize of a formal Certificate and a Cheque for $750, was Joshua Spence, Bachelor of Geology (Honours), College of Science & Engineering, James Cook University, Townsville. Joshua’s Honours thesis was titled: “Geological Characteristics of the Polymetallic Nightflower Deposit, Chillagoe, Queensland, Australia.” One adjudicator commented: “A comprehensive well-structured and researched thesis. Will serve as an industry reference for future work in the region.”

New Student

Pieter Creus

Pieter is a Ph.D. candidate working with Dr Ioan Sanislav and Prof. Paul Dirks. Pieter graduated with a BSc (Hons) from the University of Stellenbosch, South Africa. He completed a M.Sc. from the University of Stellenbosch in 2011. His masters’ thesis focused on the controls of lode-gold mineralization around the Navachab Gold Mine in the Pan-African Damara Belt of Namibia. After graduation, Pieter worked for AngloGold Ashanti - Greenfields Exploration mainly in Guinea, West Africa. Before applying for a Ph.D. position at JCU, Pieter worked as a consultant specialising in structural geology and 3D modelling of complex ore bodies and country rock.

Pieter joined EGRU as a Ph.D. candidate in March 2019. His research topic is focused on developing a model for the geotechnical behaviour of the Ore Zone and the immediate wall rock at the Dugald River Zn-Pb-Ag mine near Cloncurry, Queensland. The research will involve developing an implicit 3D geological and fabric model of the mine to constrain the structural framework of the orebody and to identify geotechnical domains. Output volumes and parameters are to be input into a numerical model for stress analysis of the mine, and to develop a predictive workflow to ultimately provide a safe work environment and optimise mining.

Keanu Stinson

EGRU Honours Scholarship 2019

This year I am a part recipient of the EGRU Honours Scholarship. I completed my bachelor degree at the University of Melbourne, and when I applied for the scholarship I didn’t believe that I had much hope for actually being successful coming from a different university. When I received the email that I had been chosen, I was excited and happy to be given a kind of confirmation that I am on the right track with my studies and career.

Whenever someone would ask me what I wanted to be when I was younger, geologist was always on the list. When the time came to choose what I wanted to study at university, I went in with a single mind, and haven’t regretted anything since. I developed a love for structural and economic geology, and the scope of my project I feel fits perfectly with this. My project itself is titled “Controls on Cu-Au mineralisation on the Starra Deposits, Eastern Fold Belt, Mt Isa Inlier”. The project is an industry sponsored project to be completed on behalf of Chinova Resources, who have asked for me to investigate and map the Starra shear from an outsider perspective. Detailed studies have been undertaken at the Starra Orebodies for over 30 years now, and I have been asked to investigate the footwall alteration of the shear. A side task to be completed will be to date some of the lithologies in the area as a part of the broader JCU Mt Isa project.

I have had little practical experience for an extended period of time within the mining sector thus far, but nonetheless it hasn’t deterred me from working towards my career goals. I want to work my way into positions of leadership and be given the ability to work on my own projects, especially within the exploration sector. I want to experience and learn about a broad range of mineralisation and deposit styles both nationally and internationally, and I am excited to see this come to fruition in my future.
Tegan Beveridge (PhD)
Geochemical characterisation of bentonites combined with high-precision geochronology for correlation and provenance in the Cretaceous Strata of North America.
Supervisors: A/Prof Eric Roberts, A/Prof. Carl Spandler

Alex Brown (PhD)
Base Metal Genesis, Stratigraphy and Structural Evolution of the Central Tommy Creek Domain, Mt Isa Inlier
Supervisors: A/Prof. Carl Spandler, Prof. Tom Blenkinsop, Prof. Paul Dirks

Michael Calder (PhD)
Zonation, paragenesis and fluid evolution from the root to top of the Far Southeast Lepanto porphyry epithermal system, Mankayan district, Philippines.
Supervisors: Prof. Zhaoshan Chang, A/Prof. Carl Spandler, Dr Jeffrey Hendenquist, Dr Antonio Arribas

Robert Coleman (PhD)
Evolution of the Tommy Creek Domain and associated rare earth mineralisation.
Supervisors: A/Prof. Carl Spandler, Prof. Paul Dirks

Pieter Creus (PhD)
Structural Paragenesis of the Dugald River Zn-Pb-Ag Mine, Mount Isa Inlier
Supervisors: Dr Ioan Sanislav, Prof. Paul Dirks

