

Mineral Deposits Studies Group AGM 2017-18

Sallis Benney Lecture Theatre, Grand Parade,
University of Brighton 3rd to 5th January 2018



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WEDNESDAY 3RD JANUARY

17.30	ICE BREAKER RECEPTION – Sallis Benney Lecture theatre, Grand Parade, Brighton
18.15-19.00	PANEL SESSION - YEAR OF THE RESOURCE

THURSDAY 4TH JANUARY

Sallis Benney Lecture theatre, Grand Parade, Brighton

Click on the Talk title to access the abstract.

Time	Presenting Author	Title
9.00	Welcome from Prof. Tara Dean, Vice Chancellor for Research	
EXPLORATION FRONTIERS		
9.15	T. Livesey	KEYNOTE: The Cukaru Peki deposit: Discovery and steps toward development
9.45	J. Cloutier	<i>The use of hyperspectral reflectance in mineral exploration: example from the Northwest Zone of the Lemarchant VMS deposit, Newfoundland, Canada</i>
10.00	J. Williams	<i>Incorporating Geological Mapping, Geological Modelling and 3D Scanning data from The Rogerley Mine, the UK's only hand specimen mine</i>
CRITICAL METALS		
10.15	J. Wrathall	KEYNOTE: Cornish Lithium – A New Metal from an Old Mining Area
10.45	A. Martin*	<i>Magmatic and hydrothermal end member volcanogenic massive sulphide (VMS) deposits: Implications for selenium enrichment</i>
11.00	COFFEE	
11.15	S. Howarth*	<i>Seamount-scale variability of E-tech elements in ferromanganese crusts: Tropic Seamount, NE Atlantic</i>
11.30	P. Josso	<i>Spatial and temporal variability of critical metals in ferromanganese crusts from Tropic Seamount, north-east Atlantic</i>
11.45	A. Finch	<i>Mid-Proterozoic Crustal Recycling and Rare Element Deposits in the Gardar Province, S Greenland</i>
12.00	A. Borst	<i>The structural state of Y and Nd in eudialyte and related REE minerals using X-ray absorption spectroscopy</i>
12.15	V.V. Ene*	<i>The magmatic evolution of post-subduction suites: the Metaliferi Mountains, Romania and Fiji</i>
12.30	LUNCH	
Ni-PGE-Cr AND ORTHOMAGMATIC MINERALISATION		
13.30	H. Hughes	HAZEL PRICHARD MEMORIAL LECTURE: Developments in platinum-group element (PGE) and Cr research
14.00	J. Andersen	<i>Vanadium and titanium mineralisation in the Skaergaard Intrusion: Concentration by silicate liquid immiscibility and crystal-liquid segregation</i>
14.15	R. Key	<i>On-going exploration for Ni-PGE mineralization in a shear/feeder zone through the centre of the Molopo Farms Complex, part of the Bushveld Large Igneous Province in southern Botswana.</i>
14.30	B. Kennedy*	<i>The Troctolite Unit of the Northern Bushveld Complex: Genesis and Mineralization Potential</i>
14.45	L. Ward*	<i>Magnetite as an indicator mineral for Ni sulfide mineralisation: a case study from Munali, Zambia</i>

15.00	D. Blanks*	<i>Sulphide mineralisation of the Munali magmatic megabreccia deposit: evidence for immiscible melts?</i>
15.15	K. McFall	<i>Evidence for hydrothermal modification in the Aurora Cu-Ni-PGE prospect, Northern Bushveld Complex, South Africa</i>
15.30	Coffees	
SECONDARY DEPOSITS AND THE WEATHERING ENVIRONMENT		
15.45	R. Herrington	KEYNOTE: Nickel-cobalt-scandium laterites of the western Tethys – formation and economic potential
16.15	G. Arfé*	<i>The Cristal mineralization (Amazonas region, Northern Peru): an example of supergene zinc enrichments in tropical areas</i>
16.30	F. Putzolu*	<i>Mineralogical association and Ni-Co deportment in the Wingellina (Western Australia) oxide-type laterite deposit</i>
16.45	E. Fallon*	<i>The fate of SMS deposits, insights from natural and accelerated oxidation and implications for future mining activity</i>
17.00	S. Johnson	<i>Low temperature pyrite to pyrrhotite reduction in black shales: implications for metal mobility at low metamorphic grades</i>

17.15-19.00	POSTER SESSION – Sallis Benney Lecture Theatre.
19.30	Conference Banquet, Grand Hotel, Brighton.

Friday 5TH JANUARY

Sallis Benney Lecture theatre, Grand Parade, Brighton

Time	Presenting Author	Title
GOLD DEPOSITS		
9.00	S. Salvi	KEYNOTE: Role of sulphides in gold enrichment: the example of the West African Craton
9.30	C. Spencer-Jones*	<i>An Early Magmatic Fluid Pulse at Cononish Gold Deposit? Tellurium Enrichment and Implications for the Genesis of Gold Veins in Orogenic Belts</i>
9.45	S. Rice	<i>Late Caledonian post-subduction gold mineralisation and lithospheric delamination in the Southern Uplands-Down-Longford Terrane of Britain and Ireland.</i>
10.00	S. Walding*	<i>The geometry of the precious metal bearing epithermal system, Tlamin, Serbia.</i>
10.15	C. Allen	<i>The gold-bearing rutiles of Ouro Preto: a novel method of characterising orogenic gold deposits</i>
10.30	E. Zygouri*	<i>LA-ICP-MS evidence for coupled geochemistry of Au, Cu and As in As-pyrite from modern sea-floor massive sulphides, Kolumbo arc-volcano, Greece</i>
10.45	COFFEE	
Hydrothermal processes and deposits I		
11.00	D. Sherman	KEYNOTE: Metal complexation and transport by hydrothermal fluids: Molecular insights from quantum chemistry and spectroscopy
11.30	E. Brugge*	<i>Habit and Chemistry of Apatite at Chuquicamata, Chile</i>
11.45	A. Doran*	<i>A detailed petrographic and isotopic (S, Pb) study of high-grade Zn-Pb mineralisation in the Island Pod orebody, Lisheen deposit, Ireland.</i>
12.00	O. Turner*	<i>LA-ICP-MS trace-element discrimination for mapping iron sulphides within an Irish-type Zn-Pb deposit, Lisheen mine</i>

12.15	J. Davey*	<i>Sources, Styles and Scales of Sedimentary-hosted Copper Mineralisation: Evidence from the Zambian and Kalahari Copperbelts</i>
12.30	J. Lang*	<i>Vein-hosted Copper Deposits from SW Ireland</i>
12.45	LUNCH	
Processing, Production and Environment		
13.45	K. Hudson-Edwards	KEYNOTE: <i>Global Impacts of Mine Wastes</i>
14.15	N. Horsburgh*	<i>Luminescence as a tool for Smart Sorting of Ore</i>
14.30	R. Pell*	<i>Communicating responsible sourcing criteria to a non-specialist audience</i>
14.45	G. Jenkin	<i>The potential of deep eutectic solvent ionic liquids for processing chalcophile critical elements</i>
Hydrothermal processes and deposits II		
15.00	H. Grant*	<i>Constraints on the behaviour of trace metals in volcanogenic massive sulphide deposits based on LA-ICP-MS data from the actively-forming TAG deposit, Mid-Atlantic Ridge</i>
15.15	COFFEE	
15.30	J. Lambert-Smith	<i>$\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in carbonate veins highlight the role of devolatilisation in Au mineralisation</i>
15.45	S. Large	<i>The magmatic evolution leading to porphyry Au-Cu mineralisation at the Ok Tedi porphyry-skarn deposit, PNG, revealed by zircon petrochronology</i>
16.00	M. Keith	<i>A new submarine hybrid-type between VHMS and epithermal-porphyry deposits, Brothers volcano, Kermadec arc</i>
16.15	M. Loader	<i>Hydrothermal apatite as an indicator of porphyry Cu deposit fertility</i>
16.30	CLOSE	

*Student presentation.

POSTER PRESENTATIONS

Presenting Author	Title
B. Simons	Characterisation of lithium minerals in granite-related pegmatites and greisens by SEM-based automated mineralogy
W. Smith*	Petrogenesis and geochronology of evolved granites in the Cornubian Ore Province: insights into dynamic magmatism and Sn-W Mineralization
Z.T. Umarbekova	Bakyrchik type gold mineralization in black shale strata and regularities of its formation
S.M. Jones*	Fluid flow and alteration associated with the ~1.1Ga White Pine sediment-hosted copper deposit, Michigan, USA
J. Lindsay	Orthomagmatic conduit-hosted sulphide mineralisation potential of the Magilligan Sill, Northern Ireland (North Atlantic Igneous Province)
S. Hollis	Sm-Nd and Pb isotope mapping of the pre-Carboniferous basement of Ireland: implications for Zn-Pb mineralization
J. Shaw	Structural and geochemical approaches to understanding orogenic gold mineralization
F. Zhang*	Discriminating porphyry, skarn-forming and 'barren' magmatic/hydrothermal systems in the Daye District, China
A. Cauceglia*	Zn-Pb exploration in the Lismore block (Co. Waterford, Ireland): Preliminary data
R. Khan*	The application of green processing technology to tackle mercury use in small scale gold mining in Colombia
C. Nathwani*	Apatite chemistry in Central Chilean volcanics: implications for the application of apatite as a fertility indicator for porphyry copper deposits
Y. Suiekpayev*	Ti-Zr placers and weathering crusts of the Karaotkel and Satpaev deposits, Kazakhstan
S. Zhong*	Sources of fluids and evolution models of the Weibao skarn Cu-Pb-Zn deposit, East Kunlun Mountains, Northern Tibetan Plateau
L. Santoro*	Cobalt recovery from Katanga ores (DRC): the importance of mineralogical evaluation
J. Smiles*	Trace elements and ore formation in the Troodos and Parys Mountain VMS systems: A link to modern SMS deposits?
J. Price*	Reverse shear, horizontal shortening and lode-gold mineralisation on the Mougooderra Shear Zone, Western Australia
L. Palmer	The IMP@CT Project: Characterising Geological Uncertainty in Small, High-grade Deposits
E. Marquis*	Late- to post-magmatic alteration of syenitic rocks of the Ambohimirahavavy Complex: Insights into fluids potentially mobilising REE
C. Spence-Jones*	Constraining Gold Placer Sources at a District Scale using Placer Gold Geochemistry and Inclusions. An Example from the Atlin Placer Camp, British Columbia.
D. Currie*	New paragenetic, geochemical, and geochronological constraints on the origin of Leadhills-Wanlockhead Pb-Zn deposit in SW Scotland
S. Aitbaeva*	Model of gold-ore mineralization forming of Bakyrchik deposit, Kazakhstan
D. Drummond*	Tara Deep: Genesis, Context and Potential in Navan, Co. Meath, Ireland
R.J. Crossley*	PGE mobilisation in subduction zones and implications for ore deposit formation

A. Dobrzanski*	Petrology and Petrogenesis of the Norra Kärr Lanthanoid (REE) Deposit
A. Dobrzanski*	The Mineralogical History of an Argyle Octahedral Diamond
H. Waizy*	Geology and genesis of the Aynak Copper Deposits, Kabul, Afghanistan
P. Josso*	The NERC MINEX advanced training course: workflow for green field exploration of mineral deposits in Milos, Greece.
D. Drummond*	Textural and Geochemical Analysis of the Lower Proterozoic, Kerry Road Volcanogenic Massive Sulphide Deposit, Loch Maree Group, Gairloch, NW Scotland.
C. Lyell*	Evolving the genetic model for the Cononish Au deposit: from prospect to mine
L. Yesares*	Mineralogy of SEDEX-Style Mineralization in the lower Upper Dark Limestones overlying the Tara Deep deposit, Navan, Ireland
J. Miles*	Paleosurface exploration using hyperspectral short-wave infrared imagery
H. Hughes	Pyroxenite xenoliths and their metal budget: Implications for the metallogeny of subduction zones and the source regions of Cu-porphyry mineralisation
H. Stephenson*	What lies beneath? Understanding the Platreef mineralisation on farm Turfspruit, northern limb, Bushveld Complex.
S. Hollis	Clumped C-O isotope temperature constraints for carbonate precipitation associated with Irish-type Zn-Pb orebodies
N. Mondillo	Geochemistry and U-Pb zircon dating of Southern France bauxites
L. Hart	Multiple episodes of propylitic alteration discriminated by hydrothermal titanite U-Pb petrochronology at Oyu Tolgoi porphyry Cu-Au district, Mongolia
S. Worbey	By-product elements in Iron-Oxide-Copper-Gold deposits: an assessment of resources and recoverability

*Student presentation.

Model of gold-ore mineralization forming of Bakyrchik deposit, Kazakhstan

Saltanat Aitbaeva, Marina Mizernaya, Boris Dyachkov

Serikbaev East Kazakhstan State Technical University (EKSTU), Oskemen, Kazakhstan

Gold ore deposits in carbonaceous volcanogenic-carbonate-terrigenous formations make up a considerable share of the world gold reserves. Large objects are known in the USA, Australia, Russia, China, Kazakhstan and other regions of the world [1, 2].

Analysis of geologic conditions for forming the Bakyrchik gold deposit proves a complicated history of gold accumulation and concentration in ores of gold-arsenic-carbon-bearing type. Ore bodies of the deposit are represented by mineralized zones of banded, phacoidal and tabular shapes of considerable thickness (up to 10-20 m) and more than 1.0-1.2 km lateral extension. Basic ore-controlling elements are fault zones of north-west and sublatitudinal direction (overthrusting, strike-slip faults), lithological composition of reservoirs and magmatic formations (granitoid mass hidden at depth of 3.0-3.5 km and dikes identified within the ore zones).

Carbon-bearing, sericitic, kaolinite-hydromica, quartz-sericitic, sericite-phlogopite-carbonate, chlorite-albite and other metasomatic associations are developed in the deposit.

Metasomatic zoning of the Bakyrchik deposit is as follows: Carboniferous kaolinite-hydromicaceous metasomatites are developed in the upper horizons, carboniferous-sericitolitic changes have "through" expansion (they are most developed in central part of ore reserves), sericite-phlogopite-carbonate with apatite and tourmaline association occupies lower levels.

Ore minerals of the Bakyrchik deposit form five paragenetic assemblages: early melnikovite-pyrite-pyrrhotite-marcasite (with nickeline and pentlandite); ore stage gold-pyrite-arsenic pyrite (with cubanite and gersdorffite), gold-quartz- polymetallic (fahlore, chalcopyrite, galenite, and sphalerite), and gold-quartz-carbonate-scheelite-chalcopyrite (with breunnerite, dolomite, aikinite, free gold); late quartz-carbonate-antimonite-tetrahedrite (with marcasite, refractory gold). Gold-pyrite-arsenic pyrite assemblage occurs widely, whereas melnikovite-pyrite-pyrrhotite-marcasite, melnikovite-pyrite-pyrrhotite-marcasite and gold-quartz-carbonate-scheelite-chalcopyrite assemblages are developed at deeper levels, gold-quartz- polymetallic and quartz-carbonate-antimonite-tetrahedrite assemblages are confined to upper and medium horizons of the deposit. Impregnated and vein-impregnated gold-pyrite-arsenic pyrite assemblages are the most significant (90 %) in total mass of sulphides and total gold balance [3]. Based on the obtained new data about magmatism and ore formation of Bakyrchik deposit and on materials of previous years, a geological-structural model of the Bakyrchik ore field is proposed, with defining perspective areas for prospecting of new gold-ore objects of this type concerning dipping of ore columns of the known deposits and occurrence of Kyzyl zone. Perspective zones are controlled by the Kalba intrusion belt and different fault zones extending to depth of 1 to 3.5 km.

References

- [1] Mizerny, A.I., Miroshnikova, A.P., Mizernaya, M., Diachkov, B.O Geological and structural features, magmatism and mineralization of Sekysivske and Vasykivske Stockwork gold deposits (Kazakhstan) Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu (3), p. 5-12.
- [2] Dolgoplova A; Seltmann R; Miroshnikova A; Mizernaya M.. Mineralogical and Geochemical Characteristics of the Vasilkovskoye Gold Deposit (North Kazakhstan) 13th SGA Biennial Meeting on Mineral Resources in a Sustainable World Местоположение: Nancy, France Aug 24-27, 2015 MINERAL RESOURCES IN A SUSTAINABLE WORLD, VOLS 1-5 p: 77-80.
- [3] Halls C, Seltmann R and Dolgoplova A (2004) Atlas of mineral deposit models of the Republic of Kazakhstan. Almaty, 142 p English edition of compilation by Bespaev KhA and Miroshnichenko LA (eds), CERCAMS NHM, London 2004.

The gold-bearing rutiles of Ouro Preto: a novel method of characterising orogenic gold deposits

Connor Allen¹, Craig Storey¹, James Darling¹, Stephanie Lasalle¹

¹School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Building, Portsmouth PO1 3QL.

Orogenic gold deposits offer compelling insights into Earth's geodynamic past, in effect highlighting how crustal scale hydrothermal processes can alter penurious geological terranes into fertile ore systems. However, gaining insight to these processes in terms of geochemical characterisation of the source(s) and mineralised systems, and in particular dating these, is fraught with difficulty. Uranium-bearing accessory minerals that can be dated and where their trace element budget can help to trace fluid(s) and fluid-rock interaction are ideal, particularly as they can be physically and chemically robust and have high affinities for certain groups of elements. Rutile (TiO₂), in particular, is enriched in high field strength elements, which can be a useful source for protolith composition in metamorphic rocks. Moreover, it readily accepts ppm levels of siderophile elements such as tungsten and molybdenum. Together with ppm levels of uranium, a moderately high closure temperature for Pb (c.500°C), and being a robust accessory mineral common in orogenic gold deposits, rutile could be a useful lode tracer. Furthermore, mineral inclusions inside rutile have been largely overlooked previously and could also offer new insight. We explore this concept here and new trace element and U-Pb geochronological data, from shear-hosted, gold-bearing veins from the Ouro Preto gold district (SE Brazil).

