In this issue:

Australia’s REE Deposits
Zircon Géochronology

ECONOMIC GEOLOGY RESEARCH CENTRE

College of Science and Engineering
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Issue: March 2017
Cover photo: Quartz-magnetite breccia near the Yangibana ironstone in the Gifford Creek Carbonatite Complex, WA (see article this issue). Photo by Paul Slezak.

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**In This Issue**

**Director’s Report**  
5

**Research**

Australian Rare Earth Element Deposits  
6
Introduction  
6
The Toongi Rare Metal (Zr, Hf, Nb, Ta, REE, Y) Deposit, NSW  
8
REE Deposits in the Mount Isa Inlier, QLD  
12
The Nolans Bore LREE Deposit, Central Australia  
18
The Wolverine HREE Deposit, Browns Range, Tanami Region, WA  
21
The Yangibana LREE Ore Deposit, WA  
24
Australian REE Deposits: General Characteristics and Tectonic Conditions of Evolution  
27
A Tool for Exploration: Applying Detrital Zircon Geochronology to Well Cuttings (or Cores) for Age Control  
30
Confocal Raman Microscopy Facility at JCU  
33

**Courses & Field Trips**

Professional Development Courses: Ore Textures, Breccias, Core Logging  
34
SEG Student Chapter Field Trip: Argentinian and Chilean Patagonia  
35

**People**

New Students  
36
EGRU Visitors  
37
Postgraduate Student Research Projects  
38

**News**

New $5m Drill Core Storage Facility for Queensland  
40

**EGRU Services**

Professional Development Training in 2017  
42
Advanced Techniques in Mining and Mineral Exploration  
42
Advanced Field Training  
42
EGRU Facilities, Equipment and Analytical Capabilities  
43
Organisation of EGRU’s largest event this year, the FUTORES II conference, is well underway. The conference has attracted a stellar line up of Australian and international speakers, including Richard Sillitoe and Dan Wood as plenary speakers. The program includes 151 abstracts for oral and poster presentations, and conference sessions cover major ore deposit type reviews and examples, tectonics and resources, and exploration technologies and concepts. Five workshops and two field trips have been organized, and a SEG Student Chapter trip to visit epithermal and porphyry deposits in Fiji is scheduled for shortly after FUTORES II. It is shaping up to be a good meeting and we thank Glencore, South32, Newmont, SEG, SGA, Aranz Geo, and the AusIMM North Qld branch for their sponsorship and support. Additional sponsors and exhibitors are welcome.

It is exciting to announce that two new staff started in the last few months: Jeffrey (Huiqing) Huang recently joined JCU as the geoscience laboratory and technical support specialist, and Espen Knutsen has a joint appointment with JCU and the Museum of Tropical Queensland in Townsville. We also welcomed four new PhD students and seven new Honours students. This brings the total number of Honours students in 2017 to 16.

JCU continues to develop its geoscience-related laboratory facilities, with the addition of a new laser Raman system (see page 33) and a new infra-red camera for the fluid inclusion stage. The infra-red camera will allow us to work on fluid inclusions in opaque minerals such as enargite, wolframite and sphalerite. Our analytical expertise also continues to develop. Jeffrey Huang has added his experience and expertise in dating apatite using U-Pb isotopes, and Yue Wang has developed procedures for processing Cu, Zn and Fe isotopes. Dr Wang has been running standards to determine analytical reproducibility. Our Cu-Zn-Fe isotope analytical facility will be online soon.

Our professional development training also continues to develop and expand. So far in 2017 we have offered five Honours short courses (also offered to industry geologists), including a new drill core structural logging course. Two Master of Mineral Geosciences subjects are scheduled in the next few months: Advanced Techniques in Mining and Exploration in April, and Advanced Field Training in June. The undergraduate 2+2 program with China University of Geosciences, Wuhan, has been signed and we are working on the implementation. In addition, the SEG Student Chapter ran an excellent field trip to epithermal and skarn deposits in Argentinian and Chilean Patagonia, and we would like to acknowledge and thank Walter Soechting for his generous help with organising the trip.

In the last few months EGRU has had the privilege of welcoming a number of local and international visitors from industry and academia. Visitors have included Dr. Alan Wilson from Antofagasta Minerals, who delivered two talks on porphyry deposits, and Erick Ramanaidou from CSIRO, who talked to us about Western Australia iron ore and nickel laterite deposits. David Champion and Karol Czarnota from Geoscience Australia, Nicky White from Cambridge University, and Pat Williams from Clump Geoscience, also visited and gave presentations in November. In March we welcomed geologists from CuDECO and Anglogold Ashanti, and also Patrick O’Connor and Nancy Stevens from Ohio University, who visited JCU colleagues and gave presentations. EGRU has also been host to several visiting scholars and PhD students from China.

EGRU staff and students appreciate the strong support from the minerals industry, JCU, and colleagues and friends worldwide. We welcome Minotaur Exploration and Laneway Resources as new EGRU members, and the expression of support from Terra Search in increasing its membership to Level 2 this year. EGRU continues to advance its research and education activities and a new web site provides profiles of research projects, staff and students (https://www.jcu.edu.au/college-of-science-and-engineering/academic-groups/geoscience). We will keep working hard to contribute to our industry and society. 
**AUSTRALIAN RARE EARTH ELEMENT DEPOSITS**

**Introduction**

Carl Spandler (EGRU - JCU)

Rare earth elements (REE; including the lanthanides, and Y) possess unique magnetic, chemical and luminescent properties, which are essential for a range of modern technology and products such as hybrid cars, fluorescent lighting, high power magnets, solar cells, rechargeable batteries, turbines, lasers, and LCD and plasma displays, to name just a few (e.g., Hoatson et al., 2011). At present, the vast majority of the world’s REE resources are supplied by China, and China’s plans to restrict REE exports have led to insecurity in global REE markets in recent years. These events have highlighted the need to ensure global resource diversity and security, and have stimulated substantial investment from the mineral resource sector toward discovery and definition of new REE resources.

Although substantial REE deposits form by heavy mineral accumulation by wind or water at the Earth’s surface (placer deposits) or by sustained weathering (laterite and ion adsorption deposits), the most economically important (an environmentally-sustainable) class of REE deposits are “hard-rock” deposits formed by magmatic or hydrothermal processes (Mariano, 1989). However, the relatively recent rise of REE as valuable commodities for our society has meant that scientific research into how and where REE ore deposits form, and ultimately is aimed at improving strategies for discovering new REE resources. Descriptions of Australia’s major REE resources are presented in Hoatson et al. (2011) and Jaireth et al. (2014), and are only briefly reviewed here. In the following articles, we present more details on deposits that EGRU is actively researching, including Toongi, Nolans Bore, Mary Kathleen-Elaine, Milo, Browns Range, and Yangibana (locations shown on accompanying map – page 7). Australia’s hard rock REE deposits include carbonatite-related deposits such as Mount Weld and Cummins Range (both occur as laterites on carbonate plugs; Lottermoser, 1990; Downes et al., 2014) and Yangibana (see Slezk, this issue), IOCG deposits, (Olympic Dam, Milo; see Coleman, this issue), hydrothermal skarn deposits (Mary Kathleen-Elaine; Coleman, this issue), deposits in peralkaline volcanic rocks (Brockmans, Toongi; see Spandler and Morris, this issue), and phosphorite deposits (Korella). Other major deposits that are not easily classified include the Nolans Bore apatite vein deposit (Spandler and Schoneveld, this issue) and the sandstone-hosted Browns Range xenotime deposits (Nazari-Dekhordi, this issue). This diversity of mineral deposit types is testament to Australia’s protracted and diverse geological evolution, and provides optimism that further REE deposits await discovery in the near future.

“**Australia is host to a large diversity of REE deposits and is uniquely placed to be one of the world’s first major REE producers outside of China.”**

**References**


The Toongi Rare Metal (Zr, Hf, Nb, Ta, REE, Y) Deposit, NSW
Carl Spandler, Caitlin Morris (EGRU - JCU)

Geological Setting and Mineralisation

The Toongi deposit (also known as the Dubbo Zirconia Project) contains over 73 Mt of mineral resources (measured and inferred) grading at 1.96 wt.% ZrO₂, 0.04 wt.% HfO₂, 0.45 wt.% Nb₂O₅, 0.03 wt.% Ta₂O₅, 0.14 wt.% Y₂O₃ and 0.75 wt.% REE₂O₃ (Alkane Resources Ltd, 2015). The deposit is entirely contained within a 0.3 km² elliptical trachyte laccolith located approximately 20 km south of Dubbo in central NSW (Fig. 1a). This mineralised laccolith is one of a number of small alkali igneous bodies (mostly trachytic plugs, flows and laccoliths that are >2 km²) that collectively form a region known as the Toongi Alkaline Magma Field (TAMF; Fig. 1b).

The TAMF lies at the boundary between the Permio-Triassic Gunnedah Basin to the north and the Late Cambrian to Carboniferous Lachlan Fold Belt to the south (Fig. 1a). The field is distinguished in regional geophysics as a zone of anomalously high gravity and relatively high Th and U (Spandler and Morris, 2016). The basement units in the region (Fig. 1b) include the Late Silurian to Devonian Cudal, Toongi and Gregra Groups of the Lachlan Fold Belt. These units are unconformably overlain by Early-Middle Triassic coarse immature sandstones within interbedded siltstones of the Napperby Formation that is part of the Gunnedah Basin. All of these sedimentary units are host to TAMF igneous bodies (Fig. 1b). Zircon fission track and bulk-rock K-Ar dating of the TAMF have returned ages of ca. 170 to 220 Ma (Meakin and Morgan, 1999), confirming a late Triassic to Early Jurassic age of magmatism. Subsequent Cenozoic geological activity in the region includes extensive basalt lava flows now preserved to the north and south of Dubbo city (Zhang and O’Reilly, 1997) and the development of thin (~4 m) discontinuous alluvium and colluvium.

Exploration drilling reveals that the intruision hostiing the Toongi deposit outcrops at the surface and extends to between ~50 and 150 m in depth. There is very little lithological variation across the intrusion, although flow banding and magmatic brecciation features can be observed in some places. The deposit largely consists of fine-grained (~0.5 mm) trachyte that may be weakly porphyritic and/or vesicular. Most of the groundmass and phenocrysts (up to 1 mm) are composed of feldspar that is either near end-member albite or pure K-feldspar in composition (Fig. 2a). The phenocrysts are commonly oscillatory zoned, with albite rim zones of variable thickness. The pyroxene is aegirine, which occurs as occasional micro-phenocrysts and as fine (<0.1 mm) acicular crystals as part of the trachytic matrix of the rock (Fig. 2a).