Elliot Foley (PhD)
Jurassic Arc - Reconstructing the Lost World of eastern Australia through basin analysis in the Laura and Carpentaria Basins, NE QLD
Supervisors: A/Prof. Eric Roberts, Dr Espen Knutsen, A/Prof. Carl Spandler

Kelly Heilbron (PhD)
Establishing a tectonic framework for the Cretaceous break-up of eastern Gondwana.
Supervisors: Dr James Daniell, Dr Rob Holm, A/Prof. Carl Spandler, A/Prof. Eric Roberts

Leigh Lawrence (PhD)
Geochemical investigation of Oligocene-aged alkaline volcanic events in the Rukwa Rift Basin, southwestern Tanzania.
Supervisors: A/Prof. Carl Spandler, A/Prof. Eric Roberts

Xuan Truong Le (PhD)
The Tick Hill gold deposit, Mt Isa Inlier
Supervisors: Prof. Paul Dirks, Dr Ioan Sanislav, Dr Jan Martin Huizenga

Theresa Orr (PhD)
Paleoenvironmental and Paleoclimatic Analysis of Selected Cretaceous, Oligocene and Miocene Palesols from the Rukwa Rift Basin, Tanzania
Supervisors: A/Prof. Eric Roberts, Prof. Michael Bird, Dr Chris Wuster

Alexander Parker (PhD)
Fluids in the lower crust: storage and mobilization.
Supervisors: Dr Jan Martin Huizenga, Dr Ioan Sanislav

Jaime Poblete Alvarado (PhD)
Geological characteristics and origin of the Watershed W Deposit, North Queensland, Australia.
Supervisors: Prof. Zhaoshan Chang, Prof. Paul Dirks, Dr Jan Martin Huizenga

Caleb Puszkiewicz (PhD)
Analyses of JCU Groundwater-Ocean Interconnection, Extent and Potential Impacts
Supervisors: Dr Christa Placzek, Dr han She Lim, Dr Bithin Datta

Jesse Robbins (PhD)
Understanding the genesis and patterns of cave fill across the Cradle of Humankind, South Africa.
Supervisors: Prof. Paul Dirks, A/Prof. Eric Roberts

David Rubenach (MSc)
Earthquake hazard mapping and modelling to support Qld Rail’s infrastructure.
Supervisors: Dr James Daniell, Prof. Paul Dirks

Postgraduate Student Research Projects

Paul Slezk (PhD)
Evolution and origin of the Gifford Creek Carbonatite Complex: understanding rare earth element mobility in the continental crust.
Supervisor: A/Prof. Carl Spandler

Christopher Todd (PhD)
Sedimentary history of the Porcupine Gorge National Park and application of U-Pb detrital zircon geochronology for correlation of Cretaceous and Jurassic strata in northern Queensland.
Supervisor: A/Prof. Eric Roberts, A/Prof. Carl Spandler

Joshua Spence (PhD)
Magma Fertility of the Mary Kathleen Fold Belt (MKFB), Mt Isa Inlier
Supervisors: Dr Ioan Sanislav, Prof. Paul Dirks, A/Prof. Carl Spandler

Michal Wenderlich (PhD)
Seismic Stratigraphy of the Great Barrier Reef.
Supervisor: Dr James Daniell

Jelle Wiersma (PhD)
Cave sedimentation processes, geochronology, and the distribution of hominins at Rising Star Cave, Cradle of Humankind, South Africa.
Supervisors: A/Prof. Eric Roberts, Prof. Paul Dirks

Matthew Van Ryt (PhD)
Geochemical characterisation of gold mineralisation in Geita Hill, Geita Greenstone Belt, Tanzania.
Supervisors: Dr Ioan Sanislav, Dr Jan Martin Huizenga, Prof. Paul Dirks

Christopher Yule (PhD)
The structure and stratigraphy of the offshore Canning Basin.
Supervisor: Dr James Daniell
Collaborative research with Chinese colleagues

This is an introduction to the Chinese scholars working with EGRU staff. Three PhD students and one post-doctoral researcher from different Chinese universities are visiting JCU for one year to do research on various ore deposits under the supervision of Jan Huizenga, and one PhD student is working with Carl Spandler.