We collected samples from two mines: the Passagem de Mariana and Chico Rei Mines. Rutiles were separated and/or studied in polished thick/thin sections. Paragenetic relationships were established by optical microscopy and SEM-EDS imaging and analysis. LA-ICPMS was used to measure trace element concentrates and U-Pb ages on selected grains.

Interstitial gold inclusions within rutile attest to a cogenetic crystallisation, therefore the age of gold mineralisation can be constrained by rutile geochronology. Hence, gold mineralisation ages were determined by the U-Pb rutile ages of 502 ± 5 & 485 ± 14 Ma from two mines. Regionally, this implicates the Brasiliano orogenic collapse as the tectonic driving force behind the gold mineralisation of this area. Rutile trace elemental chemistry revealed vast heterogeneity within the contemporaneous lodes, delineating the targeted mines through Cu, Cr, Sb, Sc, Sn, Nb, Nb/Ta, Zr/Hf, and W concentrations. These results show the Brasiliano orogenic collapse, generated a locally heterogeneous fluid, producing temporally analogous but geochemically contrasting rutiles in the lode, likely influenced by local geology during fluid migration.

Vanadium and titanium mineralisation in the Skaergaard Intrusion: Concentration by silicate liquid immiscibility and crystal-liquid segregation

Jens C. Ø. Andersen¹, S. Weatherley², M. Holness³, V. Honour³, G. Nicoli³ and B. Dyck⁴

¹ Camborne School of Mines, University of Exeter (J.C.Andersen@exeter.ac.uk)

² Geological Survey of Denmark and Greenland, Copenhagen, Denmark

³ Department of Earth Sciences, University of Cambridge

⁴ Simon Fraser University, Burnaby, British Columbia, Canada

The Skaergaard intrusion in East Greenland carries Fe-Ti oxides (ilmenite and titanomagnetite) in concentrations that are locally of economic interest for titanium (Ti) and vanadium (V). Five discrete strata-bound intervals extend across more than two kilometres in the uppermost part of the Lower Zone. They are integral parts of the primary magmatic stratigraphy.

The Skaergaard intrusion formed from evolved Ti-rich tholeiitic parental magma that differentiated in a closed system. The mechanism of differentiation is traditionally thought to be crystal-liquid separation [1,2]; however, recently the significance of silicate liquid immiscibility has become widely recognised [3,4]. We consider that immiscibility between Fe-rich and Si-rich silicate liquids contributed significantly to the development of Fe-Ti oxide-rich rocks in the Skaergaard intrusion.

The uppermost division of the Skaergaard Lower Zone is defined by the first occurrence of abundant ilmenite and titanomagnetite in the magmatic stratigraphy. However, localised concentrations far exceed the abundances that would be expected from equilibrium crystallisation and crystal-liquid separation. Five Fe-Ti oxide-rich intervals can be traced along strike for more than two kilometres across the western half of the intrusion. Each interval is between 0.5 and 1.5 metres thick but varies greatly along strike. Concentrations within the intervals also vary greatly and, in certain lateral segments, exceeds 80% titanomagnetite and ilmenite. The titanomagnetite carries up to 2 wt% V₂O₅ in solid solution [5].

The ilmenite and titanomagnetite-rich intervals each include up to 10 layers that display strong modal stratification. Intriguingly, in contrast to other gravity-stratified units, Fe-Ti oxide rich layers may display reverse as well as normal modal grading. Furthermore, discontinuous bodies of Fe-Ti oxides in the surrounding rocks are difficult to explain by crystal-liquid segregation.

If crystal-liquid segregation were the exclusive process for segregating ilmenite and titanomagnetite, then their concentrations would be controlled by cotectic crystallisation with plagioclase, olivine and augite. The modal abundances and variations that we observe in these intervals would require unreasonable degrees of modal sorting, and the corresponding oxide-poor lithologies have not been found. It is furthermore difficult to explain reverse modal grading as well as the discontinuous bodies in the surrounding cumulates. The only viable way to form these units would be to involve immiscibility within the silicate liquid.

References

1. Irvine, T.N. et al. 1998. Geological Society of America Bulletin 110, 1398-1447.
2. Wager, L.R et al. 1960. Journal of Petrology 1, 73-85.
3. Holness, M.B. et al. 2011. Journal of Petrology 52, 175-222.
4. Humphreys, M.C.S. 2011. Journal of Petrology 52, 147-174.
5. Davey, H. 2016. MSc dissertation, University of Exeter, 63 pages.

**The Cristal mineralization (Amazonas region, Northern Peru):
an example of supergene zinc enrichments in tropical areas**
Arfè G.¹, Mondillo N.¹, Boni M.¹, Joachimski M.², Balassone G.¹, Mormone, A.³

¹Dipartimento di Scienze della Terra, dell' Ambiente e delle Risorse, Università degli Studi di Napoli Federico II, Complesso Universitario di Monte S. Angelo, 80126, Napoli, Italy

²GeoZentrum Nordbayern, University of Erlangen-Nuremberg, Schlossgarten 5, 91054, Erlangen, Germany

³INGV Osservatorio Vesuviano, Via Diocleziano 328, 80124, Napoli, Italy

*Corresponding author: boni@unina.it

The small Cristal Zn deposit is located in the northernmost part of a wide mining district, the “Charlotte Bongará Zinc Project”, which covers an area of approximately 110 km² in the Amazonas district (Northern Peru). The mineralized area consists of many Zn occurrences with mixed sulphide and nonsulphide ores. The nonsulphide ores are the product of weathering of primary sulphide bodies, genetically representing a MVT mineralization. The Zn concentrations of Bongará-Cristal are hosted in the platform carbonates of the Condorsinga Formation (Early Jurassic) in the Pucará Group. The nonsulphide mineralization consists mainly of semi-amorphous orange to brown zinc “oxides” that include hemimorphite, smithsonite and Fe-(hydr)oxides. The most significant mineralized areas are present at Esperanza and Yolanda occurrences, which were also most densely explored. In both occurrences, the supergene Zn-carbonates and silicates infill solution cavities, or replace the carbonate host rocks and/or the primary sulphides. The analyzed drillcores are mainly from Esperanza, where the zinc content associated with hemimorphite-rich layers can reach ~53 wt.% Zn (average Zn grade is around 20 wt.%). Germanium concentrations are significant at Cristal, with values around 200 ppm measured on bulk rock.

The Bongará area experienced a prolonged phase of weathering from Miocene to Recent under tropical climatic conditions. Under such a climate setting, weathering processes involved many pre-existing sulphide orebodies (e.g. Cristal, Florida Canyon, Mina Grande mines), where supergene profiles were developed under locally different conditions, mainly outlined on the basis of mineralogical and geochemical data. The mineralogy and geochemistry of the Bongará mineralized zones were mainly determined at a local scale by two factors: (1) uplift rates, and (2) host rock composition. The latter may favor the development of more (e.g. Mina Grande) or less (e.g. Cristal) alkaline supergene environments. Uplift was controlled by the activity of local faults, which allowed the exposure of sulphide protorees at variable altitudes in different periods of time and hydrological settings. Such different factors and settings may result in the precipitation of isotopically different supergene carbonates (e.g. smithsonite and calcite). Contrary to the Mina Grande deposit nearby, the development of a karst network at Cristal was quenched by a limited uplift rate, and supergene alteration did not completely obliterate the roots of the original sulphide orebody.

References

Arfè, G., Mondillo, N., Boni, M., Joachimski, M., Balassone, G., Mormone, A., Santoro L., Castro Medrano E., 2017. The Cristal Zn prospect (Amazonas region, Northern Peru). Part II: An example of supergene zinc enrichments in tropical areas. *Ore Geology Review* (in press).

Sulphide mineralisation of the Munali magmatic megabreccia deposit: evidence for immiscible melts?

Daryl E. Blanks¹, David A. Holwell¹

¹School of Geography, Geology and Environment, University of Leicester, UK
(db404@le.ac.uk)

The Munali deposit is a highly complex, chaotic magmatic nickel sulphide megabreccia deposit hosted by a multi-stage mafic-ultramafic intrusion, with an unusual apatite-carbonate-magnetite-sulphide ore assemblage. Located 75 km south of Lusaka in southern Zambia, within the Zambezi belt, Munali was emplaced into carbonaceous rift sediments during the Neoproterozoic [1] in a period of extensional rifting related to the break-up of the Congo and Kalahari cratons. Munali is comprised of four deposits/prospects: Enterprise (site of the Munali Ni mine), Voyager, Intrepid and Defiant which form part of the Munali intrusive complex. The igneous complex is steeply dipping and exhibits typical characteristics of a magmatic-conduit system located along a translithospheric fault zone.

Mineralisation is hosted by a mafic-ultramafic breccia unit (MUBU), which is extensively brecciated with a sulphide infill matrix. These mafic-ultramafic rocks are intruded around the margins of an unmineralised, elongated central gabbro unit emplaced within marble. The sulphide-mineralised MUBU comprise poikilitic gabbros and a range of atypical ultramafic rocks (olivinite, phoscorite (olivine-magnetite-apatite rock) and pegmatic wehrlite), with characteristically no chromite.

Seven styles of magmatic sulphide mineralisation have been identified texturally and mineralogical by field-mapping, petrological and geochemical analysis. Mineralogy across all styles comprise pyrrhotite >> pentlandite > chalcopyrite > pyrite +/- magnetite, however, mineral abundance, geochemistry and textural association differ between the styles. The earliest styles are disseminated, interstitial sulphides hosted within the mafic and ultramafic clasts of the MUBU, and represent sulphide crystallisation prior to brecciation and associated massive sulphide infill. This is followed by main stage sulphide fill, forming as the matrix to MUBU clasts, and include; massive pyrrhotite-pentlandite sulphide; semi-massive sulphide associated with phosphate and carbonate; pyritic sulphide; carbonate hosted sulphide; and altered talc-carbonate sulphide mineralisation. The different styles within the sulphide breccia fill likely represents separate phases and timing of sulphide liquid injections. Some of the sulphide styles show distinct textures of immiscible carbonate and apatite, and include interstitial calcite and droplets of apatite within sulphide. These textures and mineralogical associations suggest the interaction of immiscible carbonate melts, potentially sourced from a carbonatite.

As such, Munali represents a magmatic sulphide deposit emplaced during intraplate rifting but with the presence of phoscorites and unusual carbonate-phosphate textures within the ore-body that may provide evidence of carbonatitic as well as mafic magmas utilising the same pathways.

References

[1] Holwell, D. A., Mitchell, C. L., Howe, G. A., Evans, D. M., Ward, L. A. and Friedman, R., 2017, The Munali Ni Sulphide deposit, southern Zambia: a multi-stage, mafic-ultramafic, magmatic sulphide-magnetite-apatite-carbonate megabreccia, *Ore Geology Reviews*, In Press

The structural state of Y and Nd in eudialyte and related REE minerals using X-ray absorption spectroscopy

A.M. Borst¹, A. A. Finch¹, H. Friis², N.J. Horsburgh¹, P.N. Gamaletsos³, J. Goettlicher⁴, R. Steininger⁴, K. Geraki⁵

¹ School of Earth and Environmental Sciences, University of St Andrews, United Kingdom
(amb43@st-andrews.ac.uk)

² Natural History Museum, University of Oslo, Oslo, Norway

³ Center for Electron Nanoscopy, Technical University of Denmark, Kongens Lyngby, Denmark

⁴ KIT Synchrotron Radiation Facility, Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany

⁵ Science Division, Diamond Light Source, Harwell Science and Innovation Campus, Didcot, United Kingdom

Eudialyte group minerals (EGM) are the focus of commercial interest because they host significant amounts of Zr, Nb and the high value middle- and heavy REE. They are structurally and chemically complex alkali-zirconosilicates that crystallize in unusually volatile-rich peralkaline magmas. On average EGM contain c. 12 wt. % ZrO₂, 1-2 wt. % Nb₂O₅ and c. 1-10 wt. % total rare earth oxides with high proportions of the valuable middle- and heavy REE (c.35% of TREO). The EGM crystal structure can accommodate REE in various sites. Light and middle REE are generally inferred to occupy the 6-fold Ca-dominated M1-site and/or the low symmetry 8-9-10-fold coordinated Na-site, while HREE may occupy the smaller octahedral Zr-site. How REE are distributed at the nano/microscale, and how REE substitution mechanisms affect the crystal structure, are poorly understood. XRD refinement is insensitive to REE site allocation, and LREE and HREE may occupy different sites due to the range of ionic radii.

Here we use synchrotron X-ray absorption spectroscopy to determine how light and heavy REE are accommodated in the EGM crystal structure. We collect Y K-edge and Nd L_{III}-edge absorption data, including the μ -XANES and μ -EXAFS regions, using Y and Nd as proxies for HREE and LREE, respectively. Natural and synthetic REE phases with REE in known coordination states were measured for comparison of μ -XANES patterns. Crystalline (XRD-confirmed) EGM from Ilímaussaq, Narssârssuk, Norra Kärr, Kipawa and Lovozero yielded indistinguishable μ -XANES for Nd and Y, indicating similar LREE/HREE site occupancy in EGM of varying compositions. The Y K-edge μ -EXAFS were processed to quantify Y coordination and bond distances, and yield optimal fits for Y in 6-fold coordination with average Y-O bond distances between 2.24-2.32 Å. This is consistent with Y substitution on the octahedral M1-site as the dominant REE substitution mechanism in all analysed EGM varieties, associated with a 3-5% decrease in size of the M1-site as inferred from XRD refinement. We exclude preferential substitution of HREE onto the smaller Zr-site (typical Zr-O distances of 2.08 Å). As such, the relatively flat REE profiles that make eudialyte an attractive target for exploration for high value REE are not the result of distribution of REE between different sites.

Epithermal(?) HREE, Zr, Nb, Ti, Th, and Mo mineralisation, related to carbonatites

Sam Broom-Fendley¹, Aoife E Brady²

¹Camborne School of Mines, University of Exeter, Penryn Campus, Cornwall, TR109FE, UK
(s.l.broom-fendley@ex.ac.uk)

²Geological Survey Ireland, Beggars Bush, Haddington Road, Dublin D04K7X4, Ireland

Most rare earth element (REE) mines and many currently-active exploration projects exploit carbonatites or carbonatite-related deposits. These are typically very large, high grade, and are rich in light (L)REE, such as Nd, but have particularly low heavy (H)REE contents. However, recent work indicates that some carbonatites exhibit localised HREE-enrichment, as well as elevated Zr, Nb, Ti, Th, and Mo concentrations, typically on the periphery of a carbonatite complex [1–4]. At least one of these localities has formerly been mined (for Ti), and several of the others have been prospected for Mo, Ti, Nb and Th, signifying their potential economic importance. In this contribution, we review some localities which exhibit such mineralisation, focussing on the Songwe Hill carbonatite, Malawi.

Preliminary work at Songwe Hill has identified three roughly circular breccia units, interpreted as vents, which host HREE, Zr, Nb and Ti mineralisation. These are located approximately 1 km from the main LREE deposit, and were first identified by ASTER anomalies, followed by gamma-ray spectrometry and geological mapping. The vents are composed of altered trachyte or phonolite, and contain clasts of nepheline syenite, phonolite, carbonatite and country-rock, indicative of late emplacement in the timeline of the complex, after the carbonatite. The host rocks are extensively altered to K-feldspar, akin to fenitisation, and are locally altered to clay, although it is unclear if this is caused by weathering. The HREE are hosted in xenotime-(Y), associated with Nb-rutile and zircon. Locally, pre-existing zircons helped nucleate further xenotime growth. Here, it is clear that extensive zircon dissolution has occurred, prior to xenotime formation, supporting the notion that mineralisation was a relatively late-stage process in the geological history of the complex.

Other localities with Zr, Nb, Ti, Th, and HREE mineralisation include Bear Lodge, Amethyst, Wet Mountains, Iron Hill, Magnet Cove (USA), Goudini, Salpeterkop (South Africa), and Gross Brukkaros (Namibia) [4–9], although the degree of exploration at each locality is highly variable. Commonalities include features of shallow emplacement, such as emplacement through extrusive rocks or breccia pipes, as well as extensive host rock alteration and silicification, similar to the process of fenitisation. In combination, these features are circumstantial evidence for formation from a late hydrothermal fluid in a shallow, subvolcanic system, and may be analogous with epithermal mineralisation.

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Habit and Chemistry of Apatite at Chuquicamata, Chile

Emily Brugge^{1,2}, Jamie J. Wilkinson^{1,2}, Andrew Miles³

¹Department of Earth Science and Engineering, Imperial College London, UK, and Department of Earth Sciences, Natural History Museum, London, UK (e.brugge@nhm.ac.uk)

²Department of Earth Sciences, Natural History Museum, London, UK, and Department of Earth Science and Engineering, Imperial College London, UK

³Department of Geology, University of Leicester, Leicester, UK

Mineral chemistry is increasingly used to study porphyry systems as it offers a more precise snapshot into its formation history compared to the time-averaged view given by whole rock studies. The large range in possible trace element substitutions in apatite can reveal crystallisation conditions that reflect key events prior to and during porphyry formation. Magmatic and hydrothermal apatite analyses can be combined to produce a detailed record of the magmatic and hydrothermal evolution.