All of the rock mass has undergone post-magmatic hydrothermal alteration, although the degree of alteration varies considerably, even at the cm scale. The most altered samples have pervasive sericite, chlorite, and goethite alteration throughout the rock, with only the albatic cores of phenocrysts and aegirine micro-phenocrysts remaining free of alteration. Assay data and petrographic examination of samples from across the intrusion reveal a remarkable level of homogeneity in ore grade, and in the mineralogy and textural setting of the ore minerals across the deposit (Spandler and Morris, 2016). The ore minerals are always sub-mm in size and are distributed throughout the rock mass. The bulk of the ore metals are hosted in complex Na-Ca-Zr silicate phases (REE-rich eudialyte, vlasovite and catapleiite) that mainly occur as sub-spherical to irregular shaped blebs that are dispersed throughout the rock matrix (Fig. 2a). These phases comprise between 5% and 10% of the rock volume. The blebs are interstitial to feldspar and aegirine phenocrysts and, in many cases, wrap or include phenocrysts. The blebs are also characterized by an abundance of fine tabular to acicular inclusions of albite, K-feldspar and aegirine that are similar to the rock matrix. These inclusions, or clusters of inclusions, are commonly aligned, and often define spiral or circular forms (Fig. 2b) that do not parallel the trachytic flow foliation of the rock matrix. This texture henceforth will be labelled a snowball texture. The dominant Nb and Ta mineral is luehsite/natronobiotite (NaNbO₃); it is found as small (~40 µm) irregular grains that also formed in the interstices between matrix feldspar and aegirine grains (see Spandler and Morris, 2016, for more details).

A second assemblage of ore minerals is found infilling vesicles and micro-fractures in the rock. The dominant minerals of this assemblage are irregular REE fluorocarbonates and Ca-Na-Zr-silicates that are associated with sericite and chlorite alteration within the rock matrix, or form thin colloform bands lining vesicles (Fig. 2c). The other major vesicle-filling phases are quartz and a Y-REE-rich variant of milarite with the approximate formula KCa(REE,Y)Be₅Si₃O₁₄. Origin of the Iegneous Rocks

The timing of TAMF magmatism coincides with the emplacement of extensive volumes of mafic magma along a belt extending from southern Africa, across the Transantarctic Mountains, into Tasmania and southern Australia. This belt is now recognized as the Karoo-Ferrar SE Australia large igneous province that formed during continental extension related to the breakup of Pangaea in the early Jurassic (Veevers et al., 2012). Plate reconstructions to this time place the Dubbo region at the northern extent of this magmatic belt (Veevers et al., 2012), so we suggest that the alkaline magmatism of TAMF and nearby areas (e.g. Garmawilla Volcanics) represent the northern termination of the Karoo-Ferrar SE Australia large igneous province. The site of the magmatism overlies a pronounced step in lithospheric thickness from ca. 100 km in the east, to ca. 140 kms in the west, as defined from seismic tomography models (Fishwick et al., 2008; Davies and Rawlinson, 2014). The timing of formation of this lithospheric step is unknown (Fishwick et al., 2008), but most conceivable developed during the Permian extension phase that formed the Surat and Gunnedah Basins (Korsch and Totterdell, 2009), and hence would have existed during the late Jurassic. We therefore favour a model for magma generation and focusing by melting of mantle due to edge-driven convection of asthenosphere (e.g., King and Anderson, 1998; Davies and Rawlinson, 2014) along this lithospheric step. This lithospheric step was again a focus of magmatism during the Cenozoic (Zhang and O’Reilly, 1997), possibly due to mantle plume activity, or due to renewed mantle flow or asthenospheric shearch (e.g., Conrad et al., 2011).
Australian REE Deposits

A. Overview of inclusion rich blebs of Na-Zr silicate within the trachytic matrix. Note the aegirine and zoned feldspar phenocrysts. Note that these blebs rather than crystallized from it. This would imply that clusters of matrix minerals included in the snowball which crystallized the matrix minerals. In this case the minerals, but this liquid was a separate phase to that precipitated from a liquid phase that was present.

Evidence that these derivative melts can obtain very homogenous distribution throughout the intrusion. That these derivative melts can obtain very high rare metal contents come from studies of melt inclusions from peralkaline complexes (e.g., Schmitt et al., 2002), which have rare metal contents as high, or higher, than the ore grades at Toongi. Therefore, key features that distinguish the Toongi Deposit Trachyte from other IAMF trachytes, such as the peralkaline composition and extensive fractional separation, and were also critically important for producing the ore grade mineralization that is unique to the Toongi Deposit.

A distinctive feature of the Toongi ore is the globular or snowball texture of the Na-Zr-silicates (Fig. 2) and their near uniform distribution throughout the intrusion. These textures resemble liquid immiscibility textures (e.g., Philpotts, 1976; Kjarsgaard and Hamilton, 1988), and we suggest that the snowball Na-Zr-silicates precipitated from a liquid phase that was present within the rock during formation of the igneous matrix minerals, but this liquid was a separate phase to that which crystallized the matrix minerals. In this case the clusters of matrix minerals included in the snowball Na-Zr-silicates (Fig. 2b) were entrained into the liquid, rather than crystallized from it. This would imply that there were two immiscible liquids were present in the rock; one aluminosilicate melt that crystallised the feldspar and aegirine, and one Na-Zr silicate liquid that crystallised the bulk of the ore minerals of the Toongi Deposit.

Our premise for liquid immiscibility is tentative, but nevertheless, there is growing evidence that silicate liquid immiscibility can have an important role in forming rare metal mineralization in igneous environments (e.g., Markl, 2001; Sørensen et al., 2003; Petrelli et al., 2014; Vasyukova and Williams-Jones, 2014). If silicate liquid unmixing did occur during low-pressure fractional crystallisation of the Toongi Trachyte, then separation and concentration of the metal rich liquid fraction into the laccolith structure that now represents the Toongi Deposit Trachyte may have been an important process in producing the high metal grades in the Toongi deposit. ;

The secondary ore mineral assemblage of REE fluorocarbonates, Na-Zr silicates and yttrian-milasite are interpreted to have formed via post-magmatic hydrothermal alteration. Based on the composition of the ore mineral assemblage, fluids for this alteration were likely Ca- and Sr-bearing CO₂-H₂O fluids that were derived either as hydrothermal fluids exsolved from the crystallizing and cooling laccolith, or from localized devolatilisation of the Grega Group country rock due to intrusion of the Toongi Trachyte. Alteration of the cooling trachyte by these fluids led to localized dissolution of some of the primary ore minerals and redistribution into vesicles and microfractures in the rock. Nevertheless, metal redistribution during this alteration was likely limited to the sub metre (probably cm) scale.

Comparison to other REE Deposits

A large fraction of the world’s rare metal ore resources is hosted by peralkaline intrusive complexes, where mineralization is thought to result primarily from magmatic processes related to extensive fractional crystallisation of peralkaline magma (Chakhmouradian and Zaitsev, 2012). Therefore, we also propose a model that we also propose for the Toongi Deposit. The most distinct difference between Toongi and rare-metal rich plutonic complexes relates to the environment and conditions of magma emplacement. The slow cooling of rare-metal rich plutons have the potential to eradicate primary mineralization textures via subselsis re-equilibration during cooling, which complicates textural interpretation of these rocks. By contrast, Toongi was emplaced at very shallow depths, which allowed rapid cooling to form the trachytic textures of the rock. Therefore, the primary magmatic mineral compositions and mineral compositions in the Toongi Deposit are well preserved, which greatly aids in understanding ore genesis processes. In particular, the textural evidence of liquid immiscibility at Toongi would be unlikely to be preserved in slow cooled plutonic environments. In this case, the textural presentation at Toongi may also be beneficial for understanding magmatic processes of rare metal mineralization more broadly.

As far as we are aware, the only other volcanic-hosted rare metal deposit of significance is the Brockman deposit in Western Australia (Ramsden et al., 1993). The Brockman deposit is similar to Toongi in that mineralization consists of unusual Zr silicates (so-called ‘zircon gel’), Ramsden et al. (1993) isolate minerals and REE carbonates, and is hosted in peralkaline rocks of trachyte to rhyolite composition. However, Brockman differs from Toongi in that the Brockman ore is very fine grained (<20 µm) and was probably extensively remobilised by F-rich hydrothermal fluids, which now manifests as abundant fluorspar in association with the ore horizon, and extensive zones of Na depletion in the volcanic sequence (Ramsden et al., 1993).

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REE Deposits in the Mount Isa Inlier, NW Queensland
Robert Coleman (EGRU - JCU)

Introduction
The Mount Isa Inlier is a multiply deformed and highly altered Proterozoic terrane exposed in northwest Queensland. The terrane is largely covered, although its distinct geophysical characteristics can be traced laterally in a north-south direction from the Gulf of Carpentaria to the Gulf of Carpentaria. The exposed section of the inlier is characterised by a series of Paleoproterozoic to Early Mesoproterozoic stacked superbasinal sequences deposited on Paleoproterozoic (>1800 Ma) basement. The basement is comprised of a series of highly deformed metamorphic rocks that crop out west of the Pilgrim Fault system. Basin sequences are predominantly comprised of metamorphosed detrital and biochemical sedimentary packages and intercalated volcanic units that have been cut by younger intrusive units.

The onset of the Isan Orogeny (1600–1500 Ma) - the dominant compressional tectonic event recorded in the Mount Isa Inlier - resulted in the termination of most basin development. East-west and north-northeast-southwest compression orientation of the Isan Orogeny resulted in the overprinting north-south structural trend of the Mount Isa Inlier. Major north-south striking fault systems have historically divided three structurally defined belts: the Western Succession, the Kalkadoon-Leichhardt Belt, and the Eastern Succession (Figure 1). Mineral exploration in the Mount Isa Inlier has historically focused on Zn-Pb-Ag, Cu, Au, and Cu-Au systems due to abundant mineral occurrences. Some prominent deposits are the Ernest Henry Iron Oxide-Copper-Gold (IOCG), Mt Elliot SWAN IOCG, Mount Isa Cu, Mount Isa Zn-Pb-Ag, Cannington Zn-Pb-Ag, George Fisher Zn-Pb-Ag, and Dugald River Zn deposits. Much of the mineral exploration in the area has subsequently targeted similar systems. Whilst occurrences of rare earth elements (REE) have been recognised (e.g. associated with IOCGs) the inlier's potential for REE mineralisation has not been realised.

Three REE deposits that have been identified in the Eastern Succession of the Mount Isa Inlier are: Mary Kathleen, Elaine-Dorothy, and Milo. The Mary Kathleen and Elaine-Dorothy deposits are situated in the Mary Kathleen Domain whilst Milo lies to the east in the Tommy Creek Domain. The three deposits are spatially associated (within 20 km) although the Pilgrim Fault system separates the Milo deposit.

The Mary Kathleen U-REE Deposit

Local Geology
Perhaps the best known REE deposit in the Eastern Succession is the Mary Kathleen U-REE deposit. The Mary Kathleen deposit is located approximately 50 km west of Cloncurry in the Mary Kathleen Domain and is an infill- and replacement-vein style U and light REE (LREE) deposit. The deposit was open-cut mined for uranium during 1958-1963 and 1976-1982 until it became uneconomic despite mineralisation continuing at depth (Oliver et al., 1999). No market was found for the co-occurring REEs which have subsequently remained in tailings dams at the mine site.

Mineralisation at Mary Kathleen is hosted in metasomatically altered rocks of the upper Corella Formation adjacent to the Mary Kathleen Shear Zone (Figure 2). These include multiply deformed skarn, metaconglomerate, and probable gabbro that have experienced up to high-amphibolite facies metamorphism during the Isan Orogeny (Oliver et al., 1999). This deformation event also resulted in the formation of the Mary Kathleen Syncline, in which Mary Kathleen is hosted.