Dr Fuchuan Chen
Fuchuan Chen is a post-doctoral researcher in the College of Earth Sciences, China University of Geosciences in Beijing. His interests mainly include skarn Fe and Pb-Zn deposits, porphyry Cu and Mo deposits, and related intrusions. His current research at JCU focuses on the genesis of the distal skarn polymetallic deposits in Baoshan block, SW China, which is funded by the National Key Basic Research Development Program, and part of the project “Typical composite metallogenic systems and their deep drive mechanism in SW China Tethyan domain”. The purpose of this research is to reveal the origin of ore-forming materials and fluids, the ore-forming process, and the main mechanism controlling metal precipitation of those skarn deposits using C-O-S isotopes, mineral geochemistry, and fluid inclusions.

Wang Ma
Wang Ma is a PhD student from the Chinese Academy of Geological Sciences in Beijing. His PhD research project is on the mineralization of the Pb-Zn-Fe-Cu-Mo metallogenic system which is situated in the north of the Gangdese orogenic belt (Qinghai-Tibetan Plateau). The northern Gangdese Pb-Zn-Fe-Cu-Mo polymetallic belt is one of the most important metallogenic belts in the Himalaya-Tibetan continental orogenic system and characterized by skarn and porphyry deposits. This belt extends for nearly four hundred kilometers and contains more than 10 large ore deposits with high potential for development. Wang Ma’s research at JCU focuses on identifying the physico-chemical conditions of mineralization using fluid inclusions, and major and trace element geochemistry of pyrite, sphalerite, and silicate minerals.

Yong Wang
Yong Wang is a PhD student from the China University of Geosciences in Beijing. He is working on the mineralogy and alteration characteristics of the Jiaoxi quartz vein-type wolframite deposit in the western part of the Bangong-Nujiang metallogenic belt (Qinghai-Tibet Plateau) in Tibet. The main aim of this study is to determine the fluid composition and the P-T-F-O2-pH conditions of the hydrothermal system and to determine the evolution of the ore forming fluids using fluid inclusions.

Zhao Xu
Zhao Xu is a PhD student at the China University of Geosciences in Wuhan. His research is on two large orogenic gold deposits (Guoluolongwa and Walega gold deposits) situated in East Kunlun Orogen, which forms part of the Central China Orogenic System. The East Kunlun Orogen is well known for recently discovered Paleozoic to Mesozoic vein-type gold deposits including Wulonggou (> 70t Au), Guoluolongwa (> 40t Au), Balong, and the Kaihuangbei deposits. He will use fluid inclusions and sulphide trace element and isotope data to determine the physico-chemical conditions of mineralization.
**Dr Yang Liu**

Yang Liu is an academic staff member in Chemistry at JCU in Townsville. She received her PhD in Analytical Chemistry from the Chinese Academy of Sciences in 2011. She has held postdoctoral positions at Nanyang Technological University, Singapore (2011-2013) and Curtin University, Australia (2013-2016). From 2016 to 2018, Yang worked as a Chemist and Research Officer in the Mining Project Development Group at ChemCentre, which is the Western Australian State Government Institute. In March 2018, she joined JCU as a Lecturer in Chemistry. Yang’s research interests encompass Analytical Chemistry and its boundaries with redox chemistry, especially the development of new sensing strategies and devices for biological and environmental analysis. She is an expert in the exploration of advanced materials with tuneable structures and properties for applications in monitoring of ionic species based on redox reactions. So far, she has published 34 papers, which have received over 2000 citations. Two of her papers ranked in the top 1% highly cited papers in the Web of Science.

**Liping Zeng**

Liping Zeng is a visiting PhD student from the Faculty of Earth Resources, China University of Geosciences (Wuhan), China. She is visiting JCU to work with Carl Spandler. Her PhD project focuses on the genesis of iron oxide-apatite (IOA) deposits located in the Middle-Lower Yangtze River Valley Metallogenic Belt, Eastern China. There are several hypotheses for the genesis of IOA deposits, included crystallization from iron-oxide melts produced by liquid immiscibility, magmatic-hydrothermal replacement, and various combinations of magmatic and hydrothermal processes. At JCU Liping is undertaking in-situ compositional analysis of saline fluid inclusions in ore-associated minerals (magnetite, apatite, scapolite, zircon, etc.) to constrain the formation conditions of IOA deposits.