Apatites from the Chuquicamata Cu-Mo porphyry deposit exhibit a variety of textures that enable division into magmatic and hydrothermal varieties (Fig. 1). Magmatic apatite occurs as inclusions or as euhedral crystals within the groundmass of porphyritic rocks. By contrast, hydrothermal apatites are commonly irregular, and those observed within veins are intergrown with other vein minerals including chalcocite and bornite.

There is little variation in the minor element chemistry of the magmatic apatite, possibly related to the limited bulk compositional range of the host porphyries. However chondrite-normalised REE plots reveal variations in HREE concentration between texturally-distinct magmatic apatite, interpreted to reflect the co-crystallisation of zircon and titanite. In comparison, the hydrothermal apatite is depleted in LREE and exhibits distinct minor and trace element compositions in apatite of different vein and alteration assemblages.

The results highlight the importance of interpreting apatite chemistry within a petrographic context. The data from this preliminary work demonstrate that magmatic and hydrothermal apatites can be distinguished compositionally and show how apatite may be used to identify successive hydrothermal events within early magmatic-hydrothermal development at Chuquicamata. The sensitivity of apatite to the crystallisation conditions also supports its use in developing fertility indicators.

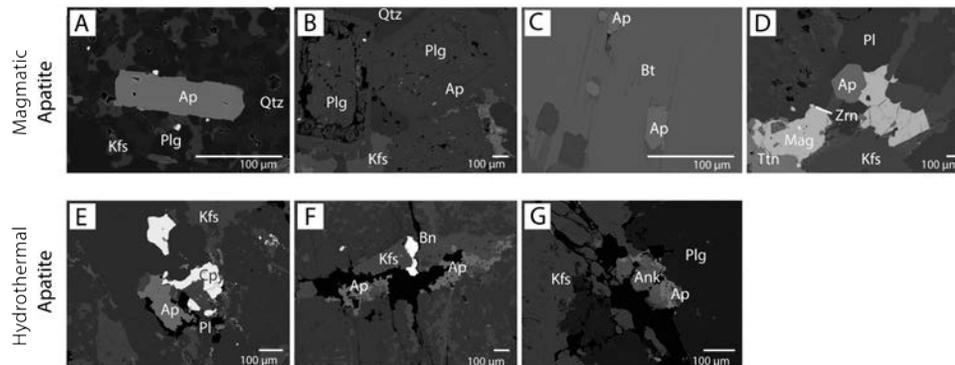


Figure 1 Apatite occurrences and habits observed within the Chuquicamata porphyry complex. (A-D) Magmatic apatite as (sub)-euhedral grains forming the part of the groundmass or as inclusions within phenocrysts. (E-G) Hydrothermal apatite is typically irregular in habit within typically contains inclusions of other hydrothermal minerals.

Zn-Pb exploration in the Lismore block (Co. Waterford, Ireland):

Preliminary data

Cauceglia A.¹, Mondillo N.¹, Balassone G.¹, Boni M.¹, Robb W.², Smith T.L.²

¹ *Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli Federico II, Napoli (Italy) (a.cauceglia@studenti.unina.it)*

² *Adventus Zinc Corporation, Kells, Co. Meath (Ireland)(wilson@adventuszinc.com)*

The Lismore block is located in southern Ireland (Co. Waterford), approximately 200 km SW of Dublin. It holds five contiguous prospecting licences, encompassing the east-west trending Lismore-Dungarvan syncline, which mostly consists of Lower Carboniferous carbonate units, bounded by a thick sequence of clastic Devonian sediments. Extensive geochemical and geophysical exploration programmes allowed identifying strong Zn geochemical anomalies both on the northern and southern limbs of the syncline. However, subsequent drilling operations revealed that much of the surface anomalies did not always reflect sulphide ores at depth. In this work, we present the preliminary results of a new geochemical exploration campaign conducted in the Lismore area by Adventus Zinc Corporation, aiming to identify any relationships between Zn and other elements in the above mentioned anomalies, potentially revealing concealed deep sulphide bodies. The data have been cross-checked with textural and geochemical characteristics of drill cores carried out in the south-central part of the syncline by Navan Resources.

More than 150 specimens of shallow soils were sampled along the syncline. Log-transformed data revealed a bimodal distribution for the elements Zn-Ag-Cd-Pb-Ge-As-Al-Mn-Ni, thus confirming the presence of anomalous samples population. Pearson correlation coefficient (PCC) reflected strong correlations between Zn and Ag-Cd-Ni-Pb-Mn-Sb-Co-Cu, and low correlations with Al and Ge. The first two principal components of the Principal Component Analysis (PCA), PCA1 and PCA2 (which explain 70% of the total variance of the data), allowed to identify two distinct groups of variables: Zn-Pb-Ag-Cd-Co-Cu-Mn-Sb-Ni and Al-K-Ge-Ga-Ba, confirming the PCC. In the cores drilled across the surficial E-W southern anomaly, at around 40-50 meters above the base of the Tournasian Waulsortian Limestone Fm., we identified a sphalerite-pyrite mineralization, disseminated into a clast- to matrix supported, poorly sorted breccia body, cemented by fine-grained dark grey dolomite. Sphalerite is almost totally oxidized in the first 10-12 meters from the surface, whereas patchy oxidation occurs at greater depth. However, part of the southern anomaly was also related to the occurrence of a mixture of Zn-bearing clays and Fe-Mn-hydroxides, in solution-karst cavities. In conclusion, this study suggests that in the Lismore area the surface anomalies are controlled by both the effective presence of concealed sulphide bodies and the occurrence of supergene Zn-bearing minerals in karst cavities. The common association of Zn and other metals in the soils (evidenced with PCC and PCA) suggests that the chemical and/or mechanical Zn dispersion which produced the anomalies was probably limited to areas very close to hidden sulphide-bodies, because a more extensive dispersion would have produced a major fractionation of metals [1], and a consequent separation of the more mobile Zn from the less mobile elements Pb, Cd and Mn.

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The use of hyperspectral reflectance in mineral exploration: example from the Northwest Zone of the Lemarchant VMS deposit, Newfoundland, Canada

Jonathan Cloutier¹ and Stephen J. Piercey²

¹ Department of Earth and Environmental Sciences, University of St Andrews, North Street, St Andrews KY16 9AL, UK (jonathan.cloutier@st-andrews.ac.uk)

² Department of Earth Sciences, Memorial University of Newfoundland, 300 Prince Philip Drive, St. John's, Newfoundland and Labrador, Canada, A1B 3X5 (spiercey@mun.ca)

Hyperspectral reflectance spectroscopy has been widely available for more than 25 years and is now undertaken as a standard procedure by many exploration and mining companies. The data collected is used to characterize the mineralogy of alteration zones but is rarely used in conjunction with geochemical datasets. In this study, we integrate hyperspectral and whole rock geochemical datasets acquired at the Northwest Zone of the Lemarchant volcanogenic massive sulphide (VMS) deposit in order to determine the dominant formation processes and to establish new exploration parameters. The mineralization at the Northwest Zone is hosted in andesitic and dacitic rocks and exhibits intense hydrothermal alteration (e.g., high CCPI, AI and Ba/Sr lithochemical signatures) extending at least 300 m along strike of the andesitic and dacitic units. The alteration corridor has hyperspectral signatures that correlate with phengitic white micas with 2200W longer than 2215nm, and Mg-rich chlorites with 2250W shorter than 2252nm. The integration of hyperspectral reflectance, geochemical alteration proxies (i.e., AI, CCPI, Ba/Sr, Na₂O) and mass volume changes has documented specific alteration processes responsible for the alteration (i.e., seawater alteration versus silicification), which is not possible using hyperspectral reflectance or geochemistry alone.

PGE mobilisation in subduction zones and implications for ore deposit formation

R.J. Crossley¹, K.A. Evans¹, N.J. Evans^{1,2}, A. Bragagni^{3,4}, B.J. McDonald^{1,2}, S.M. Reddy¹ & I.M. Speelmans^{3,5}

¹ Applied Geology, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
(rosalind.crossley@postgrad.curtin.edu.au)

² John de Laeter Centre, Curtin University, GPO Box U1987, Perth, WA 6845, Australia.

³ Steinmann-Institut für Edogene Prozesse, Universität Bonn, Poppelsdorfer Schloß, 53115 Bonn, Germany.

⁴ Present address: Institut für Geologie und Mineralogie, Universität zu Köln, Greinstr. 4-6, D-50937 Köln, Germany.

⁵ Present address: Institute for Geochemistry and Petrology, ETH Zurich, Clausiusstrasse 25, 8092 Zurich, Switzerland.

Platinum group elements are interesting tracers of geological processes and of economic importance but their mobility in many environments is poorly understood. Subducted serpentinites have the potential to carry PGEs to great depths or transfer PGE to the sub-arc mantle upon devolatilisation [e.g. 1]. The sub-arc mantle is considered to be enriched in Pd and Pt relative to IPGE [2] and therefore transport of these elements via high pressure fluids is deemed possible. However, PGE cycling in subduction zones remains poorly understood.

A combination of analytical techniques was used to trace the PGEs in serpentinites through the subduction cycle. Comparison of bulk PGE concentrations to primitive mantle and abyssal PGE concentrations provides an insight into large scale PGE transfer, mineral paragenesis work constrained the timing of sulphide growth (the major host of PGE), LA-ICP-MS determined the concentration of PGE hosted in sulphides in high-pressure serpentinites, and high resolution feature mapping provided a method to detect PGM. The bulk concentrations of PGE in the subducted serpentinites are no different to PGE concentrations of primitive mantle and abyssal serpentinites, therefore no large scale transfer of PGE occurred, with the exception of slight Pd enrichment in two samples. Millimetre to centimetre scale mobilisation is proposed from sulphides to alloys and between sulphides. Sulphide PGE concentrations and sulphide parageneses provide complementary tools to assess redox conditions throughout the subduction cycle, which is vital to the oxidation state of the sub-arc mantle and hence the formation of arc-related ore deposits. An improved understanding of the geochemical behaviour of PGE could be applicable to the exploration of ultramafic hosted PGE and nickel sulphide deposits.

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²McInnes et al., 1999, *Science*, 286(5439), 512–516

New paragenetic, geochemical, and geochronological constraints on the origin of Leadhills-Wanlockhead Pb-Zn deposit in SW Scotland

David Currie¹, Finlay Stuart¹, John Faithfull², Adrian Boyce¹

¹ Scottish Universities Environmental Research Centre, East Kilbride G75 0QF, UK
(d.currie.1@research.gla.ac.uk; Fin.Stuart@glasgow.ac.uk, Adrian.Boyce@glasgow.ac.uk)

² The Hunterian, University of Glasgow, Glasgow G12 8QQ (John.Faithfull@glasgow.ac.uk)

The vein-type Pb-Zn deposit at Leadhills-Wanlockhead, SW Scotland, has been one of the largest base metal resources in the UK. The 68 documented veins are hosted in Lower Palaeozoic strata and are dominantly concentrated along normal faults. The 16 km² mining district has yielded over 400,000 tons of Pb, 100,000 tons of Zn, and 25 tons of Ag from the 16th century until 1958. However, since the seminal work of Temple (1) published research has been scarce (2,3). By shedding new light on the ore paragenesis, and developing a new geochemical and geochronological framework, we aim to devise a genetic model for the mineralisation.

Vein cross-cutting relationships and mineral textures show that a major Fe-oxide phase pre-dates the main Pb-Zn mineralisation. This paragenesis suggests ore precipitation due to mixing of oxidized and reduced fluids at the basin/basement interface in combination with decreasing fluid to rock ratio due to boiling. New in-situ and bulk $\delta^{34}\text{S}$ data (galena: -11.6 to -6.7‰ (n=48); chalcopyrite: -8.4 to -4.6‰ (n=14); sphalerite: -7 to -5‰ (n=17); pyrite: -4.5 to -2.1‰ (n=3)) overlap the range of $\delta^{34}\text{S}$ values measured in diagenetic pyrite from regional Lower Palaeozoic shales and greywacke (3). Congruent $\delta^{34}\text{S}$ values implies that sulphide metals were sourced from underlying shales and greywacke. Sulphide $\delta^{34}\text{S}$ are distinct from $\delta^{34}\text{S}$ values of Caledonian granites (0 to 3.3 ‰ (4)), ruling out magmatic fluids as a source of the ore S. Despite obvious variations in vein orientation, host lithology, and the density of veins across the ore district, $\delta^{34}\text{S}$ values are remarkably homogeneous. This suggests that S source and ore fluid temperature remained unchanged during the mineralisation process and that sulphides precipitated at or near equilibrium. (U+Th)/Ne ages of two hematite samples from the Glengonnar mine imply a late Triassic age for the early oxide phase. This contrasts with the mid-Carboniferous K-Ar age of fault gouge illite (5) and, if substantiated, requires a radical re-interpretation of the origin of the deposit.

The dominant occurrence of ore veins on normal faults and (U+Th)/Ne ages implies emplacement during a period of extension in the late Triassic. Ore paragenesis suggests fluid mixing at the basin/basement interface in combination with decreasing fluid to rock ratio due to boiling as the means of ore precipitation. $\delta^{34}\text{S}$ data and a fluid temperature of ~150°C at 30°C/km geothermal gradient implies Pb-Zn is sourced from hydrothermal convection of sulphide bearing connate fluids at depths of ~5 km within Lower Palaeozoic strata.

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Sources, Styles and Scales of Sedimentary-hosted Copper Mineralisation: Evidence from the Zambian and Kalahari Copperbelts

Davey, J. E.^{1,2}, Roberts, S.¹, Wilkinson, J. J.², Gernon, T.M.¹

¹Ocean and Earth Science, National Oceanography Centre, University of Southampton,
Southampton, UK. Email: J.E.Davey@soton.ac.uk

²Department of Earth Science and Engineering, Imperial College London, Exhibition Road,
London SW7 2AZ, United Kingdom

The Neoproterozoic Pan-African belt stretches approximately 2000 km from the Damaran Orogen in central Namibia to the Lufilian Belt in Zambia and the DRC. A series of collisional events between ~600-500 Ma [1] along the Congo-Kalahari cratonic margin mark the closure of several Neoproterozoic sedimentary basins, many of which show a marked propensity for globally significant stratiform and vein-hosted copper mineralisation.

Evidence from several deposits across the Zambian and Kalahari Copperbelts indicate contrasting timescales and fluid chemistries associated with mineralisation. Kinematic indicators and fluid inclusion studies from the Zambian Copperbelt suggest a long-lived hydrothermal system, spanning pre- to post-orogenic times with potentially anomalously Cu-rich, high temperature-salinity fluids. Study of drillcore and fluid inclusions from two prospects in the Ghanzi Ridge zone of the Kalahari Copperbelt in Botswana indicate a more temporally restricted mineralisation event during peak Damaran Orogenesis, and lower temperature-salinity fluids.

Degrees of confidence regarding potential copper sources similarly reflect the contrasting spatial and temporal scales of the two systems, with mineralisation in the Kalahari Copperbelt potentially attributable to hydrothermally leached mafic volcanics underlying the sedimentary rift sequence, while copper sources in the Zambian Copperbelt remain less certain.

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The Mineralogical History of an Argyle Octahedral Diamond

Andrew Dobrzanski¹, Simon Howard², Lore Troalen², Peter Davidson², Rachel Walcott³

¹Department of Geology, The Grant Institute, Kings Buildings, Edinburgh, UK, EH9 3FE
(a.j.dobrzanski@ed.ac.uk)

²Collections Services Department, National Museums Scotland, Edinburgh EH5 1JA, UK

³Department of Natural Sciences, National Museums Scotland, Edinburgh EH1 1JF, UK

The Argyle diamond deposit is the only mined diamond-bearing lamproite in the world and at its peak dominated 40% of the global diamond market. Since production started in 1983 over 800 million carats of rough diamonds have been won and the mine has grown famous for its spectacular violet, red and pink diamonds [1]. But while much has been written on the gem-quality material produced by the Argyle mine there is little information available on the more abundant non-gem-quality rough material despite this material being important for fully understanding the deposit.

This study describes the surface and internal features of a fancy-red octahedral-rough-diamond from the Argyle mine, which is held in the collection of National Museums Scotland. The diamond was imaged using high resolution photography equipment and the SEM facility available at the National Museums Collection Centre in Edinburgh.

High-resolution photography has shown a range of growth and resorption features on the surface of the diamond. Due to the surface etching several major deformation planes are visible on the surface of the stone. The rest of the resorption has resulted in triangular etch pits (trigons) and rounded edges that indicate that 5-10% of the original diamond has been resorbed into the lamproite magma. The orientation of the trigons indicate that H₂O was likely to have been locally abundant during this etching stage. Hexagonal etch pits are reported to be common on gem-quality Argyle material, however this non-gem diamond only displays negative trigons and a single positive trigon indicating localised resorption processes in the lamproite during eruption.

SEM imaging has shown that notches along the edges of the octahedron display resorbed crystal features rather than brittle-fractures and further work is required to determine if these notches originate from resorption of fractures or deformation planes within the stone.

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Petrology and Petrogenesis of the Norra Kärr Lanthanoid (REE) Deposit

Dobrzanski, A.¹, Kirstein, L.¹, Walcott, R.², Butler, I.¹, Ngwenya, B.¹

(a.j.dobrzanski@ed.ac.uk)

¹School of Geosciences, The Grant Institute, Kings Buildings, Edinburgh, UK, EH9 3FE

²Department of Natural Sciences, National Museums Scotland, Edinburgh, UK, EH1 1JF

Lanthanoids or ‘Rare Earths’ are critical to a range of advanced technologies; however, the formation processes that result in concentrated economic deposits of lanthanoids remain enigmatic. This research has focused on the evolution of the Norra Kärr syenite which has measured ore grades up to 0.61% TREO (of which 52.6% are HREO) and an indicated resource of 31.1 Mt at 0.4% TREO cut-off grade [1] making it mainland Europe’s largest lanthanoid resource. Recent exploration work by Tasman Metals Ltd. has provided an opportunity investigate the 3D nature of the intrusion in parallel with the petrology and geochemistry. This contribution focuses on the petrology of the constituent syenite bodies at Norra Kärr and the major and trace element patterns associated with them.