Ore
Ore-zones at Mary Kathleen occur as 1-5m sub-parallel bodies comprised of uraninite-allanite ± garnet veins (Oliver et al., 1999). Veins are typically 2-30 cm wide and occur as irregular patches and networks predominantly within a barren calcic skarn. U-Pb dating of uraninite from the ore defines an age of 1550 ± 15 Ma (Page, 1983) whilst whole-rock data from ore yields ages of ca. 1555 Ma and ca. 1470 Ma (Page, 1983; Maas et al., 1988).

Ore Genesis
Mineralisation at Mary Kathleen is believed to have formed via a multi-stage process. The first stage saw the contact metamorphism of Corella Formation host rocks and formation of a barren calcic skarn via the emplacement of the Burstal Granite and associated dykes ca. 1740–1730 Ma (Page 1983; Oliver et al., 1999). The second stage, responsible for U-REE mineralisation, occurred from ca. 1550 Ma during subsequent upper-amphibolite facies metamorphism (Isan Orogeny). This stage altered the stage one barren calcic skarn and produced mineralised uraninite-allanite ± garnet veins. Oliver et al. (1999) postulate that stage two ore formation resulted from metasomatic alteration of the barren calcic skarn by U-REE-bearing fluids.

The source of U-REE in the fluid is not currently known, although U-REE-bearing fluid inclusions from the deposit are reported as high salinity brines (Kwak and Abeysinghe, 1987) implying a strong involvement of highly saline fluids, a premise supported by halogen systematics of hydrothermal scapolite (Hammerli et al., 2014). The U-REE-rich fluid is therefore suggested to be derived by REE-leaching from regional LREE-enriched source rocks, interaction of magmatic-hydrothermal fluids with LREE-enriched source rocks, or an LREE-enriched fluid from an unidentified granitoid (Oliver et al., 1999). Modelling by Oliver et al. (1999) showed that the Mary Kathleen Shear may have facilitated fluid flow whilst the stage one barren skarn acted as a mechanical trap where U-REE ore was redeposited in areas of brittle deformation. Oliver et al. (1999) concluded that redeposition may have been the result of fluid mixing, host-rock redox controls, or fluid unmixing during decompression.
The Elaine-Dorothy U-REE-Cu-Au Deposit

Local Geology
Elaine-Dorothy is a little-studied Cu-Au-U-REE deposit located approximately 7km south of the Mary Kathleen U-REE deposit in the Mary Kathleen Domain (Figure 2). Elaine-Dorothy is a multi-stage deposit that shares many characteristics with the Mary Kathleen deposit. It is:
1) proximal to the Mary Kathleen Shear Zone;
2) hosted in the Corella Formation;
3) hosted in the Mary Kathleen Syncline;
4) LREE-enriched, with allanite as the main ore mineral, and
5) it has a multi-phase skarn association.

Features that distinguish Elaine-Dorothy from Mary Kathleen are its associated Cu-Au mineralisation and high F content in contrast to Mary Kathleen’s lower F content and limited Cu-Au mineralisation.

Host rocks to the Elaine-Dorothy deposit are multiply-deformed amphibolite facies marble, quartzite, meta dolerite, amphibolite, sheared biotite-rich schist, and skarn (Sha, 2012; Spandler et al., 2016). Sha (2012) identified three major skarn types the region:
1) banded skarn,
2) massive-garnet skarn, and
3) coarse-grained pyroxene-skarn.

The banded skarn grades from a feldspar-pyroxene-scapolite-bearing skarn into a fine-grained garnet-pyroxene-bearing skarn. In drill core the banded skarn is observed grading into the massive garnet-skarn (Sha, 2012).

Ore
Most high-grade mineralisation is hosted in the coarse-grained pyroxene-skarn. The ore is hosted in a zoned allanite that occurs with calcite and fluorite as an infill assemblage within the coarse-grained pyroxene (Sha, 2012).

The banded skarn hosts minor uraninite, thorite and allanite; the allanite is typically ragged in appearance and is associated with fine-grained pyroxene and high F-titanite. Ragged allanite also occurs around and intergrown with ragged Al-Fe-garnet (Sha, 2012). This allanite phase is also associated with high-F titanite. Dating in contact with allanite yielded a U-Pb age of 1540 ± 24 Ma and a weighted mean Pb-Pb age of 1529 ± 6 Ma from the biotite schist (Sha, 2012).

Ore Genesis
Formation of the Cu-Au-U-REE ore at Elaine Dorothy has been interpreted as the result of multi-stage metasomatism, skarn formation, and hydrothermal activity. The first stage, akin to Mary Kathleen, is related to the emplacement of the Burstall Granite suite ca. 1740 Ma (Page, 1983; Sha, 2012). Metasomatic fluids related to the intrusion formed the massive garnet skarn and banded skarn types and associated uraninite and thorite. The subsequent influx of a Cl- and CO₂-bearing fluid is suggested to have leached REE and most U from the stage one skarns and causative intrusions (Sha, 2012). The low U content of Burstall Granite suite whole-rock data supports this theory.

Primary REE-mineralisation is interpreted to have formed after skarn formation via the interaction of F-rich magmatic-fluids from an unidentified A-type intrusion with host rocks (Sha, 2012).

Amphibole-biotite alteration occurs after primary REE-mineralisation. This assemblage is interpreted to represent decreasing temperature in an idealised skarn system. Sha (2012) also suggests that the similar ages of titanite (ca. 1530 Ma) and biotite from the foliated amphibole-biotite assemblage (ca. 1530 Ma) may indicate rapid cooling following titanite formation.

Late-stage sulphide mineralisation is the primary Cu-mineralisation event. Pyrrhotite, pyrite, and chalcopyrite replace calcite and are associated with the dissolution of andradite. This mineralisation assemblage is mainly hosted within the coarse-grained pyroxene-skarn. Sha (2012) interpreted the Cu-bearing fluid to be reducing and S-rich, due to the presence of pyrrhotite, dissolution of andradite, and coincident equilibrium with pyroxene. The bulk of the Cu-mineralisation occurs below the biotite-rich schist, which indicates that the schist may have controlled mineralising fluids and acted as an impermeable trap to mineralisation (Sha, 2012).

Sha’s (2012) interpretation is supported by scapolite trace-element analysis conducted by Hammerli et al. (2014). Scapolite from the Mary Kathleen Shear Zone near Elaine-Dorothy indicated a multi-stage growth history associated with three fluid pulses. Hammerli et al. (2014) attributed trace element compositions to “a magmatic fluid, followed by bittren brine/A-type granite REE-rich fluid, and a late magmatic fluid pulse.”

The Milo REE-Cu-Au Deposit

Local Geology
The Milo REE-Cu-Au deposit, held by GBM Resources Ltd., lies approximately 30 km to the west of Cloncurry and approximately 22 km east of the Mary Kathleen U-REE deposit. Milo is situated in the southern portion of the Tommy Creek Domain, a small triangular shaped domain, that is separated from the Mary Kathleen Domain by the regionally significant Pilgrim Fault system. Milo is a reported as a structurally controlled IOCG-style deposit with an REE-enriched halo. Milo has an inferred resource of 176 Mt at 620ppm TREEYO (total rare earth and yttrium as oxides), 96.50 t at 0.109% Cu, 126,000 oz gold at 40ppb, and 14 Mlbs U₃O₈ at 72 ppm (2012 Milo ASX Announcement).

Milo is understudied, with reports limited to public and internal company reports (GBM Resources Ltd.) and a focused study was core from the southern portion of Milo by Harvey (2014). Based on these reports Milo is hosted in a package of marble, calc-silicate, carbonaceous black shale, and chert that has been intruded by narrow mafic dykes (Harvey, 2014). The deposit is variably brecciated and bound by silicified-fenitised-sulphide E-W to NW-SE trending fault zones. Bounding faults occur at the contact between shale and calc-silicate dominated units. Of the host rocks, variable calc-silicate rocks are the most volumetrically abundant (Harvey, 2014).

Ore
There are two primary ore types recognised at Milo: REE ore and Cu-As-Au-Mo-U ore (IOCG affinity). Cu-mineralisation occurs towards the centre of the deposit whilst REE-mineralisation is hosted north and south of the Cu-mineralisation (Harvey, 2014) in the NW-SE elongated orebody.

Apatite is the primary REE ore mineral at Milo, although allanite, REE-carbonates and REE-carbonates are also REE-bearing (Harvey, 2014). Harvey’s (2014) study found that apatite-ore occurs as discontinuous apatite-rich zones in calc-silicate rock (Fig. 3a). Harvey (2014) interpreted the apatite-rich zones as vein-style mineralisation, whereas Rubenach (2011) suggested apatite may be metasomatically derived. Detailed investigation of apatite by Harvey (2014) showed that apatite is complexly zoned with Cl-REE-rich and ClF-bearing, REE-poor zones. Harvey (2014) found Cl-rich apatite typically forms the cores of apatite whereas F-rich apatite occurs in cracks and around the cores (Fig. 3b). At the deposit scale REE-carbonate is spatially associated with Cu-mineralisation and is likely the result of REE remobilisation.

Copper mineralisation is hosted in a series of breccias that form a moderate-steeply NE dipping sheet-like breccia zone. Individual breccias form branching and anastomosing lenses that merge down-dip. Host-rock composition and rheology controls the mode of brecciation and mineralisation type. Matrix, matrix-replaced and milled breccias are comprised of pyrite ± magnetite clasts in a variably mineralised and altered carbonate ± feldspar ± amphibole ± biotite ± chlorite ± hematite ± chloropyrite matrix. Primary mineralisation occurs as a fine-grained chalcopyrite-quartz-carbonate ± feldspar assemblage in stockwork vein systems. Intense pyrite alteration is characteristic of this assemblage where in some cases pyrite can comprise up to 50% of the rock. Based on reflected-light petrography, gold is interpreted to occur as the Au-Ag alloy electroly, which is observed as inclusions in pyrite.

Ore Genesis
Mineralisation at Milo formed in multiple stages, with earlier REE-apatite and later breccia-associated Cu-mineralisation. The overarching paragenetic sequence is not known due to the lack of system-scale studies conducted at Milo. Based on limited work towards the southern end of the deposit Harvey (2014) has suggested that the paragenetic sequences observed across the different phases of mineralisation were broadly correlative.

Harvey (2014) found that the earliest, pre-mineralisation alteration assemblages are comprised of titanite and amphibole. Peak metamorphism in the Tommy Creek Domain has been recorded at ca. 1575–1585 Ma (Hand and Rubatto, 2002). Harvey (2014) interpreted the formation of subsequent alteration assemblages to have occurred post-peak metamorphism.

Primary REE mineralisation was interpreted to have been initiated by allanite mineralisation associated with minor amounts of uraninite and thorite (Harvey, 2014). This was followed by major apatite mineralisation with a possible calcite association. An apparent correlation between the increasing CI-content in amphibole (from the previous assemblage) and subsequent REE-rich mineralisation led Harvey (2014) to suggest that CI was the primary REE-complexing ligand. The termination of this stage is marked by the growth of a late fluoroapatite that was interpreted to have altered early CI-rich apatite and formed CI-Fapatite in apatite fractures and as growth rims (Fig. 3b; Harvey, 2014).