**JCU researchers in related disciplines**

Yang was a primary investigator in several mining projects funded by government and industry investigator when she worked at ChemCentre. For example, in the project funded by the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE), she developed an advanced analytical technique accredited by the National Association of Testing Authority, Australia, for the determination of trace metal/metalloids in hyper-saline mine pit lakes. In a project funded by the Mineral Research Institute of Western Australia (MRIWA), she implemented a study of nano diesel particulate matter behaviour and physico-chemical changes in underground mines of Western Australia. She also led a project funded by government for the study of total suspended particulate source apportionment in a Western Australia’s port.

Yang’s current research is focused on the development of novel sensing platforms with low operation and maintenance cost for in-situ continuous monitoring of water quality. The studies include application of the recent developed technique for sensitive detection of ammonia, which is introduced to waste stream through the use of the common blasting agent ammonium nitrate fuel oil (ANFO) in mining activities. Furthermore, new techniques for analysis of inorganic species such as nitrate, sulphate and heavy metals, which are the main pollutants in surface and groundwater resulted from mining operations, are also under investigation.
Professional Geologist Short Courses

This year EGRU offered a range of skills-based short courses suitable for early career and experienced professional geologists. The first series of courses was scheduled to run over two plus weeks in late January to mid-February. Unfortunately, nature intervened and it rained, and then it rained some more. Roads were cut and several areas of Townsville were seriously flooded. Several short courses had to be cancelled, and then rescheduled for April and May.

Regardless of the damp start, the EGRU short courses attracted over 75 industry participants, along with several Honours and Postgraduate students. The short courses that have been run to date are:

**Core Logging Techniques**  
Paul Dirks & Gerard Tripp

**Ore Textures & Breccias**  
Gavin Clarke

**QGIS for Geologists**  
Grant Boxer

**QAQC for Mineral Exploration & Beyond**  
Dennis Arne

**Integrating Geochemistry & Mineralogy**  
Dennis Arne

**The JORC Code**  
An Introduction and a Refresher  
Mark Berry

Additional courses are scheduled for July - as outlined on the following page.
Management in Mineral Exploration
22 - 26 July 2019
5 x one-day courses
Dr Nick Franey, NJF Consulting
In response to feedback from industry, Nick Franey has now developed a series of one-day courses based on the EGRU Minerals Geoscience Masters subject, to provide a flexible option for time-poor explorers who are looking to enhance their management skills.

Most of these courses are suited to both technical and non-technical professionals involved in exploration management.

Five one day modules are offered as individual courses. (course details are on the EGRU web site)

**Monday 22 July**
The Principles and Key Success Criteria of Mineral Exploration Management

**Tuesday 23 July**
Day-to-Day Management for Mineral Exploration

**Wednesday 24 July**
Data Management for Mineral Exploration and Feasibility Studies

**Thursday 25 July**
The Non-Technical Aspects of Mineral Exploration Management (e.g. HR, Administration, Logistics, HSEC)

**Friday 26 July**
Financial Aspects of Mineral Exploration and Project Evaluation (for experienced geologists)

Nick Franey has taught the Business and Financial Management subject of the JCU Masters of Mineral Geoscience (MGM) since 2016, working with Andy White until Andy retired.

Nick is an exploration geologist with a broad range of experience, from grassroots to advanced project (feasibility study) and near-mine operations. He has explored for most types of gold and base metal deposit in a variety of geological terranes, in more than 20 countries, on three continents.

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A special thank you to Dr Gerard Tripp (JCU alumnus) who travelled from Perth to Townsville, in his own time and at his own expense, to share his experience and skills with students in the Core Logging course.
EGRU Annual Report 2018

EGRU Membership 2018

Level 1
Mount Isa Mines, a Glencore Company
South 32, Cannington

Level 2
Qld Department Natural Resources, Mines & Energy

Level 3
Carpentaria Gold Pty Ltd
Chinova Resources
Map to Mine Pty Ltd
Minerals Resources Authority PNG
Newmont Asia Pacific
Terra Search Pty Ltd

Level 4
CSA Global
Gnomic Exploration Services
Laneway resources Ltd
Lantana Exploration
Sandfire Resources
Signature Gold Ltd

Level 5
11 Individual members

Staffing Update

Arrivals
Huiqing Huang

Departures
Zhaoshan Chang

Conferences/Meetings

RFG2018 Conference Vancouver Canada
Paul Dirks, Carl Spandler, Kaylene Camuti, Paul Slezak, Teimoor Nazari-Dekordi
QEC Technical Forum, Brisbane Qld
Paul Dirks, Kaylene Camuti
PDAC
Zhaoshan Chang
15IAGOD
Yanbo Cheng, Stephanie Mrozek
AusIMM Complex Ore Bodies
Paul Dirks
14th National Economic Geology Conference
Hebei GEO University, China
Paul Dirks - Keynote