Based upon field and borehole relations, bulk rock geochemistry and mineral analyses two phases of intrusion can be recognised. The first intrusive phase contains the ore domains in the form of pegmatite bodies and fine-grained eudialyte bearing syenite; while later phase feldspathic magmas are non-ore bearing. The mineralogy is similar across all lithologies with petrographic relationships suggesting that aegirine formed first followed by zirconosilicate phases and finally feldspars.

Each phase of magmatism appears to display its own separate petrological trend in zirconosilicate species and abundance with electronprobe analyses (EPMA) showing that each zirconosilicate species has a different affinity for the lanthanoids. Andersen et al. [2] have shown that the species of zirconosilicate mineral formed in an alkaline magma is dependent on the relative activity of a given volatile (F^- , Cl^- , OH^-) in the magma. This suggests that variations in magmatic volatile activity could result in differing zirconosilicate trends thereby influencing the removal of lanthanoids. Future work will involve further testing of this hypothesis and synthesising the data into a holistic ore-deposit model for exploration purposes.

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A detailed petrographic and isotopic (S, Pb) study of high-grade Zn-Pb mineralisation in the Island Pod orebody, Lisheen deposit, Ireland

Aileen L. Doran^{1*}, Steven P. Hollis^{1,2}, Julian F. Menuge¹, John Güven¹, Adrian J. Boyce⁴ & Oakley Turner³

¹iCRAG/University College Dublin, Ireland (aileen.doran@icrag-centre.org).

²Geological Survey Ireland, Dublin, Ireland.

³iCRAG/Trinity College Dublin, Ireland.

⁴SUERC, Glasgow, UK.

Irish Zn-Pb orebodies are a type of carbonate-hosted deposit, with mineralization strongly associated with normal faults. Ore deposition typically occurs due to the replacement of Lower Carboniferous limestones, triggered primarily by fluid mixing, between a hot (up to 240 °C), metal-bearing, hydrothermal fluid, which ascended normal faults, and a cooler (<50 °C), hypersaline brine, carrying bacteriogenically reduced dissolved sulphide, of ultimate seawater origin.

The Lisheen deposit (23 Mt @ 13.3% Zn & 2.3% Pb), consists of several stratabound orebodies, which are strongly controlled by an extensional, left-stepping, ramp-relay fault array. The Island Pod (0.4 Mt @ 20% Zn & 1.6% Pb), discovered late in the mine's life, is a small, satellite body of high-grade mineralisation located ~ 900 m north of main orebody. Despite being distal to the main orebody, the Island Pod is still very high grade, and hosts best quality ore at Lisheen. The Island Pod also displays rapid lateral variation on a small scale (<10 m), where adjacent boreholes can have zinc concentration differences of ~ 40 %. The Island Pod also displays a weaker structural control than elsewhere in the southern Irish orefield.

We present the first detailed petrographic and S-Pb isotopic study of the Island Pod orebody. The basic sulphide mineralogy for the Island Pod is pyrite, sphalerite and galena, with multiple generations of each observed, along with several carbonate phases. Dendritic pyrite/galena, colloform sphalerite and sphalerite/dolomite intergrowth textures suggest an early, rapid mineralisation event, from a supersaturated fluid, in a nonequilibrium depositional environment, marking the onset of fluid mixing. As the mineralising system came closer to equilibrium, sulphide textures changed, reflecting a slower precipitation environment.

Galena sampled from across the Island Pod orebody and its surrounding halo has a homogeneous Pb isotopic signature, regardless of paragenetic stage, and plots on the same mixing trend as historic analyses from Lisheen. This suggests that all Lisheen ore lenses have a common Pb source. Additionally, ³⁴δS data suggest a dominantly bacteriogenic source for S in the Island Pod, with minor +³⁴δS values recorded. This is consistent with the distal position of the orebody, away from the feeder ramp-relay fault system at Lisheen, which is thought to have introduced metal-bearing hydrothermal fluids with ³⁴δS>0. In addition, the orebody and its halo have very similar ³⁴δS values, signifying that a lack of hydrothermal sulphur is not what led to the halo being sub-economic. This may suggest that other factors are responsible for ore grade, such as the availability of bacteriogenic sulphur or stratigraphic controls like the nature of host rock permeability.

Textural and geochemical analysis of the Lower Proterozoic, Kerry Road volcanogenic massive sulphide deposit, Loch Maree Group, Gairloch, NW Scotland.

Drew Drummond^{1,*}, Jonathan Cloutier¹.

¹School of Earth and Environmental Sciences, University of St Andrews, Irvine Building, KY16 9AL. drewdrummond59@gmail.com; Jonathan.Cloutier@st-andrews.ac.uk

*Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride, Glasgow G75 0QF.

The Kerry Road volcanogenic massive sulphide (VMS) deposit (~500,000 tonnes grading at 1.2% Cu, 3.5% Zn) is a metamorphosed Besshi-type (mafic-siliciclastic) VMS deposit hosted within the Lower Proterozoic Loch Maree Group (c. 2.0 Ga) (LMG) in the northwest of Scotland. The LMG is an intensely deformed, low-amphibolite facies supracrustal sequence of metavolcanics and metasediments.

Sulphide mineralisation typically consists of pyrite and pyrrhotite with subordinate chalcopyrite and sphalerite. Three types of sulphide disposition are present: (1) disseminated, (2) vein and (3) semi-massive to massive. Prolonged low-amphibolite facies metamorphism associated with Laxfordian deformation caused a remobilisation of sphalerite first, followed by pyrrhotite, and finally chalcopyrite. Maximum temperature and pressure was not high enough for pyrite to cross the brittle-ductile boundary and thus pyrite displays brittle deformation. Pyrite underwent mechanical reworking and was rounded, fractured and transported as it was carried by the remobilised sulphide varieties during ductile remobilisation. This sulphide remobilisation sequence, alongside the country rock associations of garnet, biotite, and amphibole, defines the low-amphibolite metamorphism experienced by the deposit.

The metamorphism overprints any primary VMS alteration in the surrounding host rock. However, microprobe analysis of amphibole geochemistry outlines a systematic variation in mineral chemistry ranging from ferrotschermakite ($\text{Ca}_{1.6}(\text{Mg}_{0.03}, \text{Fe}_{2.44})\text{Al}_{2.6}\text{Si}_{5.93}\text{O}_{22}(\text{OH})_2$) distal to the deposit, to actinolite composition ($\text{Ca}_{1.7}(\text{Mg}_{3.9}, \text{Fe}_{1.1})\text{Si}_{7.94}\text{O}_{22}(\text{OH})_2$) proximal to the Kerry Road deposit, highlighting an Mg- and Si- enrichment associated with the VMS system. Thus, variation in amphibole geochemistry could be used as a useful vector in the Loch Maree Group, or perhaps in similarly metamorphosed VMS regions, as an indicator for proximity to VMS mineralisation.

The origin of the LMG is disputed, with the most widely accepted model being an island arc tholeiitic (IAT) subduction-accretion model suggested by Park et al. (2001). Our data add weight to this hypothesis, as immobile element systematics of the metavolcanic amphibolite reflect an IAT signature. Furthermore, we argue that the Besshi-type classification and its tectonic associations, the P-T path highlighted through the sulphide remobilisation sequence, and the age and rare preservation of the Kerry Road deposit, are all consistent with this IAT subduction-accretion model for the genesis of the LMG.

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Tara Deep: Genesis, Context and Potential in Navan, Co. Meath, Ireland.

Drew Drummond¹, Adrian Boyce¹, Robert Blakeman², John Ashton².

¹Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride, Glasgow G75 0QF, United Kingdom.

²Boliden Tara Mines Limited, Navan, Co. Meath, Ireland.

Email: drewdrummond59@gmail.com

Abstract

Tara Deep, Co. Meath, Ireland, is the latest major discovery (announced in 2017), by the Boliden Tara Mines DAC Exploration Department, which has led to a significant addition to the Navan-cluster of Zn+Pb deposits – the Navan deposit itself is currently Europe's largest Zn resource, which has been mined now for over 40 years. Tara Deep was discovered following the acquisition and interpretation of seismic data in the area in 2011, with drill-based exploration beginning in 2012. Since then, almost continuous drilling has resulted in >96 km of drill-core, from depths regularly in excess of 1,500 m. First drill holes in the region yielded a significant ore intersection of 32 m, grading 11.0% Zn and 3.0% Pb.

This research PhD seeks to understand, in detail, the depositional processes that led to the formation of Tara Deep, including detailed textural and mineralogical relationships and S isotope geochemistry. This study will determine the genesis of the deposit, particularly ascertaining its tectonic, geological and genetic relationship to the giant Navan ore-body beside which it sits. Whilst exploring these relationships, the project will inform the prospectivity of further ore discovery in the Dublin Basin, around and beyond this deposit.

The study will apply the following techniques to deliver outcomes presentable to the company and the wider scientific community:

- Petrographic, mineralogical analyses of base-metal sulphide textures using standard transmitted, reflected light microscopy and SEM imaging, thus informing genetic modelling. This work will also include extensive, detailed logging of pertinent drill-core and the use of pXRF technology.
- Carbonate textural analyses using transmitted light, cathodoluminescence and SEM petrography to establish whether paragenetic relationships to metallogenesis exist.
- In-depth S isotope analyses of base-metal sulphides from Tara Deep using conventional and in situ laser S isotope systems to inform ore genesis and provide comparisons to the extensive database developed for the Navan deposit.
- Interrogation of drill-core intersections and current geochemical data bases, using Leapfrog and ioGas software to explore timing of metallogenesis relative to rifting and investigate stratigraphic differences and similarities between the development of Tara Deep and Navan deposit pre-, syn- and post-rift, sequences thus complementing current research.
- Digital structural analyses as drilling proceeds.

The magmatic evolution of post-subduction suites: the Metaliferi Mountains, Romania and Fiji

V. V. ENE¹, D. SMITH¹, J. NADEN², E. ROSU³, M. MUNTEANU³

¹ University of Leicester, Department of Geology, University Road, Leicester LE1 7RH, UK
(yve1@le.ac.uk, djs40@le.ac.uk)

² British Geological Survey, Environmental Science Center, Nicker Hill, Keyworth, Nottingham, NG12 5GG

³ Institutul Geologic al Romaniei, Ștrada Caransebes, nr 1, sector 1, Bucuresti
(munteanu.marian@igr.ro)

Even though tellurium is becoming a critical metal for a modern, advanced society, the underlying processes that lead to its enrichment in Au-rich deposits are still debated. A relationship has been observed between Te enrichment and post-subduction settings, and one of the key mechanisms is thought to be the melting of sulphide-bearing arc cumulates or metasomatized lithospheric mantle [1]. Due to their strongly chalcophile/siderophile nature, elements like Te and Au will be enriched in sulphides residual in the mantle, or fractionated into cumulates.

Two notable post-subduction settings are the Neogene suites of the Metaliferi Mountains, Romania, and Viti Levu, Fiji, host to world-class mining districts (e.g. Sacaramb in Romania and Vatukoula Gold Mines in Fiji). In Fiji, post-subduction extension produced mafic, alkaline (potassic) suites, after a period of intra-oceanic arc activity that produced tholeiitic and calc-alkaline basalts to andesites [2]. The Metaliferi Mountains' history is more complex, encompassing three different magmatic events in the Jurassic (back-arc ophiolite and island arc granitoids), late Cretaceous (subduction-related magmatic arc) and the Neogene post-subduction suites [3]. This led to the formation of volcanic rocks ranging from basaltic andesites to rhyolites. Both suites contain rocks with high Sr/Y values, perhaps indicating high magmatic H₂O. Post-subduction rocks in both locations have arc-like trace element profiles, with enriched fluid-mobile incompatibles (Ba, Rb, Sr), LREE, and relatively depleted HFSE and HREE. The relative enrichments and depletions are somewhat enhanced post-subduction relative to the syn-subduction, a phenomenon that cannot be readily explained through fractionation or lower degrees of partial melting; it implies an enrichment in the source region. Partial assimilation of arc cumulates may be responsible for the enhanced arc-like signature, and represents an additional source of the most chalcophile elements such as Te.

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The fate of SMS deposits, insights from natural and accelerated oxidation and implications for future mining activity

Emily K. Fallon^{1,2}, Richard Brooker¹, Thomas Scott²

¹School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol, BS8 1TJ, UK

² Interface Analysis Centre, School of Physics, University of Bristol, Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, UK
(correspondance:e.fallon@bristol.ac.uk)

As mining of seafloor massive sulphide (SMS) deposits edges closer to reality, with Nautilus Minerals Inc. poised to commence production offshore of Papua New Guinea by 2019, it is imperative that we have a full understanding of the deposit characteristics, the natural processes affecting their economic worth and the environmental impact associated with the mining process. Acid rock drainage is a natural oxidation process that is often exacerbated by mining activities, and this type of pollution is common in terrestrial sulphide mines. A related weathering process also occurs on SMS deposits, and the prospect of seafloor mining in the future raises similar environmental concerns. Unlike terrestrial deposits, it is assumed the seafloor sulphides are converted to oxides with negligible metal release and minimal net acid generation due to the buffering capacity of seawater and low solubility of iron at near neutral pH. Whilst a few dissolution studies of specific sulphide minerals in seawater exist, the majority are within the context of acid mine drainage related to terrestrial mines.

By investigating the oxidative dissolution of SMS deposits in both a natural and anthropogenically-enhanced context, we highlight some important parameters that should be considered for future mining activity. In this study, the fate of metals throughout the natural oxidation process has been investigated using SMS samples at various stages of evolution covering a range of bulk chemistry, mineralogy and trace element chemistry. Potential toxicity was assessed for samples from a wide range of tectonic settings (high temperature vent, ultra-mafic hosted, back-arc rift, hot spot) considering the specific mineralogy, trace element chemistry and other factors such as sample surface area. Following the mining process outlined by Nautilus Minerals Inc., an experimental approach was designed to simulate shipboard dewatering and subsequent return of water to the seabed, providing an understanding of accelerated oxidation and assessment of heavy metal release. Toxicity potential of mining different deposits was evaluated by comparing concentrations observed in experiments to tolerance levels of species observed at active vents.

Results indicate that oxidised deposits have lost a significant amount of target metals, but deposits associated with inactive vents that contain secondary sulphides in the presence of abundant limonite may be of economic interest based on retention of some metals combined with the reduced toxicity associated with mining them. Experiments indicate that bulk chemistry alone cannot predict the toxicity observed during mining, and instead full characterisation of deposits and leaching tests with the full range of ore mineralogy from prospective sites is required. Arc-related deposits are shown to pose the highest toxic potential, whilst Cu rich ultra-mafic deposits can be considered a 'lower risk' prospect. Zn and Cd are of most concern based on observations of both natural and accelerated oxidation. Leaching experiments indicate that localised acid generation and toxicity is a real danger and requires a refinement of the mining process to protect the fragile and complex ecosystems associated with these deposits. Results provide insight into how mining parameters can be adapted to minimise toxicity including processed grain size, fluid-rock ratio and dilution requirements. Ultimately, this study highlights a need to better understand the response of ecosystems that call these deposits home.

Mid-Proterozoic Crustal Recycling and Rare Element Deposits in the Gardar Province, S Greenland

Adrian A. Finch ^{*1}, Anouk M. Borst¹, William Hutchison¹, Nicola J. Horsburgh¹, Tom Andersen², Siri Simonsen²

1 - School of Earth & Environmental Sciences, University of St. Andrews, KY16 9AL, U.K.
(aaf1@st-andrews.ac.uk)

2 - Department of Geosciences, University of Oslo, Po Box 1047. Blindern NO-0316, Norway

The Gardar Province of Greenland refers to alkaline magmatism from intraplate rifting in the Mesoproterozoic. It is a period of geological history associated with several substantial rare element deposits, including the Nb-Ta deposit at Motzfeldt, the Ti-V deposit at Isortôq, the REE-Zr-Nb-Ta deposit at Ilímaussaq. To understand further the sources of heavy REE and HFSE in the Gardar, we analysed the Lu-Hf isotopes of several Gardar centres, representing early and late Gardar magmatism and the geographical extent of the Province from Ivigtut in the West to Paatusoq in the East.

Age-corrected Hf isotopes show low Hf values inconsistent with sourcing from depleted mantle in Gardar times. Early Gardar zircons have significantly lower age-corrected Hf than those of the Late Gardar. Hf signatures in Early Gardar zircons project back to Ketilidian or older mantle extraction ages (> 1.8 Ma). One might interpret such data to indicate that Hf in the Early Gardar zircons was scavenged from Ketilidian basement. However, primary Gardar melts are unlikely to have contained negligible Hf and an unrealistic proportion of assimilated Ketilidian Hf is required.

The data are consistent with a model whereby subduction of Archaean crust (i.e. very low $^{176}\text{Hf}/^{177}\text{Hf}$) during the Ketilidian enriched the subcontinental lithospheric mantle with Archaean Hf. In Gardar times, mantle melting preferentially accessed this subducted (Archaean) mantle component, providing magmas with anomalously low Hf isotopic ratios. As rifting continued, proportionately more contemporary Hf was present in the melts. The model suggests recycling of Archaean crust via the mantle in Gardar times and helps explain the significant numbers of rare element deposits formed in Gardar times. Such processes may be important in providing the conditions for rare element deposit formation throughout geological time.