Geochemical constraints on mineralisation are limited, and dating efforts have been hampered by the complexities in ore mineral associations. Nevertheless, in situ and bulk isochemical analysis of co-genetic allanite and REE-poor, F-rich apatite (see Fig. 3b), that replaces primary REE-rich apatite has provided an isochron age of ca. 1540 Ma (Figs. 3c). This age therefore represents a minimum age of primary REE mineralisation.
These assemblages were subsequently altered by separate pyrite, plagioclase and quartz, and chlorite assemblages (Harvey, 2014) although interpretations are limited.

The second mineralising event is interpreted to have occurred post-chlorite alteration which deposited early calcite and pyrite, followed by magnetite and chalcopyrite and late pink calcite-quartz veining (Harvey, 2014). Carbon-oxygen isotope data suggest calcite was precipitated from a mixed magmatic-meteoric fluid (Harvey, 2014). Based on isotopic data and barite-fluorite assemblage associated with C-mineralisation Harvey (2014) suggested that this event was the result of fluid mixing between F-rich and Ba-rich fluid. This is due to the limited solubility of Ba and F in the same fluid (Williams et al., 2015). Like the conclusion made by Sha (2012) at Elaine-Dorothy, Harvey (2014) speculated that an undiscovered A-type granite may be the source of the F-rich fluid and that the Ba may have been leached from the Corella Formation. The final stages observed by Harvey (2014) are a late biotite-rich vein assemblage and pyrite replacement of calcite although no relative timing relationships are known.

Harvey (2014) performed additional trace element analyses on amphibole, biotite, and titanite. Based on the results Harvey (2014) suggests that the southern and central areas of the deposit were subjected to different geochemical conditions. Mineral chemistry and redox associations suggests the evolution of the mineralising system at Milo is multi-stage and complex (Harvey, 2014) and requires further investigation to better understand the processes involved in ore genesis.

**Summary**

Exploration for REE in the Mount Isa Inlier is still in its infancy although the few deposits that have been found offer insights into the mechanisms that control and focus REE mineralisation and associated Cu mineralisation. It is evident that there are similarities between Mary Kathleen, Elaine-Dorothy, and Milo as well as some overlap with IOCG-like mineralisation styles. These deposits share a strong structural component, particularly in relation to shearing (e.g. Mary Kathleen Shear Zone) and faulting capable of concentrating fluid flow. They also share a multi-stage development involving regional and localised alteration events with a possible input from an A-type granitic fluid. The involvement of the Corella Formation is also of interest and it is a potential source of halogens for REE transport (Hammeri et al., 2014), and is a characteristic shared between Mary Kathleen and Elaine-Dorothy. Milo is also suspected to be partially hosted in Corella Formation age calc-silicate rocks although preliminary dating is inconclusive.

The relatively close proximity of the deposits and the occurrence of mineralisation across a major regional fault suggests that similar styles of REE-mineralisation could occur both within the Mary Kathleen Domain and within the broader Cloncurry region. Based on observations from known deposits in the Mount Isa Inlier favourable conditions are likely areas of concentrated fluid flow. Ca-rich rocks (Corella Formation-aged) and contrasting redox conditions also seem to be important parameters for ore formation. Only future exploration and discoveries will reveal the extent of REE mineralisation in the Mount Isa Inlier.

**References**


The Nolans Bore LREE Deposit, Central Australia

Carl Spandler, Louise Schoneveld (EGRU - JCU)

Geological Setting

Nolans Bore is located in the >70 km long, northwest-trending Reynolds Range that occupies a small section of the Aileron Province of Central Australia (Fig. 1). The region has a complex geological history spanning the Paleo-Mesoproterozoic and Paleozoic eras with major orogenic/deformation episodes at around 1.8 Ga (the Stafford Event), 1.78 Ga (Yamba Event), ~1.7 Ga (Strangways Orogeny), 1.6 to 1.52 Ga (Chequings Orogeny), 1.5 to 1.4 Ga (Redbank shear zone), and finally the 450 to 300 Ma Alice Spring Orogeny (Roberts and Houseman, 2001; Claoué-Long et al., 2008).

The Nolans Bore deposit, held by Arafura Resources Ltd, is located 135 km northwest of Alice Springs, and is a stockwork vein-style light REE deposit containing 56 Mt of identified mineral resource at 2.6% rare earth oxides (Huston et al., 2016). The deposit is poorly exposed as it is covered by up to four metres of alluvium, so geological characterisation of the deposit has been defined almost solely from logging and analysis of drillcore recovered from extensive drilling programs. The host rocks to the deposit are the Boothby granitic gneisses and metasediments of the Landers Group, both of which have experienced granulite-grade metamorphism during the Strangways Orogeny (~1.7 Ga). The identified mineral resource covers an area of 1.5 km by 1.2 km from the surface (Fig. 1) down to at least 220 m vertical depth, with the full extent of the deposit yet to be defined. The REs are hosted in four ore types:

1. massive fluorapatite veins (Fig. 2a);
2. high grade cheralite-bearing, apatite-poor kaolinized zones;
3. apatite-allanite-epidote zones hosted in brecciated calc-silicate rocks (Fig. 2b); and
4. low grade stockwork zones.

The deposit is divided into three areas: the north zone, the central zone and the south-east zone. The north and south-east ore zones are primarily ore type 1, while the central zone is largely made up of ore type 3.

Ore Zones

Most of the REE mineralisation found in the north and southeast zones occurs as steeply north dipping, northeast trending fluorapatite veins with 4-6% rare earth oxides (Huston et al., 2016). These veins are dominated by coarse pale-yellow apatite grains with subordinate quartz, allanite, calcite and REE-rich carbonates, and are surrounded by relatively thin (< 1 metre) alteration selvages consisting of clinopyroxene and amphibole, with or without garnet, K-feldspar, quartz and calcite (Fig. 2a).

The central zone is distinguished from the other zones by the distinct north-south trend of the ore lens, the highly sheared and brecciated nature (Fig. 2b) and relatively high allanite content of the ore, and the broad quartz + epidote ± amphibole alteration envelope. Ore mineralogy and textures is much more variable in this zone, although RREE grades overall are similar to the north and south-east zones. Schoneveld et al. (2015) identified four main types of brecciated fluorapatite-bearing ore in this zone, labelled BX1 to BX4. These breccia types vary in their mineralogy, texture and composition from BX1 breccia that is fluorapatite crackle breccia with >10% calcite+apatite infill, to BX4 breccia (Fig 2b, 3b), which is an angular rubble breccia with 50-70% matrix, and multiple clasts of other breccia types, altered wallrock, and minerals (pyroxene, epidote, amphibole, fluorite).

The main ore mineral of the deposit is fluorapatite, which contains up to 5 wt.% RREE. Recrystallised fluorapatite in some of the ore breccias has lower RREE contents, but is crowded with micrometre-sized inclusions of allanite, REE-silicates, REE fluorocarbonates and/or monazite (Fig. 3). These inclusion phases, along with RREE-rich epidote may also be important components of the breccia matrix (Fig 3B), and hence are important ore minerals in the central zone (Schoneveld et al., 2015). The ore has relatively low U contents, but elevated Th, which manifests as thorianite, thorite, and Th-rich monazite.

Origin and Evolution of the Mineralisation

The unique mineralisation style of Nolans Bore, both locally and globally, and lack of regional scale alteration related to mineralisation, present a significant challenge to understanding the origin and evolution of this ore system. On the basis of radiometric dating of early-formed allanite, Huston et al. (2016) place the timing of primary ore formation to between 1.55 and 1.52 Ga, which is similar to the age of pegmatites of the Boothby Orthogneiss, and marks the termination of the Chequings Orogeny. Huston et al. (2016) suggest that the primary fluorapatite veins form at ~400 °C from halogen- and phosphate-rich alkali fluids that originated from mantle-derived alkaline magmatism. Based on experimental work, Annenbürg (current PhD, ANU) provides evidence that the deposit may represent mineral precipitates (i.e. cumulates) from evolved carbonatite magmas. In either case, the parental magma for the mineralisation or mineralising fluids may have been generated by low degree melting of the lithospheric mantle that was previously enriched by convergent margin tectonics during the Stafford and Strangways Orogensies (Huston et al., 2016).

Unfortunately, there is little evidence of mantle-derived magmatism at the time of mineralisation to further support this theory. Extensive isotopic analysis of ore and ore minerals from the northern and central core ore zones show that there has been multiple episodes of recrystallisation and reworking of the ore zones that extend to over 1 billion years after primary formation. Reworking events have been identified at ca. 1.400 Ma (Schoneveld et al., 2015; Huston et al., 2016), which may related to deformation associated with the Redbank Shear Zone, and between 450 and 300 Ma. This latter episode corresponds to the Alice Springs Orogeny, and was responsible for formation of most of the brecciation and alteration of the Central Zone (Schoneveld et al., 2015). This event is suggested to be related to exhumation of the deposit at this time (Huston et al., 2016), with brecciation and recrystallisation driven by infiltration of either magmatic, or mixed metamorphic and meteoric fluids at 450-600 °C (Schoneveld et al., 2015).

Understanding the regional geological context of the genesis of ore bodies is essential for further mineral exploration targeting. However, it is often difficult to obtain meaningful geochemical, geochronological and petrological information from the mineral assemblages that define many sulfide ore bodies. By contrast, multiply deformed and reworked REE orebodies, such as Nolans Bore, may be exceptional archives of the regional geological history, as they contain REE- and actinide-rich mineral parageneses that are excellent geochronological and geochemical recorders of geological events. The competency contrasts between the apatite-rich ore of Nolans Bore and the granulite-grade host rocks, and an elevated local geothermal gradient due to radiogenic heating (see Huston et al., 2016) would have favoured repeated brecciation of this zone during regional-scale deformation events.

We expect that other REE orebodies may also have experienced multiple episodes of ore recrystallisation, which may be used to help unravel the origin and history of these ore systems and their geological setting.

References
**The Wolverine HREE Deposit, Browns Range, Tanami Region, Western Australia**

Teimoor Nazari-Dehkordi (EGRU - JCU)

**Introduction**

A recently-identified and very promising style of rare earth element (REE) mineralisation is hosted by the Browns Range Metamorphics (BRM) located at the northwest of the Tanami Region, North Australian Craton. This sediment-hosted vein mineralisation occurs as several separate deposits, with Wolverine being the largest (Fig. 1), all of which are characterised by xenotime ((Y,HREE)PO₄) and minor florencite (LREEAl₃(PO₄)₂(OH)₆) mineralisation emplaced alongside steeply dipping faults entirely within Archean meta-sandstones. The total mineral resource for the Wolverine deposit is now estimated at 4.97 Mt @ 0.86% total rare earth oxide (TREO), comprising 38.27 tonnes contained TREO, using a cut-off grade of 0.15% TREO (Northern Minerals, 2014).

**Regional Geology**

The HREE deposits and hosting BRM lie on the western side of the Browns Range Dome, in the northwest of the Tanami Region (Fig. 1a). Stratigraphically, the Tanami Region comprises basal deformed and metamorphosed Archean metasedimentary rocks unconformably overlain by Paleoproterozoic sedimentary and volcanic rocks, all of which have been intruded by extensive granitic plutons. All of these units are unconformably overlain by non-metamorphosed / deformed Mesoproterozoic sedimentary rocks (Figs. 1b-c; Crispe et al., 2007).