Industry & Academic Liaison
SEG Publications Board Meeting, Toronto, Canada
Assoc. Prof. Zhaoshan Chang
Chinese University of Geosciences, Wuhan, China
Prof. Paul Dirks

Visiting Speakers
Prof. David Cooke
Haddon Forrester King Lecture:
Dr Ross Cayley
Geological Society of Australia Guest Speaker
Prof. Christoph Heinrich
ETH Zurich (Swiss Federal Institute of Technology)
Colin Hooper
AusIMM Sir George Fisher Lecture

EGRU Short Courses/Workshops/Seminars

JCU Campus
Ore Textures and Breccias: Recognition Techniques
Dr Gavin Clarke
Core Logging Techniques
Prof Paul Dirks
Management in Mineral Exploration
Nick Franey
A Better Understanding of Exploration Geochemistry
Carl Brahart, CSA Global
Fluid Inclusions in Economic Geology
Jan Marten Huizenga

EGRU Short Courses/Workshops

Off-campus
Mineral Systems of the Mount Isa Inlier
Prof. Paul Dirks, Assoc. Prof. Carl Spandler
JCU-CUGB Fluid Inclusion
Dr Jan Huizenga
Advanced Field Training
Prof. Paul Dirks, Dr Ioan Sanislav
Archean Tectonics
Prof. Paul Dirks

EGRU Field Trips

Mineral Systems of the Mount Isa Inlier
Minesite Rehabilitation Mt Leyshon, NE Qld – student field trip
Research Grants

Continuing Grants
Grantee: Ioan Sanislav, Jan Huizenga, Thomas Blenkinsop, post-graduate Alex Brown
Source: Mount Isa Mines
Title: Geology of the Tommy Creek Block Mount Isa Inlier
Commencing Year: 2016
Completing Year: N/A
Amount: $30,000.00

Grantee: Robert Holm
Source: JCU Rising Star
Title: Investigating the the source of Enigmatic Pliocene-Quaternary Magnetism in PNG
Commencing Year: 2016
Completing Year: N/A
Amount: $15,000.00

Grantee: Paul Dirks, post graduate research Fredrik Sahlstrom
Source: Evolution Mining
Title: Regional Mapping at the Mt Carlton High sulphidation Au-Cu-Ag Deposit
Commencing Year: 2017
Completing Year: 2018
Amount: $28,540.00

Grantee: Paul Dirks, post graduate research Truong Le
Source: DNRM
Title: Geological characteristics, genesis and ore controlling factors of the Tick Hill Au deposit, Djarra District NW QLD
Commencing Year: 2017
Completing Year: 2021
Amount: $59,000.00

Grantee: Paul Dirks, Honours research Renee Bensemann
Source: Spitfire Materials Ltd
Title: Gold mineralisation styles in the Alice River Gold Field Far Nth Qld
Commencing Year: 2017
Completing Year: 2018
Amount: $40,500.00

New Grants
Grantee: Carl Spandler, Eric Roberts, Tony Kemp, Bob Henderson
Source: Australian Research Council-Discovery Projects
Title: Jurassic Arc? Reconstructing the Lost World of Eastern Australia
Commencing Year: 2018
Completing Year: 2020
Amount: $284,390.00

Grantee: Espen Knutsen
Source: Jurassic Foundation
Title: In Search for Australia's Jurassic Dinosaurs
Commencing Year: 2018
Completing Year: 2018
Amount: $2396.00

Grantee: Hannah Hilbert-Wolf, Eric Roberts
Source: Leakey Foundation
Title: Dating Hominin Fossils in the East African Rift, Malawi
Commencing Year: 2018
Completing Year: 2019
Amount: $25,683.00

Grantee: James Daniell
Source: Fisheries Research & Development Foundation
Title: Improving Mortality Rate Estimates for Management of the Queensland Saucer Scallop Fishery district NW QLD
Commencing Year: 2018
Completing Year: 2019
Amount: $52,800.00