Constraints on the behaviour of trace metals in volcanogenic massive sulphide deposits based on LA-ICP-MS data from the actively-forming TAG deposit, Mid-Atlantic Ridge

Hannah L.J. Grant¹, Mark D. Hannington¹, Sven Petersen¹, and Matthias Frische¹

¹GEOMAR Helmholtz Centre for Ocean Research, Kiel
Wischhofstrasse 1-3, D-24148 Kiel, Germany
Email: hgrant@geomar.de

There is systematic behaviour of trace and ultratrace metals in seafloor hydrothermal systems that can be directly linked to primary ore-forming and subsequent secondary modification processes, dissolved metal-complexing in hydrothermal fluids, and mechanisms of metal incorporation in sulphide minerals. We investigated the behaviour of trace metals in the active basalt-hosted TAG seafloor hydrothermal system on the Mid-Atlantic Ridge, one of the largest known currently-forming seafloor massive sulphide deposits, by analysing multiple generations of pyrite formed under well-constrained conditions in the subseafloor. In particular, the trace element geochemistry of pyrite, which is the dominant mineral in the TAG deposit, records a number of different processes related to the evolution of the deposit. Mineral mass balances and element budgets show that pyrite is the principal host for many of the trace and ultratrace elements, in contrast to other deposits that have experienced less zone-refining.

Laser ablation inductively-coupled mass spectrometry (LA-ICP-MS) has been used to investigate the concentration and distribution of trace metals in pyrite and to distinguish between multiple episodes of mineralization on a millimeter to micrometer-scale. Trace metal signatures show systematic partitioning into seven distinct pyrite textures. Lattice-bound elements such as Co, Se, Ni, Mo, and Tl discriminate primary high-temperature trace-metal-depleted pyrite and primary lower-temperature trace-metal- and inclusion-rich pyrite from recrystallised secondary lower-temperature trace-metal-depleted pyrite. The incorporation of different trace metals into pyrite occurs by (i) lattice substitution, (ii) sulphide micro-inclusions, (iii) surface adsorption, or (iv) the inclusion of metalliferous nanoparticles. Known thermodynamic properties of minerals and dissolved species, and a detailed paragenetic history allows constraints on the physico-chemical conditions of primary and secondary pyrite formation at TAG, and fingerprinting of hydrothermal fluid fluctuations at both a deposit- and mineral-scale.

Comparisons to other mid-ocean ridge deposits indicate that the mature TAG deposit is depleted in many trace and ultratrace elements due to over-refinement, but is notably enriched in Co, Ni, and Se, indicating the retention of these elements in the pyrite structure, and possibly either an ultramafic footwall contribution to the element budget or a primary Co, Ni, and Se-enriched end-member hydrothermal fluid.

Multiple episodes of propylitic alteration discriminated by hydrothermal titanite U-Pb petrochronology at Oyu Tolgoi porphyry Cu-Au district, Mongolia

Lisa Hart^{1,2}, Robin Armstrong² and Jamie Wilkinson^{1,2}

¹Imperial College London, London, SW7 2AZ (l.hart14@imperial.ac.uk)

²Natural History Museum, Cromwell Road, London, SW7 5BD (j.wilkinson@nhm.ac.uk; r.armstrong@nhm.ac.uk)

There is currently a focus on research into the trace element chemistry of alteration minerals within the far-reaching and subtle geochemical footprints of known hydrothermal ore deposits, as researchers aim to develop new techniques for mineral exploration that could be used as vectors to new discoveries that may occur undercover or at depth. The propylitic halo of porphyry deposits is one area where systematic variations in the concentrations of key pathfinder elements within certain minerals have been identified as useful guides towards the centre of these systems^[1,2]. Porphyry systems, however, are complex and it is common for porphyry alteration to be overprinted by later alteration events or by regional metamorphism, especially in ‘older’, long lived porphyry camps such as the Central Asian Orogenic Belt, which hosts Paleozoic porphyries including the world class Oyu Tolgoi (OT) porphyry Cu-Au deposits of Southern Mongolia. In complex systems such as OT, in order to elucidate any truly useful patterns in trace element mineral chemistry, we need to be able to distinguish porphyry related propylitic assemblages from later overprinting events.

Titanite $\text{CaTi}[\text{SiO}_4](\text{O},\text{OH},\text{F})$ is an accessory phase common to propylitic assemblages, and can incorporate trace amounts of uranium and thorium into its structure making it a useful geochronometer. In-situ LA-ICP-MS U-Pb analysis of hydrothermal titanite within propylitically altered rock samples from across the OT district identified distinct multiple episodes of titanite growth at approximately 370 Ma, 340 Ma, 320 Ma and 290 Ma. These dates are consistent with known major intrusive events in the district including porphyry emplacement and mineralisation in the late Devonian, the intrusion of granodiorite plutons, andesite dykes, and rhyolite dykes and sills in the early Carboniferous, a second pulse of granodiorite and granite plutonism later in the Carboniferous, and finally emplacement of the Khanbogd Granite in the Permian. Propylitic titanite records episodic growth in the OT district. Propylitic assemblages at OT may therefore be associated with porphyry mineralisation, or could be associated with later non-mineralising magmatic activity. Through titanite petrochronology it is now possible to definitively classify porphyry and non-porphyry alteration in a rock sample. The ability to classify alteration in this way is critical in the development of geochemical vectoring tools, as we can be confident that alteration observed in the rock is the same age as known mineralisation in a porphyry camp.

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Clumped C-O isotope temperature constraints for carbonate precipitation associated with Irish-type Zn-Pb orebodies

Steven P. Hollis^{1,2}, Julian F. Menuge¹, Aileen L. Doran¹, Paul Dennis³, Brett Davidheiser-Kroll⁴, Alina Marca³, Jamie Wilkinson^{5,6}, Adrian Boyce⁷ & John Güven¹

¹ICRAG, University College Dublin, Ireland (steve.hollis@icrag-centre.org)

²Geological Survey Ireland, Dublin, Ireland

³University of East Anglia, Norwich, UK

⁴University of Colorado Boulder, Colorado, USA

⁵Natural History Museum, London, UK

⁶Imperial College London, London UK

⁷SUERC, Glasgow, UK

Clumped C-O isotope analysis of carbonate phases offers a powerful new technique to deliver accurate fluid temperatures and fluid O isotope compositions, refining current models and developing new tools for exploration. The technique relies on the degree of ordering of rare ¹³C and ¹⁸O isotopes in the carbonate mineral lattice, with an increasingly random distribution at higher temperatures. Of particular importance is the ability to obtain accurate temperatures for phases that contain fluid inclusions often too small (<3 µm) for conventional analysis. These include black matrix breccias (BMBs) intimately associated with Zn-Pb mineralization throughout the Irish orefield, and hanging-wall white matrix breccias (WMBs). In addition, ¹⁸O and ¹³C of fluids in equilibrium with carbonates can be determined as part of the same isotopic analyses.

We present the first clumped C-O isotope results for paragenetically constrained carbonate phases from several Irish-type deposits. Preliminary analysis of dolomite from hanging-wall WMBs from Lisheen shows no systematic temperature variations (100-170°C) towards mineralization, although calculated fluid δ¹⁸O increases with temperature. Post-ore pink dolomite at Lisheen and crosscutting calcite veins formed at significantly lower temperatures (67 to 42°C). Clumped C-O isotope temperatures of 61 to 110°C were obtained for sphalerite-bearing calcite veins from the hanging-wall of the Randalstown Fault near Navan. This temperature range is similar to the spread of fluid inclusion temperatures within individual samples for carbonate veins from above the Randalstown Fault (e.g. 68-92, 73-102, 85-102, 69-133°C). A comparison between clumped and standard fluid inclusion temperatures reveals a close match between datasets (e.g. Clumped T / T_{homog} = 89 / 81°C, 107 / 93°C, 110 / 109°C) using the UEA calibration equation ($\Delta 47 = ([0.0389 \times 10^6]/T^2) + 0.2139$). Extrapolation of this calibration line passes through a sample of Carrara marble experimentally re-crystallised at 600°C and 1000 MPa before quenching.

Oral Presentation preferred

Sm-Nd and Pb isotope mapping of the pre-Carboniferous basement of Ireland: implications for Zn-Pb mineralization

Steven P. Hollis^{1,2}, Julian F. Menuge², Aileen L. Doran¹, Stephen J. Piercey³, Mark R. Cooper⁴, J. Stephen Daly², Oakley Turner⁵ & Brian McConnell¹

¹Geological Survey Ireland, Dublin, Ireland (steve.hollis@icrag-centre.org)

²iCRAG, University College Dublin, Ireland

³Memorial University, Newfoundland, Canada

⁴Geological Survey of Northern Ireland, Belfast, UK

⁵iCRAG, Trinity College Dublin, Dublin, Ireland

In the last 50 years, five orebodies have been mined and over 20 sub-economic prospects discovered in the Irish Zn-Pb orefield. Conditions required for the formation of Irish-type Zn-Pb deposits include normal faults that allowed ascending, warm, metal-bearing fluids equilibrated with Lower Palaeozoic basement to mix with sinking, cooler, hypersaline brines that carried bacteriogenically reduced dissolved sulfide. A key, understudied aspect of this metallogenic environment is the role that inherited Caledonian terranes and structures have on the regional distribution of metals and the focussing of hydrothermal fluids from depth.

Our research aims to use Sm-Nd and Pb isotopic methods to identify and map Lower Palaeozoic Caledonian terranes across Ireland. Areas of juvenile and evolved crust will be identified through variations in Nd_{2DM} (two-stage Nd isotope evolution model age) and εNd_t of granites and felsic volcanic rocks. Through a similar method using Pb isotope constraints from galena occurrences, a more direct link to mineralization will be established. This research follows several cutting-edge studies across Australia which have highlighted the effectiveness of the combined Pb and Sm-Nd isotope systems to detail regional-scale crustal evolution and mineral prospectivity^[1].

Preliminary Pb isotope maps of Ireland have been produced with data compiled from 11 peer-reviewed sources (n=504), complemented by new data (n=63) from galena occurrences across Ireland not previously analysed (e.g. Kilbricken, Rapla, Curraghinalt, Navan - Tara Deep, Lisheen – Island Pod, Whitespots). In this preliminary dataset, variations in ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, ²⁰⁸Pb/²⁰⁴Pb and μ (source rock ²³⁸U/²⁰⁴Pb) correspond well with known terrane boundaries in most areas, with significant differences across the Iapetus Suture. Apparent ²⁰⁷Pb/²⁰⁴Pb vs ²⁰⁶Pb/²⁰⁴Pb mixing trends are deposit specific and reflect the derivation of Pb from two sources – probably Laurentia (μ 9.2) and Ganderia (μ 9.9). High μ for galena from the Down – Longford Terrane is interpreted to reflect the presence of Ganderian basement underlying the outcropping Silurian accretionary prism. Relative to other parts of the Leinster – Lakesman Terrane, anomalously low μ values are mapped for the Rathdowney Trend (host to mineralization at Lisheen, Galmoy and Rapla). Lead isotope data from galena occurrences in Newfoundland has also been compiled (n=294) and will be discussed with respect to regional terrane correlations across the Caledonian-Appalachian orogen.

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Poster Presentation preferred

Tellurium as a tracer of the lithospheric flux of volatiles and metals in post subduction settings

David A. Holwell^{1*}, Marco Fiorentini², Daniel J Smith¹, Manuel Keith¹ and Iain McDonald³

¹School of Geography, Geology and Environment, University of Leicester, UK
(dah29@le.ac.uk)

²Centre for Exploration Targeting, School of Earth Sciences, ARC Centre of Excellence in Core to Crust Fluid Systems, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.

³School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff, CF10 3AT, UK

Magmatic arcs are host to some of the greatest metal concentrations on Earth, with such deposits fundamentally linked to magmatic and hydrothermal processes in subduction and/or post-subduction settings. During active subduction, arc magmatism is voluminous and basaltic to andesitic in composition, forming Cu, Mo, Sn W deposits. In contrast, post-subduction settings are characterised by relatively small volume and predominantly alkaline magmatism that is enriched in Te and Au.

Through a series of post-subduction magmatic systems, we show the chalcophile element evolution from the mantle source, through the lower and mid crust to the upper crust. These systems have a number of commonalities: they are low volume, hydrous melts that produce an alkaline chemistry from ultramafic (lower crust) through to phonolitic (uppermost crust); and secondly, they are characteristically enriched in Te and Au, relative to other chalcophile metals found in magmatic ore systems. We propose there is a continuum of magmatism and metal transport sourced from subduction metasomatised mantle and then transported up through the crust. In this, the chalcophile metal signatures record a number of processes including: metal extraction from Au-Te-rich mantle source; sulfide saturation in the lower crust; sulfide dissolution in the mid crust, which is a key precursor to producing melts for the upper crust that are enriched in Cu-Te-Au, and prime those magmas to form magmatic-hydrothermal deposits of these elements.

This set of processes represents one of the greatest fluxes and concentrations of Au and Te on Earth. Furthermore, the link between alkaline magmatism and Te-Au mineralisation in post subduction settings is not mutually causative. Rather, the alkaline nature of the igneous rocks, and the Te-Au-rich nature of the metal budget are separate functions of the partial melting of a hydrous, subduction metasomatised mantle source.

Luminescence as a tool for Smart Sorting of Ore

Nicola J. Horsburgh^{1*} and Adrian A. Finch¹

¹School of Earth and Environmental Sciences, University of St. Andrews, KY16 9AL.
(*njh36@st-andrews.ac.uk)

Run-of-mine (ROM) material consists of ore mineral/s, gangue and potential deleterious minerals. Optimising the ROM at the sorting stage reduces energy consumption, water usage and processing time by reducing waste before the ore enters the crushing and concentration, separation stages. This increases the productivity and results in processing of higher grade ore and increased overall recovery of target product.

Luminescence is invoked by X-ray techniques, such as X-ray Fluorescence (XRF) and X-ray Transmission (XRT), also by excitation with photons from optical sorting operating 3-D lasers, making the coupling of luminescence to existing sorting methods practical. For example, diamonds are separated from gangue minerals by X-ray luminescence methods, and in principle the same ‘fingerprinting’ can be applied to REE minerals.

REE minerals show characteristic luminescence emission lines related to f-f energy cascades in lanthanide (III) ions. Many minerals, however, contain multiple REE, local defects (including chemical substitution) and lattice damage. These features affect the energy cascades and quantum efficiency of REE leading to complex spectra. We have investigated the radioluminescence (RL) of several REE-bearing minerals, including bastnaesite, catapleiite, eudialyte, fluorite and monazite from multiple localities. Most REE ore minerals are luminescent. Common features include isolated REE emissions, evidence for energy transfer between REE, thermoluminescence (TL) and thermal hysteresis of luminescent properties. Luminescence spectra from these minerals show a strong provenance dependence, with the same mineral from different localities producing quite different spectra.

These data show that smart sorting of REE ore based on X-ray or laser excited luminescence is feasible. However one would need to characterise the ore mineral from that particular locality rather than using ‘off the shelf’ spectral features common to a particular mineral types.

Seamount-scale variability of E-tech elements in ferromanganese crusts: Tropic Seamount, NE Atlantic

Sarah Howarth^{*1}, Bramley Murton¹, Isobel Yeo¹, Paul Lusty²

¹National Oceanography Centre Southampton, SO14 3ZH (*S.A.Howarth@soton.ac.uk)

²British Geological Survey, Nottingham, NG12 5GG

The demand for the critical raw materials required to sustain the expansion of renewable energy technologies is increasing rapidly. Many of these “E-tech elements”, including cobalt (Co), tellurium (Te) and rare earth elements (REEs), suffer from a high risk of supply-shortage. As a result, this is driving research into alternative and more diversified metal resources. Ferromanganese (FeMn) crusts form globally by direct precipitation of Mn-oxides and Fe-oxyhydroxides from seawater and encrust large areas of the seafloor [1]. They present a potentially important future source of E-tech elements, with average Co concentrations of 0.5 wt% and Te concentrations of 50 ppm [this study; 2, 3]. Until now, most studies utilised disperse and sparse sample sets collected across ocean basins using spatially imprecise dredging techniques. Yet crust formation and composition is dependent on a large range of local conditions, including biological productivity, sediment supply and current energies [4], hence the demand to understand the role of seamount-scale processes. Here, I focus on the local-scale processes controlling FeMn deposit formation and the extreme enrichment of elements such as Te, Co and REEs.

Samples were collected as part of a comprehensive and holistic study of Tropic Seamount, NE Atlantic (Fig.1). Systematic ROV sampling collected crust samples from a range of substrate lithologies, local hydrographic conditions, outcrop morphologies and local environments. Outcrop mapping from high-definition videos show crust environments and features at a range of depths on the seamount are delineated by a series of “type” environments. These are combined with SEM images of crust surfaces to determine trends in the distribution of recent crust growth. While ICP-MS analyses show trace element compositions vary with depth, as expected, there is a similarly large variation laterally, reflecting local conditions of formation. Understanding how these control the distribution of metals of interest is key to developing mining protocols which maximise output and minimise negative impacts, particularly environmental impacts that may pose a barrier to future exploitation.