The BRM are mainly composed of white- to cream-colored metasandstones with reddish interlayers due to fine hematite staining. The metasandstones are mainly coarse-grained (>1.5 mm grains) with intermittent fine-grained intervals (usually <0.5 mm grains) and local conglomerate layers, and occasionally contain calc-silicate rocks and banded iron formations. The metasediments experienced regional metamorphic conditions mostly of greenschist facies, but locally up to amphibolite grade. This sequence has been intruded by mafic-ultramafic to granitic intrusions (Fig. 1a), and is unconformably overlain by the Gardiner Sandstone to the west.

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**Figure 1**: Simplified geological maps of the Browns Range Metamorphics (a) and the Tanami Region (b), as well as a brief stratigraphy of the Tanami Region (c). Map (a) is located in the north-west of map (b).
Australian REE Deposits

Uranium-Pb dating of detrital zircons from several samples of the BRM yielded a tightly-defined detrital age of ~3.1 Ga, indicating the presence (or former presence) of Mesoarchean crystalline basement in the North Australian Craton (Nazari-Dehkordi et al., 2016). We have also conducted Hf isotope analyses on the ~3.1 Ga detrital zircons, which mostly produced relatively radiogenic εHf value (mean = ~+0.9). This in turn suggests derivation of the Browns Range Metamorphics from a granitic source of juvenile origin. No zircons of this age occur in the overlying Gardiner Sandstone, indicating that the Archean basement and BRM were not exposed, or were not sampled during deposition of the Gardiner Sandstone.

The HREE Mineralisation

The Wolverine HREE deposit is essentially characterised by a very simple ore mineralogy, containing two phosphate minerals: xenotime and florencite, of which the former is by far the dominant. Cook et al. (2013) reports that xenotime hosted by the BRM is more enriched by 3-7% total REE than other occurrences in the world. The mineralisation occurs in hydrothermal lodes within the BRM. Steeply dipping mineralisation is usually associated with silification and hematitic alteration at major fault junctions, and is hosted within breccias. High grade, low tonnage lodes with large (>10m long and 1m wide) veins are usually associated with chaotic (Fig. 2a) and mosaic (Fig. 2b) breccias, whereas low grade, probably higher tonnage xenotime-quartz veins are mainly hosted within crackle breccias (Fig. 2c). Mineralisation is also associated with sericite alteration, which replaces K-feldspar in the sandstones. SHRIMP U-Pb dating of xenotime (Morin-Ka et al., 2016) and LA-ICP-MS xenotime dating at JCU returned mineralisation ages of between 1.62 and 1.65 Ga. However, detailed geochronological work is ongoing, as xenotime and florencite occur in a number of morphological types and may have formed/recrystallised during multiple hydrothermal phases. Collectively, the chaotic and mosaic breccias define an early phase of mineralisation, characterised by massive accumulation of anhedral (Fig. 3a) or occasionally blade-like (Fig. 3b) fine- to coarse-grained (2 µm to 200 µm) xenotime. Florencite tends to appear as mostly small cubic-like grains individuals or clusters (Fig. 3c), and displays a complicated petrographical relationship suggesting both coeval (Fig. 3d) and post-xenotime crystallisation (Fig. 3e). The vein-type mineralisation hosted within the crackle breccias contains anhedral to euhedral medium- to very coarse-grained xenotime of up to 1000 µm in size, commonly associated with hydrothermal quartz (Fig. 3f), which is partially replaced by florencite.

Conclusions

1. The Wolverine HREE mineralisation occurs alongside major faults hosted by the Mesoarchean Browns Range Metamorphics, which primarily are metasandstones derived from a ~3.1 Ga source of juvenile origin.

2. The HREE mineralisation is mainly accommodated within xenotime, deposition of which occurred during at least two generations of hydrothermal activity, defined by early fine-grained hosted within chaotic and mosaic breccias and late coarse-grained quartz-xenotime veins of crackle breccias.

3. Work is ongoing to understand the origin and evolution of this unique mineralisation style. Results to date indicate that there is no significant magmatism associated with mineralisation, rather (based on geochemical and isotopic data) the HREE seem to be sourced from leaching of the BRM and then deposited via xenotime precipitation from hydrothermal fluids in fault intersections.

References


Fig. 2: Breccias hosting Wolverine HREE mineralisation:
(a) chaotic breccia, (b) mosaic breccia, (c) crackle breccia.

Fig. 3: Backscattered electron images of the Wolverine ore minerals hosted within the chaotic and mosaic (a-e) and crackle breccias (f):
(a) fine-grained anhedral xenotime and florencite
(b) blade-like xenotime
(c) fine-grained cubic-shaped florencite
(d) straight contact between xenotime with florencite suggesting coeval crystallisation
(e) florencite replacing fine-grained xenotime
(f) coarse-grained quartz-xenotime vein
The Yangibana LREE Ore Deposit, Western Australia

Geologic Setting

The Yangibana Project is a monazite-bearing, LREE deposit found in "ironstones" associated with carbonatites and phoscorites in Gascoyne region of Western Australia. The deposit contains a JORC resource of 13.4 million tonnes of ore at 1.18% TREO (Hastings Technology Metals Limited, 2017). The Yangibana LREE deposit is hosted in the Gifford Creek Carbonatite Complex (GCCC). The GCCC is located along the eastern margin of the Mamarang Zone within the Gascoyne Province. The complex is predominantly composed of granitic intrusions belonging to the Durlacher Supersuite (1680-1620 Ma) as well as pelitic schists, arkosic schists, gneisses, and migmatites belonging to the older Pooranoo Metamorphic suite (1780-1680 Ma) (Pearson, 1996; Pearson et al., 1996; Sheppard et al., 2005; 2010a; 2010b). Furthermore, the GCCC is unconformably overlain by the Edmund Group sediments (1680-1610 Ma) of the Ashburton Basin and cross-cut by carbonatite dykes, called the Lyons River Sills as well as the Yangibana "Ironstones" (1380-950 Ma) (Martin et al., 2005; 2008; Slezak and Spandler, 2016; Zi et al., 2016). The GCCC is bounded in the south by the Lyons River Fault, which strikes NW-SE. The Lyons River fault is a deep crustal lineament that has been traced to the Mohorovicic discontinuity using seismic reflection surveys. The Lyons River Fault is interpreted to be the suture between the Glenburgh Terrane of the Gascoyne Province and the Bandee Seismic Province of the southern Pilbara Craton (Johnson et al., 2013).

Yangibana Ironstones, Carbonatites, and Phoscorites

The main ore mineral at Yangibana is (Ce, Nd) monazite. It is found in the "ironstone" dykes, which are composed mainly of quartz, hematite, and goethite (Fig. 2A). The "ironstones" appear to be the weathered remnants of dolomite and ferroan dolomite, aegirine, riebeckite, macro-crystalline ferrocarbonatites found at depth near the Lyons River fault (Fig. 1). The phoscorites are typically composed of biotite (phlogopite-annite), magnetite, monazite, and apatite with minor potassium feldspar (Fig. 3A). These dykes are light blue to pale green depending on the amount of riebeckite and aegirine present (Fig. 2B).

The macro-crystalline ferrocarbonatites are associated with the ore-bearing ironstones found at Yangibana North and Yangibana West (Fig. 1). They are composed of macro-crystalline ankerite with subordinate calcite. Small inclusions and veins of silicate and phosphate minerals are found within the carbonates. The inclusions are comprised predominantly of quartz, biotite (phlogopite-annite), magnetite, monazite, and apatite with minor potassium feldspar (Fig. 3A). Phoscorites have also been found associated with the ore-bearing ironstones and carbonatites along the central trend (Yangibana North, Yangibana West, Hook, Bald Hill) as well as in the eastern areas of the GCCC (Auer North, Mosander, Leceq, Demarcay and Fraser's; see Fig. 1)).

Age and Origin of the Yangibana LREE Deposit

Monazites found in the phoscorites and carbonatites from Yangibana North, Yangibana West, and Léon’s Ear were dated using U-Pb and Sm-Nd isochron methods. A range of Proterozoic ages (1262 to 986 Ma) were found. Uranium-Pb SHRIMP analyses conducted by Zi et al. (2016) on monazites found in the Lyons River sills revealed a similar range of ages (1380 to 950 Ma). These age ranges are coincident with two major orogenic events in the Gascoyne Province: 1) the Matherbukin Tectonic Event (1385–1200 Ma) and; 2) the Edmundian Orogeny (1030–955 Ma; Martin and Thorne, 2004; Sheppard et al., 2010b; Johnson, 2013). The Lyons River Fault may have acted as a fluid conduit from the mantle during these tectonic events, contributing to the emplacement and hydrothermal alteration the carbonatites and phoscorites over several hundred million years.

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Australian REE Ore Deposits: General Characteristics and Tectonic Conditions of Evolution
Carl Spandler (EGRU - JCU)

General Characteristics
From the articles presented in this issue of the EGRU Newsletter, we hope the reader finds an appreciation for the diversity of Australia’s hard rock REE ore deposits. They are widely dispersed across the continent and are hosted in rocks of Archean to Mesozoic age, although a high proportion of deposits (Yangibana, Browns Range, Mt Isa, Nolans Bore) are of Mesoproterozoic age. The mineralisation styles and geological settings are very diverse, ranging from magmatic deposits (e.g., Toongi), to magmatic/hydrothermal deposits where halogen-bearing fluids played a crucial role in mineralisation (Nolans Bore, Mary Kathleen/Elaine) to deposits that appears to have no direct link to magmatism whatsoever (Browns Range). Collectively, Australian REE deposits also show a much greater inventory of ore minerals compared to other places in the world; important ore minerals here include fluor- and chlorapatite, monazite, xenotime, florencite and other REE-Al-phosphates, allanite, endiolite and other Zr silicates, and a range of REE-bearing carbonates.

This complex geology, coupled with the remote locations of most deposits, presents challenges for ore processing and economic viability, but also provides optimism that there may be many other REE orebodies within the Australian crust awaiting discovery. Especially promising is the occurrence of some mineralisation styles over very large areas. For example, the newly recognised quartz-xenotime vein mineralisation at Yangibana (extending over ~300 km²) which respectively are 100 km and 200 kms distant from the mineralisation at Browns Range (Nazari-Dekhordi, this issue). Collectively, Australian REE deposits also show a much greater inventory of ore minerals compared to other places in the world; important ore minerals here include fluor- and chlorapatite, monazite, xenotime, florencite and other REE-Al-phosphates, allanite, endiolite and other Zr silicates, and a range of REE-bearing carbonates.

Tectonic Evolution
Despite the variety of REE deposit styles in Australia, there are similarities in their broad geological setting that allow assessment of the tectonic conditions that are favourable for REE ore formation. There are four common geological aspects worthy of discussion here:

1. All of the deposits examined here are hosted in orogenic/mobile belts that had undergone extensive and repeated episodes of magmatism and orogenesis prior to the REE mineralisation (see Table 1). These orogenic episodes are expected to have led to mantle lithosphere fertilisation (enrichment in incompatible elements and volatiles) due to subduction-related metasomatism and magmatism (Fig. 1, stage 1). In most cases, there is a time gap of between 50 and >500 million years between this orogenic activity and the timing of REE mineralisation (Table 1).