Grantee: Paul Dirks, Ioan Sanislav, Carl Spandler
Source: Qld Dept. of Natural Resources, Mines & Energy
Title: Magmatic History, Fertility and Metallogenesis of the Mary Kathleen Domain of the Mt Isa Inlier
Commencing Year: 2018
Completing Year: 2021
Amount: $352,500.00
Postgraduate and Honours Courses
MGM Postgraduate Courses
EA5024 Management in Mineral Exploration
Nick Franey
Honours Courses
Ore Textures and Breccias: Recognition Techniques
Gavin Clarke
Core Logging Techniques
Paul Dirks
Analytical and Optical Mineralogy
Jan Huizenga, Carl Spandler
Geology of Australia
Bob Henderson
Geology of Australia Field Work
Ioan Sanislav
Exploration Geophysics
James Daniel
Student Awards
EGRU Honours Scholarship
Eric Zurek, Ross Chandler
New PhD Students
Theresa Orr
Elliot Foley
Joshua Spence
Caleb Puszkiewicz
Completed PhD Students
Ashish Mishra
Teimoor Nazari-Dehkordi
Fredrik Sahlstrom
Stephanie Mrozek
Completed MPhil. Students
Helge Behnsen
Honours Completions
Marama Kariko
Mason Baty
Ross Chandler
Renee Bensemann
Jezzedine Bredalay
Kevin Tidy
Megan Carey
Hans Dirks
Eric Zurek

Equipment Purchases
Holman 800 Wilfley Table for mineral separation
Analyte G2 laser ablation system and a Thermo Fisher iCAP-RQ Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)
Scanning Electron Microscope -Hitachi SU5000 Field Emission SEM.

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EGRU

presents an international geological conference on

Sn-W-Critical Metals & Associated Magmatic Systems

24 - 28 June 2019

Tinaroo Lake Resort
Tinaroo, Atherton Tablelands
Queensland, Australia
EGRU Facilities/Equipment

- ICP-MS: 2 quadrupole ICP-MS units.
- LA (Laser Ablation) System (193nm)
- MC-ICP-MS (Multi-collector-Inductively Coupled Plasma-Mass Spectrometer)
- Clean Lab: class 350 clean lab
- Microprobe: Jeol JXA8200 “Superprobe” – 5WDS, EDS, BSE, SE, CL
- SEM: with cathodoluminescence imaging capacity
- XRD: Siemens D5000 Diffractometer (XRD)
- ICP-AES: Varian Liberty Series II
- SWIR spectral instruments: PIMA-SP and specTERRA
- Raman microspectrometry facility
- Fluid inclusion stage: Linkam MDS600 freezing/heating stage
- Melt inclusion / fluid inclusion stage: Linkam TS1500 heating stage
- Lapidary/Mineral Separation Laboratory Equipment available includes - RockLabs crusher and splitter, Temer and Disc mills, Franz magnetic separator, Wilfley table, and dental drill for micro-sampling. Magnetometer: GeoMetrics G 816/826A
- Photomicrography set 1: Leica DM2500P microscope + Leica DFC420 C Camera
- Photomicrography set 2: Leica DM RXP microscope + Leica DC 300 v2.0 Camera
- Magnetic susceptibility meter: Fugro GMS-2 (Serial No: 1942)
- Microscopes: Transmitted light + reflected light optical microscopes, including a Nikon Eclipse E400 POL, a Nikon Labophot2 POL, and ~45 Leica microscopes
- Gigapan robotic camera
- 3D visualisation laboratory

EGRU Analytical Capabilities

- SWIR (Short Wavelength Infra-Red) spectral analysis
- Thermometric measurements of fluid inclusions and melt inclusions
- Composition of individual fluid/melt inclusions
- Mineral major element compositions by EDS and/or WDS on a Jeol ‘Superprobe’ electron microprobe
- Cathodoluminescence (CL), Back-Scattered Electron (BSE) and Secondary Electron (SE) imaging, using SEM and electron microprobe
- Full CL wavelength spectra analysis by electron microprobe equipped with a CL spectrometer (XCLent)
- Mineral trace element composition
- Mineral elemental mapping
- Stable isotope analysis (C, O, Cu)
- Geochronology (U-Pb on zircon, titanite, monazite, xenotime)
- Radiogenic isotope analysis
- In situ Lu-Hf and Sm-Nd isotope analyses
- High pressure / temperature experiments

For information on EGRU analytical services contact A/Prof. Carl Spandler: carl.spandler@jcu.edu.au
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