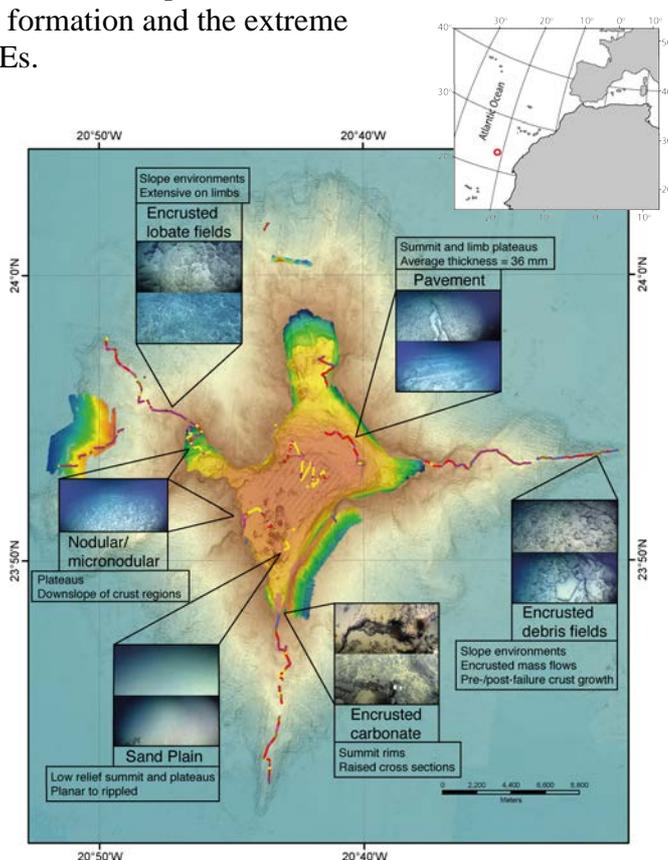


Figure 1 (inset) Location of Tropic Seamount and (main) showing different crust environments mapped from direct observation during ROV dives. Systematic changes in crust are observed according to spatial environment on the seamount.

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Pyroxenite xenoliths and their metal budget: Implications for the metallogeny of subduction zones and the source regions of Cu-porphyry mineralisation

Hannah S. R. Hughes^{1*}, Magdalena M. Matusiak-Malek², Iain McDonald³, Ben Williamson¹

¹ Camborne School of Mines, University of Exeter, Cornwall, UK (*h.hughes@exeter.ac.uk)

² University of Wrocław, Wrocław, Poland

³ School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK

Pyroxenite xenoliths are characterized by cumulus textures and may be of upper mantle and/or lower crustal origin. On the basis of trace element geochemistry for Scottish pyroxenite xenoliths (and other global examples), these rocks have been interpreted as fragments of crystallized basaltic (alkaline and tholeiitic) magma underplating the continental crust (Downes et al., 2007). Therefore pyroxenite xenoliths may be directly analogous to material from the melting, assimilation, storage and homogenization ('MASH') zone overlying subduction environments (Hildreth & Moorbath, 1988; Richards, 2003 and references therein), and hence provide a unique insight into the magma and metallogenic processes operating at depth below porphyry mineralising systems.

We will use Scottish and Swedish pyroxenite xenoliths to assess the palaeotectonomagmatic environment of the Grampian event (active oceanic subduction) of the Caledonian orogeny (e.g., Atherton & Ghani, 2002). Through *in situ* mineralogical and geochemical analysis of base metal sulphides in these pyroxenites, we can gain an insight into the metal budget and its mobility (including precious and critical metals) in the suprasubduction mantle wedge and overlying MASH zone. This study will ascertain: (1) what were the parental melts (and/or metasomatic characteristics) of these cumulates? And (2) what was the metal budget for the pyroxenitic lithology, in the context of the mineralization potential of the region? Direct analysis of pyroxenite metal budgets via *in situ* analysis of Cu, Co, Mo, Au and precious metal-bearing mineral phases (sulphides) has thus far been largely overlooked.

Scotland has experienced multiple tectono-magmatic events and provides an ideal framework in which to assess the metallogenic record of the lithospheric mantle and lowermost crust through time. *In situ* sulphide analysis of Scottish peridotite xenoliths has shown that there are regional trends in metal content. Caledonian basement forms the southern terranes of Scotland (south of the Great Glen Fault, GGF) providing a direct comparison between on- and off-craton lithospheric mantle and lower crust geochemistry. Cobalt is consistently elevated in sulphides from peridotite xenoliths south of the GGF (> 2.9 wt.% Co) but only present in trace levels in sulphides from peridotite xenoliths north of the GGF (< 0.36 wt.% Co). The cause for Co enrichment south of the GGF remains unclear, but it is suggested that the subduction of the Iapetus during the Caledonian Orogeny was critical to this process [1]. In this way, the lithospheric mantle and the lowermost crust (including the MASH zone) may act as a record for slab-derived partial melts, metasomatism and volatiles – they are our direct insights into metal mobility at this depth and may be fundamental to testing previous model-based predictions centred on lava and/or intrusive rock composition from palaeo or active arcs.

Through this study, we aim to ascertain the underlying controls on subduction-related metallogeny. Thus we seek to understand how these rocks might melt and how much metal they may contribute to a magma in doing so. This project is funded by the Polish National Science Centre grant no. UMO-2016/23/B/ST10/01905.

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The potential of deep eutectic solvent ionic liquids for processing chalcophile critical elements

Gawen RT Jenkin¹, Hugh Graham¹, Daniel J Smith¹, Andrew P Abbott², David A Holwell¹, Eva Zygouri¹, Robert C Harris², and Christopher J Stanley³

¹Department of Geology, University of Leicester, LE1 7RH, UK (grtj1@le.ac.uk)

²Department of Chemistry, University of Leicester, LE1 7RH, UK

³Earth Sciences Department, Natural History Museum, London SW7 5BD, UK

Gold and copper concentrates often contain high enrichments of scarce or critical elements such as Te, Bi and Sb, but there are few financial incentives for recovery of these elements as by-products. Deep eutectic solvents (DES) may provide novel processing opportunities – these are a form of ionic liquid that are mixtures of salts such as choline chloride with hydrogen-bond donors such as urea. DESs are environmentally benign, yet chemically stable and, furthermore, the components are already produced in large quantities at low cost.

We have demonstrated that gold is rapidly dissolved in DES by iodine oxidation [1,2], whereas many base metal sulfides are unreactive or react only slowly. However, most trace minerals that host the majority of Te, Bi and Sb in a concentrate, such as native Te and Bi, tellurides, or Bi- or Sb-bearing sulfosalts, are rapidly dissolved at similar rates to gold, suggesting routes to recovering gold *and* critical elements.

Systematic patterns are observed in the leaching rate in homologous mineral series, for example Ag₂Te leaches more rapidly than Ag₂S and in turn that leaches more rapidly than Ag₂Se. Similarly the leach rates for HgTe > HgS > HgSe. Sometimes sulfides leach most rapidly, e.g. Bi₂S₃ > Bi₂Te₃ > Bi₂Se₃. In all cases investigated so far the selenide leaches the slowest suggesting lower solvation energy. These observations are enabling us to predict and quantitatively model the bulk leaching behavior of various ore concentrates and design bulk leaching tests.

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Low temperature pyrite to pyrrhotite reduction in black shales: implications for metal mobility at low metamorphic grades

S.C. Johnson^{1,2}, R.R. Large², T.D. Raub³, A.J. Boyce⁴, B.J. Cave⁵, P.A. Meere¹

¹iCrag, School of Biological, Earth and Environmental Sciences, University College Cork, Ireland
(sean.johnson@ucc.ie)

²CODES- ARC Centre of Excellence in Ore Deposits, University of Tasmania, Hobart, Australia

³Dept. of Earth and Environmental Sciences, University of St. Andrews, St. Andrews, Scotland

⁴Scottish Universities Environmental Research Centre, East Kilbride, Scotland

⁵Sciences de la Terre, Université du Québec à Chicoutimi, Canada

Pyrite and pyrrhotite are common sulfide minerals in organic-rich sediments and their metamorphic equivalents. During prograde regional metamorphism desulfidation reactions pyrite commonly recrystallizes to pyrrhotite. In most geological systems this breakdown is typically constrained at middle-greenschist facies temperatures and above (i.e. >350°C, Toulmin and Barton, 1964; Craig and Vokes, 1993; Pitcairn et al., 2006; Large et al., 2011).

However, we present compelling results from a controlled-temperature laboratory rock magnetometry detection study on pyrite samples from Mina Ampliación, Spain that observes a significant increase in isothermal remnant magnetization at ~170°C. This, we suggest, marks the early breakdown of pyrite to form pyrrhotite. In addition, we present observational and in-situ trace element geochemical data from two real-world examples (Narva deposit, Estonia; Pechenga Belt, NW Russia) of pyrite converting to pyrrhotite at conditions below greenschist facies.

Trace element analyses reveals that during recrystallization S, Au and As are likely the first to be liberated in early stages of reduction to pyrrhotite, followed by Cu, Zn, Pb, Bi and Cd. These results are supportive of recent models for orogenic Au mineralization whereby the recrystallisation of sedimentary pyrite to pyrrhotite releases trace elements that are suggested to be the source of metals in these deposit class. Furthermore, the low-temperature recrystallization of pyrite to pyrrhotite observed in this study, suggests that sub-greenschist facies rocks may also be prospective for large tonnage low-grade Au deposits.

Overall, we suggest that the low temperature transformation of pyrite to pyrrhotite requires mineral-scale solid-state diffusion-limited reactions, or the formation of pyrrhotite inclusions or domains within pyrite. Sufficient reduction potential to aid this recrystallisation reaction, we suggest is provided by the concurrent breakdown of organic matter in the shale during catagenetic to low-metamorphic conditions.

Fluid flow and alteration associated with the ~1.1Ga White Pine sediment-hosted copper deposit, Michigan, USA.

Jones, S.M.¹, Cloutier, J.², Raub, T.D.³ and Prave, A.R.⁴

¹ School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL, UK (smj5@st-andrews.ac.uk)

² School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL, UK (Jonathan.Cloutier@st-andrews.ac.uk)

³ School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL, UK (timraub@st-andrews.ac.uk)

⁴ School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL, UK (ap13@st-andrews.ac.uk)

The White Pine and Copperwood deposits form part of a giant (>2Mt contained copper) sediment-hosted stratiform copper system in the ~1.1 Ga Midcontinent Rift System (Bornhorst & Williams, 2013). Copper sulphide mineralisation occurs predominantly as disseminations in the basal Nonesuch Formation overlying immature conglomerates and sandstones of the Copper Harbor Formation.

Previous work (e.g. Mauk et al., 1992) proposed two-stages of copper mineralisation. An early-diagenetic phase of mineralisation at ~1075 Ma is postulated to have replaced bacterial sulphate reduction-derived pyrite to form stratiform Cu ± Fe-sulphides. A second phase of mineralisation at ~1060 Ma is described as dominantly native copper introduced along reverse faults during the Grenville Orogeny, overprinting and upgrading earlier syn-diagenetic mineralisation and partially replacing interstitial petroleum in sandstones beneath White Pine.

We present new data which indicate copper mineralisation at White Pine formed earlier in the basin history than has previously been thought, and possibly during one single event. Mineralising fluids were focused where syn-sedimentary faults dissect an anticlinal petroleum trap at White Pine. A fluid-rock reaction between mineralising fluids and pyrite and situ organic matter formed Cu-sulphide minerals in the Nonesuch Formation. In the footwall sandstone of the Copper Harbor Formation, a fluid-fluid reaction between the mineralising fluid and petroleum formed native copper in the absence of sulphur.

We also demonstrate the importance of basin architecture and sedimentology in the genesis of these copper deposits. Features indicative of tidal and marine environments, together with evaporite textures, suggest seawater was the likely source of Cl⁻ ligands for aqueous copper transport and that evaporite formation and, or, dissolution may have contributed sulphur to basinal fluids.

The distribution of peak temperatures in the Nonesuch and Copper Harbor formations, estimated from illite-smectite crystallinity using XRD and carbon maturity using Raman spectroscopy, are best explained by burial. We therefore favour burial compaction as the dominant mechanism of fluid drive during mineralisation at White Pine and Copperwood. The White Pine and Copperwood deposits occupy the flanks of a paleo-topographic high where the basal portion of the Nonesuch Formation is particularly rich in organic carbon, and would have experienced an abnormally high fluid flux during basin dewatering.

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Spatial and temporal variability of critical metals in ferromanganese crusts from Tropic Seamount, north-east Atlantic

Pierre Josso¹, Paul Lusty¹, Simon Chenery¹, Matthew Horstwood¹, Jeremy Rushton¹, Bramley Murton²

¹British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, UK. (piesso@bgs.ac.uk)

²National Oceanography Centre, European Way, Southampton SO14 3ZH, UK

Ferromanganese (Fe-Mn) crusts are marine mineral deposits formed by the accumulation of Fe and Mn colloids onto rock surfaces in high-energy environments such as seamounts, ridges and oceanic plateaus. The precipitation of Fe and Mn oxyhydroxides from seawater is triggered by redox changes caused by the mixing of different water masses around these topographic anomalies. The extremely slow accumulation rates of Fe-Mn crusts (a few mm/My) and other physical properties mean these reactive particles are very effective at scavenging trace metals (e.g. Co, Te ± Pt) from seawater, resulting in concentrations rarely encountered in other ore-forming environments. Accordingly, these extensive marine deposits are considered to be a major repository of many critical metals required by high technology and green energy applications.

Our general understanding of the major oceanographic and geological processes controlling their formation (e.g. water depth, topography, sedimentation rates) has permitted delineation of the most prospective zones in the oceans and global estimates of their total metal resources. However, the local-scale oceanographic processes affecting their lateral continuity, thickness and grade at the seamount-scale are poorly constrained.

We present preliminary results of the study of a large and unique suite of Fe-Mn crust samples, acquired during the ‘MarineE-Tech’ project expedition to Tropic Seamount, in the north-east Tropical Atlantic. Samples from the summit of the seamount (1100 m beneath sea level) were recovered by in situ drilling of the Fe-Mn crust pavements, using a remotely operated vehicle (ROV)-mounted drill, which provides excellent spatial control on the location of samples. We report the results of a high-resolution geochemical profile obtained from micro-drilled subsamples, and LA-ICP-MS Pb isotope data to investigate the spatial and temporal variation in Co, Te and Pt content of crusts from Tropic Seamount.

The NERC MINEX advanced training course: workflow for green field exploration of mineral deposits in Milos, Greece.

Pierre Josso¹, David Cavell², Nicky Horsbrough³, Eva Marquis⁴, Andrew Martin⁵, Katie McFall⁵, Jonathan Naden¹

¹British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, UK

²School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT

³School of Earth and Environmental Sciences, University of St Andrews, North Street, St Andrews, KY16 9AL

⁴School of Environment and Technology, University of Brighton, Lewes Road, Brighton BN2 4GJ

⁵School of Earth & Ocean Sciences, Cardiff University, Park Place, Cardiff, CF10 3AT

The mineral exploration industry requires numerate, multidisciplined geoscientists with a strong core of field-based observational skills coupled with knowledge of field-based instrumentation. The MINEX workshop is a NERC financed training opportunity for PhD students and early career researchers to gain experience in the various techniques employed by the mining industry for the exploration of new deposits related to volcanic and magmatic processes.

Last summer, XX young scientists followed this program with application of their training on the exploration of the wealth of the Greek island of Milos. Located in the Aegean Arc, recent and ongoing geothermal activity has resulted in a variety of prospects related to epithermal and low-temperature hydrothermal style deposits.

Starting with 3 days of preparation for the initial reconnaissance of the island, the participants were introduced to the interpretation and analysis of remote sensing data using high-resolution airborne imagery in BGS' offices near Nottingham. Four prospects were identified as potential deposits requiring further exploration and ground truthing. Campaign planning was realised using a 3D visualisation suite to assess accessibility and suitability of exploration prospects with regard to the proximity of population centres. A 7 days fieldwork campaign was then organised on Milos to visit key localities of the island and investigate the different prospects. In addition to field observations, the exploration campaign integrated the use of several instrument technologies such as spectroscopy, portable XRF, portable XRD and ground LiDAR for the rapid acquisition of data while on site.

Following a work of synthesis on the data acquired, each prospect was discussed regarding the potential resource held by the deposit and the feasibility of an extraction including problematics of accessibility, processing techniques, sustainability, work ethics, social impacts and environmental hazards.

A new submarine hybrid-type between VHMS and epithermal-porphyry deposits, Brothers volcano, Kermadec arc

Manuel Keith¹, Karsten M. Haase², Daniel J. Smith¹, Reiner Klemd², Ulrich Schwarz-Schampera³, Wolfgang Bach⁴

¹University of Leicester, School of Geography and Geology, Leicester, LE1 7RH, UK
(mk528@le.ac.uk)

²GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Erlangen, D-91054, Germany

³Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, D-30655, Germany

⁴Fachbereich Geowissenschaften der Universität Bremen, D-28334 Bremen, Germany

Most magmatic-hydrothermal Cu deposits are genetically linked to arc magmas. However, most arc magmas are barren, and hence new methods have to be developed to distinguish between barren and mineralised arc systems. Source composition, melting conditions, the timing of S saturation and an initial chalcophile element enrichment represent important parameters, which control the potential of an arc setting to host an economically valuable deposit (Richard, 2011).

Brothers volcano is one of the best studied examples of arc-related submarine magmatic-hydrothermal activity. This study, for the first time, compares the chemical and mineralogical composition of the Brothers seafloor massive sulphides and the associated dacitic to rhyolitic lavas that host the hydrothermal system. The results presented here suggest that the circulating hydrothermal fluids were modified by a magmatic volatile component, which also affected the composition of the seafloor massive sulphide ores at Brothers volcano. Melt inclusion data and the occurrence of sulphides along vesicle margins suggest that a S-rich, Cl-poor and potentially Cu-bearing volatile phase exsolved from the Brothers melts. However, thermodynamic modelling calculations revealed that the melts reached volatile saturation subsequent to the onset of sulphide segregation. Copper is a chalcophile element, and hence it is highly compatible in immiscible sulphide liquids. Some of the Brothers magmatic sulphides have Cu contents similar to those of mid-ocean ridges (Keith et al., 2017), where Cu is commonly leached from the magmatic rocks that host the hydrothermal system. Consequently, we conclude that a combined process of Cu leaching and degassing may explain the formation of the Cu-rich seafloor massive sulphides at Brothers volcano (up to 35.6 wt. % Cu, de Ronde et al., 2011).