2. Most deposits are related (directly or indirectly) with mantle-derived alkali magmatism. Low–degree melting of the re-fertilised mantle lithosphere via hot asthenosphere upwelling or flow due to extensional tectonics (Fig. 1, stage 2) and/or plume activity generates alkaline magma (carbonatites, alkali basalt, etc.) that may be volatile rich. These magmas are effective REE transport agents.

3. Most of the deposits are found in close proximity to major lithosphere-scale faults (Table 1). Activation or reactivation of such faults during tectonism can enhance/trigger mantle melting, and provides conduits to transport alkaline magmas towards the surface and the site of REE mineralisation. Post-mineralisation tectonic activity on these fault systems may subsequently be recorded by recrystallisation of REE minerals in these settings.

4. Halogen-rich fluids/melts are implicated in REE transport and deposition. Alkaline magmas undergo crystal fractionation, and/or liquid unmixing during migration and ponding in the crust. High halogen contents in these melts can enhance their REE transport.


Figure 2. A) Ironstone outcrop at Fraser’s prospect.
B) Blue dolomitic carbonatite with riebeckite from the Lyon’s River Sills in the southern GCCC.

Figure 3. Backscattered electron images of:
A) coarse-grained ferrocarbonatite from Yangibana North with silicate-iron oxide veinlets and inclusions;
B) Phoscorite from Yangibana West.
Figure 1. Multi-stage tectonic model for REE ore formation.

Stage 1: Convergent-margin mantle fertilisation

Stage 2: Subsequent tectonic activity allows low-degree melting of enriched (fertile) lithospheric mantle to produce alkaline magmas, which then are channelled up lithospheric scale faults toward the surface. Fractionation and evolution of these magmas enroute to the surface produces REE enriched magmas and/or fluids that may form a REE orebody.

Characteristics and Evolution cont’d

Table 1. Tectonic conditions and timing of mineralisation for Australian REE deposits.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Pre-Mineralisation Lithosphere Fertilisation Event</th>
<th>Mineralisation Age</th>
<th>Associated Crustal-Scale Fault/Fault</th>
<th>Post-Mineralisation Reworking/Resetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toongi</td>
<td>&gt;500 to ~350 Ma, Lachlan Fold Belt</td>
<td>185 Ma</td>
<td>LFB-Gunnedah Basin</td>
<td>?</td>
</tr>
<tr>
<td>Nolans Bore</td>
<td>1.8 - 1.7 Ga, Stafford &amp; Strangways</td>
<td>~153 Ga</td>
<td>Redbank Shear Zone</td>
<td>~1.4 Ga, 0.9 Ga, 450-300 Ma</td>
</tr>
<tr>
<td>Browns Range</td>
<td>1.8 Ga, Tanami Event</td>
<td>1.65 - 1.62 Ga</td>
<td>?</td>
<td>1.56 Ga?</td>
</tr>
<tr>
<td>Yangibana</td>
<td>1.8 Ga, Capricorn Orogeny</td>
<td>~1.3 Ga</td>
<td>Lyons River Fault</td>
<td>~1.25 Ga, 1.0-0.9 Ga</td>
</tr>
<tr>
<td>Mary Kathleen /</td>
<td>1.6 Ga, Isa Orogeny</td>
<td>1.53 Ga</td>
<td>Mary Kathleen</td>
<td>?</td>
</tr>
<tr>
<td>Elaine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milo</td>
<td>1.5 Ga, Isa Orogeny?</td>
<td>1.65 - 1.55 Ga?</td>
<td>Cloncurry Flexure</td>
<td>1.55 Ga?</td>
</tr>
<tr>
<td>Cummins Range*</td>
<td>1.9 - 1.8 Ga, Halls Creek Orogeny</td>
<td>~1.0 Ga</td>
<td>Halls Creek Fault</td>
<td>0.9 Ga, 590 Ma</td>
</tr>
</tbody>
</table>

*Data for Cummins Range from Downes et al., 2016.

References


A Tool for Exploration: Applying Detrital Zircon Geochronology to Well Cuttings (or Cores) for Age Control

Hannah Hilbert-Wolf (JCU)

Introduction
Constraining the age of geologic units is essential for understanding stratigraphic patterns and contextualizing the Earth. With increasing technologic capabilities and decreasing usage costs in terms of time and money, dating a geologic unit has become an expected, and often critical, practice. Accurate dating and correlation of rock units is necessary for weaving together the story of Earth’s evolution, and is also important for understanding natural resource development and prospectivity, such as the generation of oil or deposition of mineralized sediments.

James Cook University’s Dr. Hannah Hilbert-Wolf, Dr. Eric Roberts, Dr. Cassy Mtelela, along with their colleagues Bob Downie (Heritage Oil Ltd.), Dr. Nancy Stevens (Ohio University), and Dr. Patrick O’Connor (Ohio University) have developed an application of detrital zircon geochronology via laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) that enables dating of well cutting (or core) samples. The results of this work were published last month (February) in the American Association of Petroleum Geologists Bulletin, in an article that describes this approach as a powerful tool for exploration (or mineral exploration to a lesser degree), particularly for constraining depositional ages from well cuttings (or cores). Our study shows that this technique, whereby the youngest zircon grains in a stratigraphic interval serve as a proxy for the age of sediment deposition, can be quite reliable even when the sample size is limited, such as samples derived from well cuttings. We believe that this new application of LA-ICP-MS detrital zircon geochronology to well cuttings (or core samples) will be useful for researchers and industry professionals to better approach the often difficult task of dating small samples of subsurface sediments of different compositions via a low-cost, efficient, and accurate technique: U-Pb LA-ICP-MS detrital zircon geochronology.

Conclusion
While the application of U-Pb detrital zircon geochronology to studying clastic sedimentary strata has become a routine tool in geologic investigations focused on tectonics and provenance, it is surprising that it has not yet become a standard tool in hydrocarbon exploration (or mineral exploration to a lesser degree), particularly for constraining depositional ages from well cuttings (or cores).

Stevens (Ohio University) have developed an application of detrital zircon geochronology to help date a sedimentary rock unit based on dating a random suite of detrital zircons (traditionally 60-100+ zircon grains) via U-Pb LA-ICP-MS geochronology and assuming that the youngest grain population is the maximum depositional age of that sampled unit or interval. However, Cawood et al. (2012) noted that basin types in close proximity to active volcanic centers, such as forearc and backarc basins, are the most likely to contain young zircon grains. It is also expected that a large sediment sample size (>1-3 kg) is best for ensuring complete documentation of all detrital zircon age populations in a sample. However, as we have demonstrated in this study, other basin types (i.e., rifts) and small sample sizes can still yield age constraining zircons, critical for refining the depositional age of sedimentary units. This radiometric approach to dating and correlating wells can in some cases be more robust than biom stratigraphy (especially in continental settings), and is an inexpensive, relatively quick way to establish age control, particularly of subsurface units, within prospective basins.

Case Study – Rukwa Rift Basin, Tanzania

We demonstrated the potential of this dating approach via a case study through hydrocarbon prospective Miocene-recent volcaniclastic sediments in the Rukwa Rift Basin of the East African Rift System in Tanzania. Detrital zircon geochronology performed on well cutting samples from the Galula-1 exploration well document an uphole younging trend in the youngest detrital zircon populations, suggesting maximum depositional ages for the Lake Beds succession from 6.9 – 4.6 Ma (Fig. 2), which correlate with dated tuffs from outcrop (see Hilbert-Wolf et al., 2017). These results are highly valuable, because they play an important role in resolving biot stratigraphic inconsistencies and issues associated with poor fossil yield; demonstrating for the first time that sedimentation in the basin began by 8.7 Ma, which is critical for burial and thermal history modelling and therefore for establishing the probability of a working hydrocarbon system in this portion of the rift.

References


A part of the great East African Rift Valley (overlooking the Rukwa Rift Basin) in southwestern Tanzania. 

Photo by Eric Roberts.
Applying Detrital Zircon Geochronology cont'd

Confocal Raman Microscopy Facility at JCU
Jan Marten Huizenga (JCU)

The recent installation of the Raman microspectrometry facility in the Advanced Analytical Centre will greatly enhance geology research at JCU. Raman microspectrometry is a non-destructive imaging technique and is, in particular, used in mineralogical and fluid inclusion studies. It can, for example, be used for the identification of individual mineral phases with a grain size of less than one micron. As such, Raman microspectrometry is an extremely useful tool in petrographic studies in addition to the electron microprobe, scanning electron microscope, and the laser-ablation ICP-MS. In geology, Raman spectroscopy has typically been used for the identification of mineral phases, the chemical analysis of fluid inclusions (CO₂, CH₄, N₂ etc.), quantifying graphite crystallinity, crystallographic orientation imaging, and phase composition imaging.

The new instrument (WITec Alpha 300) has been funded by the university, engineering, and EGRU. Key features in the Alpha 300 include confocal Raman imaging with high resolution and the possibility for 3D image generation and depth profiles. The Raman is supplied with a standard Zeiss transmitted/reflected microscope. Sample preparation is minimal; normal glass-covered or polished thin sections can be used.

The new Raman microspectrometry facility at JCU shown above.

Anyone who is interested in using this instrument should contact Jan Marten Huizenga (jan.huizenga@jcu.edu.au).

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From Hilbert-Wolf et al. (2017).

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Figure 2. Stratigraphically ordered display of all Neogene zircons recovered from the Galula-1 well cuttings (single grain ages are listed in white boxes). The results of four different methods for calculating maximum depositional age for each sample interval are shown, and uphole younging trends are highlighted by rectangles (red). Galula-1 well log data were provided by Heritage Rukwa Tanzania Limited.

Stratigraphic interpretations are based on Roberts et al. (2004, 2010) and all available well data sets (not all presented here).

Dashed lines through the mudlog lithology are suggested unconformities, based on three distinct detrital zircon zones:

1. up-hole zircon younging trend (zircons of Neogene age),
2. reworked Neogene zircons, and
3. no Neogene zircons.

Wavy lines (purple) represent correlated unconformities recognized in outcrop, and rows of T symbols show the correlated stratigraphic positions of tuffs from outcrop (see Figure 3 in full paper).

# zircon = number of Neogene zircon ages/total number of concordant zircon ages acquired. DT = sonic; GR = gamma ray; MSWD = mean square weighted deviation; WM = weighted mean; YC1σ (2+) = weighted mean of youngest zircon cluster of greater than or equal to two grains overlapping in age at 1σ; YC2σ (3+) = weighted mean of youngest zircon cluster of greater than or equal to three grains overlapping in age at 2σ; YSG = youngest single grain.

From Hilbert-Wolf et al. (2017).
Professional Development Course: Ore Textures, Breccias, Core Logging

This five-day course, in two modules, was offered to industry geologists in late January this year. The training course is part of the honours coursework program at JCU in 2017 and participants worked alongside current JCU honours students.

Module 1
Ore Textures and Breccias
Recognition Techniques
Course Leader: Dr Gavin Clarke

This three-day module introduced participants to the fundamentals of textural observation and interpretation in mineralized hydrothermal systems. Course delegates applied practical, simple and highly effective techniques to altered and mineralised rocks, and considered critical evaluation factors, including:
- Infill: Recognition Criteria
- Alteration: Recognition & Evaluation
- Channelways: Recognition Criteria
- Overprinting and Paragenesis: Recognition & Sequencing Criteria
- Breccia: Recognition Criteria
- Breccia: Rudimentary Classification system
- Intrusive Breccia Systems
- Tectonic Breccia Systems
- Paragenetic Core Logging

Module 2
Core Logging Techniques
Course Leader: Prof. Paul Dirks

This course module introduced participants to the basic skills and methodology required to review and log geological core. Emphasis was placed on the recognition, description and acquisition of oriented data (bedding planes, faults, fractures, shear zones), and how this data relates back to field observations. The aim of the two-day course was to familiarise participants with the key requirements of core logging, and how logs should be interpreted and integrated with geological models.

Course participants were introduced to the principles of core logging and the integration of core logs into structural sections and geological maps during short morning lectures on days one and two. The lectures were followed by substantive practical sessions that incorporated the collection of data from drill core, and the construction of cross-sections from core logs, orientation data and geological maps.

SEG Student Chapter Field Trip: Argentinian and Chilean Patagonia
Jaime Poblete (JCU SEG Student Chapter President, EGRU - JCU)

The James Cook University (JCU) SEG Student Chapter recently organized a geological field trip to the Argentinian and Chilean Patagonia from 22 November to 5 December, 2016. Eighteen people attended this trip including three PhD students from JCU and one from the University of China, two undergraduate students from JCU, ten participants from industry and our Student Chapter Academic Advisor A/Prof. Zhaoshan Chang. Participants represented nine countries: Argentina, Australia, Brazil, Chile, China, France, Peru, Portugal, and United States. The aim of this trip was to see and appreciate different geological features across Patagonia which included Au-Ag low-sulphidation epithermal and Zn-Au skarn mines and advanced projects, paleo-geothermal fields and archaeological sites.

The trip started in Esquel on November 22nd with a group dinner (Photo 2) and the following day a 25 km day hike of the Esquel Au deposit was completed. The following day, the group headed to Chile to visit the El Toqui Zn-Au skarn mine (Laguna Gold) on Friday November 25th. On Sunday November 27th the group visited the Cerro Bayo silver mine (Mandalay Resources) located 25 km to the west of the town of Chile Chico in Chile. The same day the group crossed the border back to Argentina to visit the Cerro Negro (Goldcorp, November 28th), the Cerro Moro (Yamana Gold, November 29th) and the Cerro Vanguardia (AngloGold Ashanti and Formicruz, November 30th) gold mines and advanced projects. In all of the mines we were happily received by the geologists in charge, they gave us geological presentations, we visited key outcrops and in the El Toqui mine we were able to visit the underground workings (Photo 3).

During this continental wide scale traverse, the group was able to visualize large scale geological features like the Jurassic Chon Aike volcanic large igneous province (LIP) outcrops, glacial moraine deposits along the Patagonian Cordillera from the Quaternary, regional scale fault systems (e.g. the Liquine-OQUI fault zone), among others. The Chon Aike LIP has been recognized to be associated with the early stages of the Gondwana break-up as well to be the precursor of this Au-Ag rich metallogenetic province of southern South America. In addition after November 30th the group was able to enjoy roadside geology along the famous Ruta 40 with the possibility to contemplate the Perito Moreno Glacier (El Calafate), the only advancing glacier in the area, and the Cerro Fitz Roy (El Chalten).

Finally, the JCU SEG Student Chapter would like thank the generosity of all our sponsors that contributed to make this fantastic fieldtrip happen. Thank you very much to the Australian Institute of Geoscientists (AIG), James Cook University (JCU), the Economic Geology Research Centre (EGRU), the Society of Economic Geologists (SEG), Bunnings Warehouse, Coles and Woolworths.

Photo 1. JCU SEG Student Chapter Academic Advisor A/Prof. Zhaoshan Chang explaining skarn and epithermal models to the Patagonia fieldtrip participants. Photo by Stephanie Mrozek.

Photo 2. Group picture at Dr. Walter Soechting (fieldtrip guide) home where we had the official first dinner and kick-off of the Patagonia trip on November 22nd. Photo by Stephanie Mrozek.

Continuing on with the Rukwa Rift Basin Project, Leigh's PhD under the supervision of A/Prof. Carl Spandler and A/Prof. Eric Roberts will continue to adopt a melt inclusion approach in conjunction with comprehensive mineralogy of these volcanic tuffs to better understand the magmatic processes at Rukwa during the Oligocene. An extension of this research will examine major and trace element partitioning within alkaline systems, and melt inclusions hosted within titanite, and revealed a majority of this work involved the microanalysis of modern volcanic tuffs hosted within the stratigraphy of the Rukwa Rift Basin, southwestern Tanzania. The extension and expansion of previous honours work. Now in 2017, Michal has commenced his doctorate continuing his work with his advisor Dr James Danniell. By processing, interpreting and analysing more seismic data and integrating sediment core/well data he aims to further unravel the mysteries of the Great Barrier Reef’s underlying continental shelf and adjacent slope. Stitching together resultant seismic maps to create a three dimensional model(s) of the seismic stratigraphy beneath the Great Barrier Reef, identifying and mapping geological processes and analysing sediment flux comes together to bring this still enigmatic underworld to life.

**NEW STUDENTS**

**Leigh Lawrence**
Leigh joined EGRU and graduated from James Cook University with a Bachelor of Geology (Honours) in 2016. His Honours thesis examined the Oligocene aged magmatic episodes preserved as volcanic tuffs hosted within the stratigraphy of the Rukwa Rift Basin, southwestern Tanzania. The majority of this work involved the microanalysis of melt inclusions hosted within titanite, and revealed a rich history of alkaline magmatism.

**Michal Wenderlich**
Michal graduated from James Cook University with a Bachelor of Geology honours degree in 2015. Michal’s honours project allowed him to (1) process reflection seismic data collected over the continental shelf and slope of the southern central Great Barrier Reef, (2) verify the regional applicability of the model for the evolution of the continental shelf of northeastern Australia across the central Great Barrier Reef province, and (3) resolve and map a complex interplay of geological processes occurring within sediments deposited since the opening of the Coral Sea. Now in 2017, Michal has commenced his doctorate continuing his work with his advisor Dr James Danniell. By processing, interpreting and analysing more seismic data and integrating sediment core/well data he aims to further unravel the mysteries of the Great Barrier Reef’s underlying continental shelf and adjacent slope. Stitching together resultant seismic maps to create a three dimensional model(s) of the seismic stratigraphy beneath the Great Barrier Reef, identifying and mapping geological processes and analysing sediment flux comes together to bring this still enigmatic underworld to life.

**Tegan Beveridge**
Tegan graduated from James Cook University in 2015 with a Bachelor of Geology and was awarded the Sandvik Third Year Prize. In 2016 she undertook an honours research project under the guidance of Eric Roberts and Carl Spandler. This project involved major element and isotope (La/He) geochronology to “fingerprint” devitrified volcanic ash in fossiliferous Upper Cretaceous strata in North America. In February 2017, Tegan began her PhD research as an extension and expansion of previous honours work. Along with collaborators at the Massachusetts Institute of Technology and other key researchers in North America, she plans to develop a multifaceted approach to provenance analysis of zircons. This novel method is based on geochemistry of the zircon crystals and glass (mel) inclusions found within them coupled with high precision IDTIMS geochronology. Tephra from a broader range of Upper Cretaceous fossil localities in the US and Canada will be included as well as samples from potential volcanic sources. An investigation into the co-occurrence of abundant tephra and increased fossil preservation is also planned.

**Christopher Yule**
Chris completed a bachelor of science with honours in 2016 after graduating from a BSc (Advanced) majoring in Geology in 2015. During undergraduate studies Chris participated in the student exchange program at the University of Hawaii at Hilo and has incorporated physics such as electromagnetism and nuclear physics into his degree. His honours research focused on developing a 3D model and the stratigraphic history of the Marion Plateau which makes up the Southern portion of the Great Barrier Reef. This was achieved by combining seismic, bathymetric and IODP drill core data and mapping structural and sedimentary features. Chris’ PhD project will implement acquired skills from his honours project to develop a 3D model and determine the seismic stratigraphy of the Mentelle Basin, south west Western Australia. The focus will be on optimising seismic data processing techniques and identifying and mapping potential petroleum systems. He will be working in conjunction with Geoscience Australia for this project.

**Matthew Van Ryt**
Matthew was born and grew up in Mount Isa. After first studying engineering, he was awarded his BGeol at James Cook University, and continued on to Honours. His honours thesis was focused on fluid inclusion microthermometry, studying the ultra-high temperature rocks of the Bakhuis Granulite Belt in Suriname. After completing Honours, Matthew started a MPhil in 2015 under the supervision of Ioan Sanidas, Jan Marten Huzenga and Paul Dirks. The project forms part of an ongoing JCU research effort with AngloGold Ashanti, focused on gold mineralisation in the Geita Greenstone Belt of northwestern Tanzania. In 2016 the project was expanded to a PhD. Matthew’s research involves investigating fluids and hydrothermal alteration at the Geita Hill deposit. The project aims to constrain a mineral paragenesis, fluid source, and genetic model for the deposit.

**EGRU VISITING SPEAKERS**

**Alan Wilson**
International Exploration Manager
Antofagasta Minerals

**Presentations:**
- Field evaluation of porphyry copper deposits
- Calc-alkaline vs alkalic porphyry comparisons

**Niccy White**
Cambridge University

**Presentation:**
- Measuring vertical motions caused by mantle convection

**David Champion**
Geoscience Australia

**Presentation:**
- Carboniferous-Permian felsic magmatism in Northern Queensland

**Pat Williams**
Clump Mountain Geoscience

**Presentation:**
- New geological and chronological constraints on the origin of the Prominent Hill hematitic IOCG deposit, Gawler Craton, South Australia

**Patrick O’Connor**
Ohio University

**Presentation:**
- 15 years of discovery: Cretaceous dinosaurs, crocodiles, mammals and other vertebrates from central Africa

**Nancy Stevens**
Ohio University

**Presentation:**
- Cenozoic faunal dynamics on continental Africa: A view from the Rukwa Rift Basin of Tanzania

**Erik Ramanaidou**
CSIRO

**Presentation:**
- Western Australia iron ore / Nickel laterite deposits

**STUDENT AWARDS**

**Ava Stephens**
2017 EGRU Honours Scholarship
Honours Project: The Artemis IGS deposit, Cloncurry Region, NW Qld

**Joshua Spence**
2017 EGRU Honours Scholarship
Honours Project: The Nightflower Pb-Ag vein deposit, NE Qld

**Tegan Beveridge**
2016 AIG Geoscience Honours Bursary
**Postgraduate Student Research Projects**

**Helge Behnsen (PhD)**
Magma fertility related to Au-Cu mineralization in north Queensland, Australia - evaluating the potential for linked porphyry Cu-Au (±Mo) deposits at depth.