Similarities, between the Brothers magmatic-hydrothermal system and epithermal-porphyry deposits on land suggest that Brothers and probably other shallow marine island arc (and back-arc) hydrothermal systems may represent a new hybrid-type between those subaerial systems and classic Cyprus-type volcanic-hosted massive sulphide deposits.

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The Troctolite Unit of the Northern Bushveld Complex: Genesis and Mineralization Potential

B. Kennedy¹, I. McDonald¹, D. Tanner², L. Longridge³

¹School of Earth and Ocean Sciences, Cardiff University, Cardiff, CF10 3AT, (kennedyb1@cardiff.ac.uk)

²School of Earth & Environmental Sciences, University of Wollongong, Wollongong, NSW, Australia

³VM Investment Company (PTY) Ltd., 24 Flicker Road, Block A, Illovo, Johannesburg

The Main Zone (MZ) of the Bushveld Complex of South Africa is composed of gabbro-norite and generally lacks both olivine and platinum-group element (PGE) mineralization. Olivine reappears in the MZ of the northern limb of the Bushveld Complex as a >200 m thick PGE-enriched zone of olivine-norite cumulates known as the Troctolite Unit (TU). The TU appears to be absent from the eastern and western Bushveld Complex but olivine-rich rocks with PGE also characterise the lower (F Zone) part of the Waterberg PGE deposit, located further north. Any relationship (or not) between the TU and the F Zone remains to be established. This study is the first to tackle the petrology, mineralogy, geochemistry and PGE distribution in the TU and surrounding MZ to determine the genesis of the TU and its role within the stratigraphy of the northern limb. Samples were taken from Bushveld Minerals' VSF2 borehole, the Council for Geoscience BV1 stratigraphic borehole and outcrop samples.

Models suggesting that the TU represents a raft of Platreef or Critical Zone rocks, a new input of mafic magma into the MZ, or a post-Bushveld sill can all be dismissed on mineralogical and/or geochemical grounds. Detailed logging of the TU reveals: an absence of typical 'cyclic units' of harzburgite-troctolite-anorthosite; no evidence for mixing or reaction between TU and MZ; no thermal contacts with the surrounding MZ or within the TU; and limited evidence for either chromite or base metal sulphide (BMS)-rich PGE mineralisation. The TU shows unexpected textures and phases for a conventional 'dry' magmatic system including interstitial olivine (with melt and fluid inclusions), hydrous minerals, rounded and zoned plagioclase, mottles of olivine and pyroxene and noritic autoliths. The TU has constant An# and Mg# ratios throughout which do not change significantly between TU and MZ. Cr- and PGE enrichment are decoupled with the highest PGE grades found at and below changes between lithological subzones and high grade zones confined to less mafic lithologies (troctolite>anorthosite>harzburgite>pyroxenite). The TU is enriched in PPGE and depleted in IPGE and Au compared with the Platreef or Critical Zone. Fractionation of Pt and Pd also differs between PGE-enriched and depleted samples; enriched samples generally have Pt/Pd <1 whereas depleted samples have Pt/Pd >1. Platinum-group minerals (PGM) are fine grained with the majority of measured PGM < 1 µm in diameter (range between 50 µm - <100 nm). Distinctive PGM associations (either enclosed in silicate, enclosed in BMS or BMS-silicate alteration zone) characterise particular high grade zones with PGM types increasing in the order Sb>Bi>Te>alloy>As>Pb. There is strong textural evidence of fluid(s) reworking and redistributing PGM and leaching of PGE from BMS on a local scale. The majority of measured PGM are found in BMS-silicate alteration zones.

Based on the above observations, we propose that the TU formed during development of the MZ by fluid-driven flux melting reactions that transformed gabbro-norite proto-cumulates into the olivine-rich lithologies. Current PGE enrichment and mineralisation might have been localised by the redissolution of BMS or primary PGM in the fluid that caused the flux melting. This is evident in the size (< 2 mm) and distribution (highly disseminated) of BMS. Visible BMS are only found in areas of high fluid activity; at and below the change between lithological subzones, pegmatitic lithologies and in the reaction zone with a granite dyke.

On-going exploration for Ni-PGE mineralization in a shear/feeder zone through the centre of the Molopo Farms Complex, part of the Bushveld Large Igneous Province in southern Botswana.

Roger Key¹, Simon Bate¹ and Andy Moore¹

¹Kalahari Key Mineral Exploration Company (Pty) Ltd.

(kalaharikey@gmail.com)

Over the last 50 years the largely unexposed Molopo Farms Complex (MFC) in southern Botswana has been explored for PGE mineralization. Exploration mostly focused on finding laterally continuous PGE mineralization similar to that found in the contemporaneous Bushveld Igneous Complex, several hundred kilometres to the east in South Africa. However, PGE mineralization found in individual drillholes was always laterally discontinuous. Our exploration is focusing on classic-feeder zone Ni-PGE mineralization in a geophysically defined ENE-WSW shear/feeder zone through the centre of the MFC, which has been interpreted to represent an extension of the Thabazimbi-Murchison Lineament. Re-processing of available Landsat DTM and high-resolution airborne magnetic data produced gross 3D models of target areas but resolution is limited by the 200-250m line spacing used in the airborne magnetic survey. Follow-up ground magnetic and gravity measurements will be used to refine the 3D shapes. Existing regional gravity data over the MFC completed by the BGS in the 1980s is at a nominal 2km spatial station separation. This separation is larger than the target horizons and target areas we are seeking to identify. It does, however, provide a general view of the regional lithological and structural regime. Soil sampling over the targets is also planned to support the ground geophysics.

Drill core from previous exploration as well as thin sections from the BGS/Botswana Geological Survey study of the entire MFC in Botswana in the 1980s (Gould et al., 19897) have been examined. This work confirmed that the lower ultramafic part of the Complex away from the central shear/feeder zone is intensely deformed to explain, at least in part, the laterally discontinuous PGE mineralization found previously. It is proposed that the MFC is a syn-tectonic intrusion with emplacement linked to major lateral crustal movement along sub-continental shear zones defining the northern margin of the Kaapvaal Craton during the Palaeoproterozoic.

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KEYNOTE - Nickel-cobalt-scandium laterites of the western Tethys – formation and economic potential

Richard Herrington, The Natural History Museum, London.

The obducted ophiolite terranes of the western Tethys region are host to numerous Ni-Co-(Sc) laterite deposits developed during the Mesozoic and Cenozoic, with a peak of formation coincident with the Paleocene-Eocene Thermal Maximum (PETM) when geology, paleogeography, and climate were ideal for the deep weathering of favourable lithologies. Comparable bauxite deposits developed on the continental masses adjacent to ophiolitic remnants. Ni-Co-(Sc) laterites developed on fragments of the obducted ophiolites uplifted and exposed to weathering only after prolonged periods of collision commencing in the Jurassic. The laterites range in style from oxide, to clay-silicate, to hydrous-silicate types, comparable to types previously described in the literature, but a further distinctive, type of redeposited clay-oxide laterite is also important. This diversity of styles probably reflects the differences in topography and uplift history since the deposits all formed within a similar, restricted climatic time window. Economically significant Ni-Co-(Sc) laterite resources are found through a geographic area stretching from Serbia in the west through Turkey and beyond into Iran. Ni production is now mainly restricted to Greece, yet the region still accounts for around 1% of world production. However, due to processing methods employed, there is little or no recovery of Co and Sc. Many undeveloped deposits are recorded in the region, but for oxide-dominated mineralization, current metallurgical techniques remain largely uneconomic. Technology change, spearheaded by hydro- and bio-metallurgical techniques have the potential to unlock large low-grade redeposited lateritic Ni-Co-Fe deposits like Mokra Gora in Serbia, which alone has an untapped resource of more than 1 Gt of ore with an average grade of 0.7% Ni and 0.05% Co. The range of mineralisation styles and distribution of elements of economic interest will be highlighted and discussed in terms of the geological and geochemical models for formation as well as assessing the potential for future exploitation.

Global Impacts of Mine Wastes

Karen Hudson-Edwards

Environment & Sustainability Institute and Camborne School of Mines, University of Exeter,
Penryn, Cornwall TR10 9FE, UK. k.hudson-edwards@exeter.ac.uk

Mining has been practiced on Earth since the dawn of civilization, bringing wealth, jobs, goods and scientific knowledge. However, these activities produce enormous quantities of liquid and solid wastes, because the valuable commodities extracted only form a small percentage of the mined materials. The amounts of mine wastes are increasing globally because of growing demand for metals and the exploitation of lower grade ores with higher waste to ore ratios [1]. Historic mine wastes have equal or greater environmental impacts due to the lack of legislation, less efficient processing and the use of toxic components (e.g. mercury) to recover ores [2]. Solid mine wastes can be dispersed by wind as dust, or by rivers either chronically through regular discharge, or episodically during tailings dam failures [3], causing erosion and/or alluviation, and contamination. Liquid mine wastes can contaminate surface and ground waters with a large number of potentially toxic elements (e.g., antimony, lead, mercury), posing health hazards. Mine wastes also contain elements such as iron and sulfur which are involved in many natural geological processes (acidification, mineral precipitation). A number of mine waste elements (copper, selenium) are micro-nutrients in the oceans, rivers and soils, but are toxic if their concentrations exceed critical thresholds [4]. Millennia of discharge of mine wastes to the Earth's surface environment has therefore impacted on global biogeochemical cycles, fluvial and marine morphodynamics, water and soil supply and quality, and ecosystem and human health. This presentation will give an overview of these global mine wastes impacts, and discuss trends for the future.

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Hazel Prichard Memorial Lecture: Developments in platinum-group element (PGE) and Cr research

Hannah S. R. Hughes^{1*}

¹ Camborne School of Mines, University of Exeter, Penryn Campus, Cornwall
*h.hughes@exeter.ac.uk

Hazel M. Prichard was an outstanding mineralogist and a remarkable woman. Her fundamental contributions to the fields of PGE and Cr research have made it what it is today, and exceeded the more traditional confines of layered intrusions. Through numerous published reports she lobbied government to highlight that our way of living is underpinned by an economy requiring secure supply of minerals. This ultimately led to the current research initiative “*SoS MinEerals*”, a NERC programme for *Security of Supply of Mineral Resources* which has fed into applied and economic research groups worldwide – indeed this supports much of the science presented at MDSG. The aim of this contribution is to summarise some of the developments and research in the field so close to Hazel’s heart. No researcher works alone and Hazel was the epitome of a collaborative scientist, thus the overview presented in this talk serves to highlight the achievements of numerous groups in this discipline.

Oceanic crust makes up approximately 70% of the Earth’s crust and fundamental to its formation are mafic and ultramafic magmatic processes – it was from this standpoint that Hazel began her research career. She and her colleagues discovered that an array of platinum-group minerals (PGM) may be found within podiform chromitites in ophiolites (e.g., [1]). Alongside collaborators and the PGE community, this led to advances in our understanding of mantle melting, oceanic crust formation and of course, PGE and Cr mineralisation. Together with observations of PGM in stratabound chromitites in layered intrusions, recent analytical developments, such as X-ray computed microtomography (μ CT) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) have allowed researchers to investigate the physical as well as chemical controls on PGE mineralisation (e.g., [2, 3]). Such advances range from observations of PGM as exsolved minerals within chromite, sulphides or silicates; through to the discovery that arsenic (and other semi-metals) can act as ‘collectors’ for PGE in some geologic systems (e.g., [4]). Changes in the mineralogy of PGM are detected across large-scale magmatic systems, including the Bushveld Complex of South Africa (e.g., [5]) and such observations may be valuable clues towards unpicking the magmatic plumbing system and intrusive mechanisms of these enigmatic layered intrusions. Indeed, by furthering our understanding of magma fertility and intrusion processes, we may hone exploration models in the pursuit of orthomagmatic mineralisation. Part and parcel of Hazel’s focus on exploration geology, security of mineral supply and sustainable development was her recognition of novel sources of metals. This included unique studies into the abundance and possible utilisation of precious metals (especially Pt and Pd) in road dust, sewage and urban waste (e.g., [6]).

Throughout her distinguished career Hazel was a stalwart of the UK mineral deposits community and the discipline of exploration geology, an understated role model for collaborative international science, and a champion for student opportunities. She was, not least, a role model for female geologists and equality. It is a privilege to convey even a fraction of her enthusiasm for the community and her achievements to the MDSG.

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The Cukaru Peki deposit: Discovery and steps toward development - Re-setting the Maturity Clock in the Balkans.

Tim Livesey, Lelantos Consulting Limited, January 2018.

The Cukaru Peki discovery in 2012 was the culmination of a dedicated and consistent focus on this prospective part of the Tethyan Belt. The deposit consists of Copper-gold epithermal and porphyry style mineralization preserved under 400 metres of sedimentary cover, hosted in the late Cretaceous (Carpatho-Balkan) segment of Tethyan metallogenic belt.

Initially attractive due to the historical productivity of the Region, good geological understanding and field work, combined with a supportive and well funded partner led to the discovery of one of Europe's highest grade copper gold deposits. This discovery 'under cover' in turn led to a resetting of the perceptions of maturity for the wider Bor district, and for the Region in general.

On the back of this discovery there has been a surge of interest and investment in the Region across the junior, mid-tier and major sectors.

Role of sulphides on gold enrichment: the example of the West African Craton

Stephano Salvi, Géosciences Environnement Toulouse (GET)

The West Africa craton is host to a world-class gold province, with endowments comparable to the Superior and Yilgarn cratons in Canada and Australia, respectively. In this part of the African continent, gold mineralization occurs in a variety of styles, ages, host rocks and structural environments. Nevertheless, a parameter that is consistent with all primary deposits is that gold is almost always associated with sulphides, particularly pyrite and arsenopyrite, and that the latter invariably contain trace amounts of this metal in their structure. Although these features are also common in other gold mineralizations elsewhere in the world, their implications on high grade enrichments are not well understood.

This talk reviews mineralogical, textural and chemical data from numerous deposits in the West African craton. It illustrates the main characteristics of this gold-sulphide relationship and how fine-scale features and compositional details can help unravel the mineralizing processes and determine their role in the formation of an economic deposit.

The work presented here is part of an on-going multi-disciplinary research and training program focused on the mineral potential of the West African craton (West African Exploration Initiative).

Metal complexation and transport by hydrothermal fluids: Molecular insights from quantum chemistry and spectroscopy

David M. Sherman, School of Earth Sciences, University of Bristol, Bristol BS8 1RJ
dave.sherman@bris.ac.uk

High temperatures strongly favor the formation of complexes between metal ions and Cl and HS ligands in hydrothermal fluids; the formation of these metal-ligand complexes enhances the partitioning of metals from melt to fluid and the solubility of metal sulfide minerals. If we had thermodynamic models of these processes, we could develop quantitative models of ore deposit formation. For the past 50 years, nearly all of our understanding of hydrothermal solution thermodynamics has been based on extrapolations of low-temperature mineral solubilities using the classical model developed by Helgeson and coworkers. This work has yielded a “database” of equation of state parameters that enable prediction of mineral solubilities and the stability constants for metal complexes. However, parameters for many systems are absent; moreover, many of the equation of state parameters are preliminary estimates based on empirical correlations. More fundamentally, the Helgeson et al models are based on a physical picture of aqueous electrolytes (the Born model), that may not reliably extrapolate to high temperature, concentrated brines.

An alternative approach is to treat a hydrothermal fluid for what it is: a collection of interacting ions and molecules. If we have a good model of the physics of how these ions (Sn^{+2} , Cu^+ etc.) and molecules (H_2O , CO_2) interact, we can apply this model to a large assemblage of atoms in computer simulations that explore “phase space” using molecular dynamics. Such simulations enable us to determine thermodynamic properties such as stability constants of metal complexes. To describe the forces between ions and molecules, however, we must resort to computational quantum chemistry as implemented using density functional theory. Until recently, such ab initio molecular dynamics simulations were not feasible for the complex fluids of interest to geochemists. However, the availability of high-performance computing resources and recent advances in computational techniques now enable simulations that will bring about a new era in our understanding of hydrothermal fluids.

In addition to new theoretical techniques, a molecular-level understanding of hydrothermal fluids is emerging via the application of synchrotron-based X-ray spectroscopy. With bright synchrotron sources and new autoclave cells (e.g., at ESRF) we can obtain XANES and EXAFS of metal ions in dilute concentrations at elevated P,T and directly observe changes in metal complexation. As I will argue, however, limitations of these experiments often means that they cannot be interpreted without recourse to theoretical molecular simulations.

In this talk, I will review some recent fundamental applications of ab initio molecular dynamics and spectroscopy to understanding metal speciation (Cu, Zn, Ag, Sn and Pb) in hydrothermal fluids and discuss how I see molecular-level science will be applied to our understanding of crustal fluids and models of ore formation.

KEYNOTE: Cornish Lithium – A New Metal from an Old Mining Area

Jeremy Wrathall, Cornish Lithium Ltd.

j.wrathall@cornishlithium.com

Lithium is rapidly becoming a metal of crucial importance to our modern world given the imperative to move to a low carbon economy. There is currently no commercial alternative to the lithium-ion battery which is taking centre stage in the revolutionary move towards electric cars and power storage batteries. Whilst lithium is an abundant element it is difficult to extract on an economically viable basis and this is expected to generate an ever widening search for new sources.