*Supervisors: A/Prof. Carl Spandler, Prof. Paul Dirks*

**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*

**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: A/Prof. Zhaoshan Chang, A/Prof. Carl Spandler, Dr Jeffrey Hedenquist, Dr Antonio Arribas*

**George Case (PhD)**
Ore genesis and alteration paragenesis of the E1 group and Monakoff IOCG deposits, Concurry region, north-west Queensland.

*Supervisors: A/Prof. Carl Spandler, A/Prof. Zhaoshan Chang*

**Robert Coleman (PhD)**
Evolution of the Tommy Creek Domain and associated rare earth mineralisation.

*Supervisors: A/Prof. Carl Spandler, A/Prof. Zhaoshan Chang*

**Kelly Heilbron (PhD)**

*Supervisors: Dr James Daniell, Dr Rob Holm, A/Prof. Carl Spandler, A/Prof. Eric Roberts*

**Peter Illig (PhD)**
Magma related hydrothermal gold and base metal deposits in the Chillagoe district, NE Queensland, Australia: relationships, transitions and controls.

*Supervisors: A/Prof. Zhaoshan Chang, A/Prof. Carl Spandler, Dr Jeffrey Hedenquist, Dr Antonio Arribas*

**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)**
Geological setting and mineralisation characteristics of the Pac Lang Au-W deposits, Bac Kan Province, northeastern Vietnam.

*Supervisors: A/Prof. Zhaoshan Chang, Dr Jan Martin Huizenga*

**Kairan Liu (MPhil)**
Geochronology and formation conditions of the Wolfram Camp W-Mo-Bi deposit, Qld. Bif.

*Supervisors: A/Prof. Zhaoshan Chang, Dr Yanbo Cheng*

**Asish Mishra (PhD)**
Rates of Erosion and Weathering in the Tropics.

*Supervisors: Dr Christa Placzek, Prof. Michael Bird*

**Stephanie Mrozek (PhD)**
Uplift History, Intrusive Sequence, and Skarn Mineralisation at the Giant Antamina deposit, Peru.

*Supervisors: A/Prof. Zhaoshan Chang, A/Prof. Carl Spandler, Prof. Lawrence Meinert*

**Teimoor Nazari Dehkordi (PhD)**
The origin and evolution of heavy rare earth element mineralisation in the Browns Range area, Northern Australia.

*Supervisors: A/Prof. Carl Spandler, Prof. Nick Oliver, Prof. Paul Dirks*

**Michael Nugus (PhD)**
Mechanisms of mineralization in amphibolite facies, BIF-hosted gold deposits, using the example of the Golden Pig deposit, SXGB.

*Supervisors: Prof. Tom Blenkinsop, Prof. Paul Dirks*

**Prince Owusu Agymang (PhD)**
Mesozoic detrital zircon provenance of Central Africa: implications for Jurassic-Cretaceous tectonics, paleogeography and landscape evolution.

*Supervisors: A/Prof. Eric Roberts, A/Prof. Carl Spandler, Dr Rob Holm*

**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: A/Prof. Zhaoshan Chang, Prof. Paul Dirks, Dr Jan Martin Huizenga*

**Jessie Robbins (PhD)**
Understanding the genesis and patterns of cave fill across the Cradle of Humankind, South Africa.

*Supervisors: A/Prof. Paul Dirks, A/Prof. Eric Roberts*

**Behnam Sadeghi (PhD)**
Quantification of uncertainty in univariate geochemical anomalies for mineral exploration.

*Supervisors: A/Prof. John M. Carranza, Prof. Paul Dirks, Dr. Arianne Ford, Dr. Jan Marten Huizenga, Prof. Jef Caers (Stanford University)*

**Fredrik Sahlström (PhD)**
Mt Carlson high-sulphidation epithermal deposit, Queensland Australia: Geological characteristics, genesis and implications for exploration.

*Supervisors: A/Prof. Zhaoshan Chang, Prof. Paul Dirks*

**Paul Slezak (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.

*Supervisors: A/Prof. Eric Roberts, A/Prof. Carl Spandler*

**Michal Wenderlich (PhD)**
Seismic Stratigraphy of the Great Barrier Reef.

*Supervisor: Dr James Daniell*

**Jella 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 at Geita Hill, Geita Greenstone Belt, Tanzania.

*Supervisors: Dr Ioan Sanislav, Dr Jan Martin Huizenga*

**Christopher Yule (PhD)**
Seismic Stratigraphy and Petroleum Systems of the Mentelle Basin, south west Western Australia.

*Supervisor: Dr James Daniell*
Queensland’s resources exploration industry now has access to more information thanks to a $5 million expansion of the Queensland Government’s Exploration Data Centre (EDC) at Zillmere on Brisbane’s north side.

The Minister for Natural Resources and Mines, Dr Anthony Lynham, and the State Member for Nudgee, Ms Leanne Linard, officially opened the EDC expansion on Thursday the 20th of October last year.

The expansion will provide greater access and storage capacity for exploration samples from throughout Queensland, adding to the 800-plus kilometres of core samples currently stored at the facility.

The Exploration Data Centre offers the resources exploration industry a comprehensive catalogue of samples from over 11,600 drill holes collected by the Geological Survey of Queensland over the last 100 years, with the oldest being from the Mitchell town bore drilled in 1886.

This new expansion will provide storage for an estimated 500 km of additional samples, complementing the Geological Survey of Queensland’s (GSQ) HyLogger™ digital spectral scanning technology which provides the exploration industry with access to a virtual core library.

The new facility was constructed by Northbuild Constructions Queensland and built over eight months, creating more than 100 jobs for designers, engineers and contractors.

The expansion of this facility gives industry, universities, researchers and Government scientists even greater access to a reference collection of the geology of Queensland.

Exploration is a vital part of the Queensland’s resources industry and this new facility will provide industry with the tools they need to get on with the job for decades to come.

The Exploration Data Centre is open from 8am to 5pm Monday to Friday or other times by appointment.

68 Pineapple Street, Zillmere
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Facebook: Mining Qld
Twitter: @miningqld

https://www.business.qld.gov.au/industry/mining/mining-online-services

Above: New drill core storage facility with state of the art drill core racking and inventory management.

Above left to right: The Geological Survey of Queensland’s Chief Government Geologist, Tony Knight, Minister for Natural Resources and Mines, Dr Anthony Lynham, and State Member for Nudgee, Ms Leanne Linard.

Above: Drill core from locations across Queensland is stored at the EDC.

Above: The Hylogger™ - the hyperspectral logging system available for industry use at the EDC.

Above: Analysing data from the Hylogger™ at the EDC.
EGRU Professional Development Training in 2017

Advanced Techniques in Mining and Mineral Exploration
18-28 April 2017, JCU Townsville

Course Leaders
A/Prof. Zhaoshan Chang
Dr Arianne Ford
Dr Ioan Sanislav
Dale Sims
A/Prof. Carl Spandler

Course Content
Module 1:
Mineral Geochemistry and its Application in Exploration
In the past decade, with the development of laser ablation – inductively coupled Plasma – Mass Spectrometry (LA-ICP-MS) analytical methods, mineral geochemistry has been demonstrated to contain subtle primary signatures of hydrothermal mineralising systems. These signature can be used as indicators up to ~10km from orebodies, and as vectors towards orebodies. This module will cover LA-ICP-MS methodology and the application of mineral geochemistry in exploration.

Module 2:
Structural Controls of Mineralisation
This module will look at the principles behind structural controls on mineralisation through analysis of structures, geomechanical modelling, case studies and practical exercises.

Module 3:
3D Geological Modelling of Hard Rock Deposits using Leapfrog Geo
This module aims to enhance attendees’ data analysis and communication skills through hands-on training in the application of Leapfrog Geo, an industry-leading 3D modelling and communication package.

Module 4:
Modelling the Spatial Distribution of Mineral Deposits
This module will introduce the concept of fractal and multifractal analysis and their practical applications in mineral exploration and mining.

Advanced Field Training
21-28 June 2017
(excluding travel days to and from Cloncurry)
Roxmere Field Camp, Cloncurry Qld

Course Leaders
Prof. Paul Dirks
Dr Ioan Sanislav

Course Content
This intensive 8-day course is designed to provide geoscientists with essential exploration-related field skills in complexly deformed and altered rocks. Real field mapping is a dying art and this course does not encourage wandering around with a GPS making random observations. Genuine ‘form surface’ mapping of contacts, alteration zones and structures will be integrated with paragenesis, geophysical interpretation and the use of alternate knowledge-based and data-based exploration models, including an introduction to the simple and useful application of semi-quantitative prospectivity tools.

The course will include:
- Veins, breccias, shear zones: paragenesis, overprinting, mechanisms, geometry
- Advanced structural geology and structural controls
- Developing exploration strategies from field observations

Module 1:
Mary Kathleen-Style Uranium
An area of awesome exposure and outstanding geophysics forms the basis for this module. This is an ideal module for those wishing to appreciate alteration recognition in the field, basic structural geology, skarns and intense metasomatic activity, and correlation of geophysical data sets with geology in order to identify drill targets.

Module 2:
IOCG Deposits, Breccias and Crustal Fluid Flow
The Eastern Succession of the Mount Isa inlier is world renowned for its variety of IOCG deposit types. This module will examine field aspects of exploration for IOCG deposits, emphasising characterisation and mapping of breccias and fluid systems in the field.

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

EGRU Facilities/Equipment
- ICP-MS: 2 quadrupole ICP-MS units.
- LA (Laser Ablation): Geolas 200 Excimer Laser Ablation System (193nm)
- MC-ICP-MS (Multi-collector-Inductively Coupled Plasma-Mass Spectrometer):
- Clean Lab: class 350 clean lab
- Microprobe: Jeol JXA8100 “Superprobe” – 5WDS, EDS, BSE, SE, CL
- SEM: with cathodoluminescence imaging capacity: Jeol JSM5410LV
- 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 MD5600 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: GeoMetrix G-8x6/8x6A
- 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 E600 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 microscope
- Cathodoluminescence (CL), Back-Scattered Electron (BSE) and Secondary Electron (SE) imaging, using SEM and electron microscope
- Full CL wavelength spectra analysis by electron microscope equipped with a CL spectrometer (XCLent)
- Mineral trace element composition
- Mineral elemental mapping
- Stable C & O isotope analysis
- Geochronology (U-Pb on zircon, titanite, monazite, xenotime)
- Radiogenic isotope analysis
- In situ Lu-Hf and Sm-Nd isotope analyses
- High pressure / temperature experiments

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EGRU Members receive discounted registration for EGRU conferences, short courses and workshops.

Membership information is available at http://www.jcu.edu.au/egru/

Delegates attending EGRU conferences, short courses and workshops may earn Professional Development points from their professional bodies.

FUTORES II
Future Understanding of Tectonics, Ores, Resources, Environment and Sustainability
4 - 7 June 2017
Rydges Southbank
Townsville, Queensland, Australia

CONFERENCE THEMES
- David Groves Symposium: New Insights in Mineral Deposit Understanding
- New Technologies and Approaches in Mineral Exploration
- Tectonics, Basins and Resources

PLENARY SPEAKERS
- Richard Sillitoe
- Dan Wood

PRE-CONFERENCE SHORT COURSES
POST-CONFERENCE FIELD TRIPS