Cornish Lithium believes that the presence of lithium bearing brines in Cornwall may now represent a commercial opportunity. Recent advances in lithium extraction without using solar evaporation now offer the potential to extract lithium from brine at much lower levels of concentration. Cornish Lithium was formed in 2016 to explore the possibility of extracting lithium in Cornwall and has successfully secured rights to extract lithium from brine over an area of approximately 300km². The company recently raised £1m to further its exploration efforts.

The application of green processing technology to tackle mercury use in small scale gold mining in Colombia

Rumana Khan¹, David A Holwell¹, Shaun D Graham², Gawen RT Jenkin¹

¹Department of Geology, University of Leicester, LE1 7RH, UK

²Carl Zeiss Microscopy, 509 Coldhams Lane, Cambridge, CB1 3JS

The global use of mercury in small scale mining is a persistent problem within the gold mining industry. As the world's largest mercury polluter per capita, Colombia epitomises this issue [1]. One solution currently in development is the use of deep eutectic solvents (DES), which are a form of ionic liquid, to extract target minerals in an environmentally stable, cost-effective, and mercury- and cyanide-free way. This study aims to assess the feasibility of applying this green processing technology to a small scale mine by building a comprehensive understanding of the ore mineralogy and characteristics. The small scale mine investigated in this study is located in the municipality of Segovia, 130 km northeast of Medellin.

Characterisation of the ore has been achieved through SEM-EDX analysis using the Zeiss Sigma 300 VP with Mineralogic software. The fully automated mineralogical assessment has shown the ore is dominated by a quartz-muscovite host with pyrite, arsenopyrite, barite and rutile gangue. Gold is present in native form and as electrum. Silver and bismuth are also present as potential by-products. Base metal sulphides include chalcopyrite and minor galena and sphalerite.

Ore that had been milled with mercury was sieved into four size fractions in order to assess the variation in target mineral liberation. Assessment of the liberation using Mineralogic shows a trend of increasing liberation of target minerals within decreasing size fractions. In addition to this, geochemical data obtained by using X-Ray Fluorescence (XRF) shows a strong trend of increasing concentrations of many target elements, including Ag, Bi and Cu, in finer size fractions.

Textures within unprocessed ore display three styles of pyrite mineralisation including vein networks, concoidal pyrite and smooth, euhedral pyrite; the latter appears to be the sole host of gold inclusions.

Further steps will aim to repeat mineralogical and liberation analyses on feed material that has not been milled with mercury in an attempt to demonstrate a mercury-free processing pathway for this ore. Conducting 2D leaching experiments of the gold and potential by-products will record the ionic liquid selective dissolution. This will provide a foundation to further build on by using X-Ray Microscopy (XRM) to model 3D gold dissolution.

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$\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in carbonate veins highlight the role of devolatilisation in Au mineralisation

James S. Lambert-Smith¹, David M. Lawrence², Adrian J. Boyce³ & Peter J. Treloar⁴

¹School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff CF10 3AT, UK (Lambert-SmithJ@cardiff.ac.uk)

²Randgold Resources Ltd, Unity Chambers, Halkett Street, St Helier, Jersey, JE2 4WJ

³Scottish Universities Environmental Research Centre, East Kilbride, Glasgow, Scotland, G75 0QF

⁴School of Natural and Built Environments, Kingston University London, Kingston upon Thames, KT1 2EE

Fluid and metal sources remain a contentious issue in orogenic gold deposits, both at the deposit scale and worldwide. Proponents argue for metamorphic devolatilisation, mantle degassing, and magmatic activity as potential sources. We examine this issue through the lens of paired $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data from Au-related hydrothermal carbonate veins, which provide strong evidence for a crustal fluid source lacking magmatic input.

The Loulo Mining District is one of the most prospective orogenic gold districts in West Africa. The District hosts the Loulo-Goukoto complex, which comprises three world-class deposits: Gara, Yalea, and Goukoto (combined reserves of 8.4 Moz at 4.5 g/t). The question of fluid sources at Loulo has remained contentious due to the unusual characteristics of the hydrothermal system. Detailed fluid inclusion studies reveal two end member hydrothermal fluids: 1) a low salinity (<10 wt. % NaCl equiv.), $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}-\text{H}_2\text{S}\pm\text{N}_2-\text{CH}_4$ fluid between 315-340 °C and 2) a hypersaline (~40 wt. % NaCl equiv.), $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}\pm\text{FeCl}_2-\text{B}$ fluid at temperatures up to 445 °C. On the basis of this complex fluid chemistry, the Loulo District is a useful test bed for discerning fluid sources in challenging geological conditions.

Sulphide-bearing hydrothermal veins in the Loulo District exhibit light $\delta^{13}\text{C}$ values (-21.7 to -3.7 ‰) and rock buffered $\delta^{18}\text{O}$ values (11.4 to 23.2 ‰), characteristics not uncommon to orogenic gold systems. Furthermore, these contrast markedly with the isotopic character of the dolomitic country rocks ($\delta^{13}\text{C}$: 3.1 to 1.3 ‰; $\delta^{18}\text{O}$: 19.1 to 23.3 ‰) and barren carbonate veins ($\delta^{13}\text{C}$: -2.4 to 3.8 ‰; $\delta^{18}\text{O}$: 11.7 to 21.1 ‰).

Preliminary modelling suggests that the range of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values exhibited by mineralised veins in the Loulo District can largely be explained by Rayleigh fractionation during metamorphic devolatilisation of dolomitic limestones. In contrast, barren veining shows isotopic compositions more consistent with batch devolatilisation of similar lithologies. Very light $\delta^{13}\text{C}$ values at the Yalea deposit (down to -21.7 ‰) require contribution of C from organic matter in addition to the inorganic carbon sourced from devolatilisation. It is unclear whether C_{org} is present in the fluid source region or incorporated during wall rock reactions at the site of deposition. The devolatilisation model we propose is reinforced by additional stable isotopic data from quartz ($\delta^{18}\text{O}$), pyrite ($\delta^{34}\text{S}$) and tourmaline ($\delta^{11}\text{B}$). These data indicate that hydrothermal gangue minerals show isotopic characteristics consistent with those of the Kofi Series metasedimentary rocks, or their equivalents.

Our data show that even in Au districts with geological complexity which may disguise fluid sources, it is possible to find convincing evidence that orogenic gold deposits are consistently the product of metamorphic devolatilisation reactions.

Vein-hosted Copper Deposits from SW Ireland

J. Lang¹, P. Meere¹, R. Unitt¹, S. Johnson¹, G. Solferino²

¹iCrag, School of Biological, Earth and Environmental Sciences, University College Cork, Ireland
(juergen.lang@icrag-centre.org, p.meere@ucc.ie, r.unitt@ucc.ie, sean.johnson@ucc.ie)

²Department of Earth Sciences, Royal Holloway University of London, United Kingdom
(giulio.Solferino@rhul.ac.uk)

Copper has been exploited in SW Ireland for thousands of years, leaving a legacy of features from the earliest bronze-age trench mines to the industrial revolution Cornish Engine Houses. A recent increase in the demand for copper world-wide has led to renewed interest in these occurrences and their overall implication for copper metallogenesis in Ireland.

The study presented here focuses on historically mined vein-hosted copper deposits in southwest Ireland, identifying the dominant structural and geochemical controls to mineralisation in an Upper Devonian continental clastic sequence. This includes detailed maps of mining areas at Allihies (Beara Peninsula) and Gortavallig (Sheep's Head), as well as a 3-dimensional model of the vein system and its structural relationship to mineralisation.

Detailed mapping at Allihies has described a set of E-W striking early extensional (pre-orogenic) quartz veins and large scale SW-NE trending (syn-Variscan) faults and folds with minor quartz veining. Ore-bearing veins, with a general E-W to SE-NW trend, are associated with post-orogenic (extensional) fault systems. These late E-W striking fault systems are possibly a reactivation of early syn-basinal extensional features. The structural observations are compared with those from vein-hosted deposits on Mizen Head and Sheep's Head peninsulas, which are possibly related to sediment hosted Cu mineralisation. Interpretation of GIS-supported satellite imagery and drone footage served as a key tool for visualization of large and small scale structures.

Petrographic and fluid inclusion studies of selected samples of pre-, syn- and post-Variscan quartz veins from Allihies display homogenisation temperatures (T_h LV-L) in two predominant clusters. One ranges from 160°C to 270°C (T_h) with salinities between 5 Wt.% and 17 Wt.% (NaCl equivalent), and the other shows a T_h from 120°C to 220°C with salinities between 21 Wt.% and 26 Wt.% (NaCl equivalent). Most of the copper lodes consist of quartz-chlorite with syn-genetic chalcopyrite, minor bornite, chalcocite and tetrahedrite.

Stable isotope geochemistry has been undertaken to aid in understanding the source of sulphides and nature of the metal-bearing fluids. The $\delta^{34}\text{S}$ ratios in chalcopyrite are between -15.5 ‰ and -11.4 ‰, $\delta\text{D}_{\text{SMOW}}$ in quartz ranges from -27.3 ‰ to -22.0 ‰, and $\delta^{18}\text{O}_{\text{SMOW}}$ yielded a tight cluster between 12.8 ‰ to 13.9 ‰. These isotope ratios indicate a sedimentary to metamorphic fluid-rock interaction [1], possibly resulting from the late remobilisation of sediment-hosted copper into post-Variscan quartz veins, this has implications for the source and formation of other similar deposits across the region.

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The magmatic evolution leading to porphyry Au-Cu mineralisation at the Ok Tedi porphyry-skarn deposit, PNG, revealed by zircon petrochronology

Simon J. E. Large¹, Albrecht von Quadt¹, Jörn F. Wotzlaw¹ and Christoph A. Heinrich¹

¹ Institute of Geochemistry and Petrology, ETH Zürich (simon.large@erdw.ethz.ch)

Metal endowed porphyry deposits are the result of the magmatic-hydrothermal interplay in the upper crust. These porphyry stocks are small rapidly cooling apophyses of much larger magma chambers below that are the locus of zircon crystallization. Understanding the magmatic evolution in this larger magma reservoir together with the pace of emplacement of a single porphyry stock are key questions in understanding these deposits. In order to fully quantify these processes we apply a combination of spatially resolved in-situ geochemistry with high precision CA-ID-TIMS geochronology on zircons from the OK Tedi Au-Cu deposit, PNG, one of the youngest (~1.2 Ma) giant porphyry deposits. This combination of techniques enables us to reconstruct the magma chamber evolution from zircon saturation to the emplacement of the porphyry intrusions with the highest temporal resolution.

Zircon geochronology from pre- and syn-mineralisation porphyry intrusions at OK Tedi indicates protracted zircon crystallisation within the magma chamber over a few 10^5 years ending in rapid mineralisation. Similar geochemical trends in zircons from all samples indicate fractional crystallisation within the magma reservoir and point to a common magmatic source of all investigated intrusive rocks. A portion of the youngest zircons from the syn-mineralisation porphyry records distinct chemical characteristics that are not coherent with the fractional crystallisation trend and point to melt injection towards the end of zircon crystallisation, just prior to high-grade Cu-Au mineralisation. The temporally resolved trace element variations of zircon can be further utilised to infer the conditions of melt storage within the magma reservoir underlying and sourcing the porphyry-skarn deposit.

Orthomagmatic conduit-hosted sulphide mineralisation potential of the Magilligan Sill, Northern Ireland (North Atlantic Igneous Province)

Jordan J. Lindsay^{1*}, Hannah S. R. Hughes¹, Dermot Smyth², Iain McDonald³, Adrian J. Boyce⁴, Jens C. Ø. Andersen¹

¹ Camborne School of Mines, University of Exeter, Cornwall (*jl731@exeter.ac.uk)

² Lonmin (Northern Ireland) Ltd., Antrim

³ School of Earth and Ocean Sciences, Cardiff University

⁴ SUERC, East Kilbride, Glasgow

The Magilligan Sill (Magilligan Peninsula, Northern Ireland) is a ~60 m thick intrusive sequence of dolerites and gabbros, part of the British Palaeogene Igneous Province (BPIP) in the North Atlantic Igneous Province (NAIP). The sill is intruded into a thick sequence of Mesozoic sediments comprising mudstones and marls, which has subsequently undergone moderate intrusion-related contact metamorphism. Since 2014, the sill has been an exploration target for Lonmin (Northern Ireland) Ltd. in pursuit of orthomagmatic Ni-Cu-PGE sulphide mineralisation analogous to Noril'sk Talnakh (Siberia). We present new petrological, geochemical and S-isotope data to assess the prospectivity of the sill and the underlying magmatic 'plumbing system'.

The sill is layered, contains disseminated fine sulphides throughout, and primarily consists of hydrothermally altered dolerite units (with chilled vesicular margins) and at least one layer of less altered olivine-gabbro towards the centre of the sill. Most sulphides in the dolerite portions of the sill are very fine (<50 µm) and comprise only pyrite with PGE abundances below detection limit, and under 595 ppm Co and 6.4 ppm Ag. In the olivine-gabbro layer, pentlandite, chalcopyrite and pyrrhotite grains over 150 µm in diameter were observed, with individual sulphide grains containing up to 4 ppm total PGE, 1,456 ppm Co and 88 ppm Ag. The S-isotopic composition of sulphides in each of these packages are distinct, with pyrite from the dolerites having a $\delta^{34}\text{S}$ of -10.0 to +3.4 ‰, while the $\delta^{34}\text{S}$ of sulphides in the olivine-gabbros range from -5.7 to -2.5 ‰. The $\delta^{34}\text{S}$ values observed in the sill reflect deviations from mantle isotopic ratios, due to crustal contamination by the surrounding sedimentary country rock. The S/Se ratios of the dolerite units and the olivine-gabbro unit range from 7,242 to 19,453, and from 2,854 to 3,031 respectively. The significantly lower S/Se ratios in the olivine-gabbro unit are closer to a primary mantle signature. This may either reflect a lower degree of crustal contamination, or magma replenishment in the system. In light of the greater volume of large sulphides, higher abundance of olivine, lower degree of alteration, and changes in silicate mineralogy in the olivine-gabbros compared to the dolerites, we favour the latter model.

The Magilligan Sill records multiple injections of mafic magma into an inflating sill package, each with distinct S-saturation pathways, as follows: (1) The initial emplacement of mafic magma cooled rapidly, quenching in its outermost portions. The S-rich country rocks (with extreme $\delta^{34}\text{S}$ values) contaminated these magmas *in situ* such that pyrite with negligible PGE content formed synchronously with magma injection and cooling. (2) Later magma batches progressively inflated the sill package, in a S-saturated state. (3) A chemically-distinct partially crystalline mush was emplaced into the inflating sill. This magma underwent fractional crystallisation and S-saturation at a deeper level in the magmatic plumbing system, such that the sulphides had scavenged PGE from the silicate magma prior to ascent to the Magilligan Sill. Whilst the sulphide minerals in the sill do not constitute any significant quantity of mineralisation themselves, they do serve to demonstrate the multiple injections of magma and the complex S-saturation history of the intrusion. If lower branches of the conduit system linked to this later generation of melt are located, analogous to the Noril'sk Talnakh system, it is possible that they will contain *in situ* Ni-Cu-PGE mineralisation. This aligns with the predictions made by Andersen et al (2002) [1] that the BPIP represents the most prospective area in Western Europe for conduit-hosted orthomagmatic sulphide mineralisation.

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Hydrothermal apatite as an indicator of porphyry Cu deposit fertility

Matthew A. Loader¹, Jamie J. Wilkinson^{1,2}, Robin N. Armstrong¹

¹Natural History Museum, Cromwell Road, London SW7 5BD (matthew.loader@nhm.ac.uk)

²Imperial College London, South Kensington Campus, London, SW7 2AZ

Apatite, $\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl},\text{OH})$, is the most common phosphate mineral in igneous rocks, and has shown potential as an indicator of porphyry-Cu deposit fertility [1]. In addition, hydrothermal apatite is commonly observed in the K-silicate and propylitic hydrothermal alteration domains of porphyry-Cu systems. This means that apatite has the potential to record the physico-chemical conditions of an evolving magmatic-hydrothermal system, and may contain geochemically unique indicators of porphyry fertility.

In this study, we present LA-ICP-MS and EPMA data for hydrothermal apatites from the Oyu Tolgoi porphyry Cu-Au system in southern Mongolia. The Oyu Tolgoi cluster is a useful natural laboratory, because it contains deposits of different metal tonnages and grades, thus allowing for an assessment of whether apatite may predict the size or grade of a deposit. In particular, the Heruga deposit carries a much lower Cu grade (0.48%) [2] than the Hugo Dummett deposit (1.18%) [2].

Hydrothermal apatites can be readily distinguished texturally from igneous apatite as they are intergrown with alteration phases including sulphides, with which they appear to be in local equilibrium. They show a wide range of trace element characteristics, but the main difference between hydrothermal apatites from Heruga and Hugo Dummett is the concentrations of Mn and Fe, which are significantly enriched at Hugo Dummett (up to 1.5 wt. % Mn, and 0.6 wt. % Fe). These divalent cations and others (Mg, Pb) show positive correlations with apatite Cl content, suggesting a link between fluid salinity and apatite metal contents. High salinity fluids have been shown to transport higher concentrations of Mn, Fe, and also Cu [3,4]. Significantly, rocks with high Cu grade (>0.75 wt.%) do not contain apatites with low Mn and Fe. We therefore suggest that the locally high Cu contents in rocks from Oyu Tolgoi, in particular at Hugo Dummett, may be explained by deposition from particularly saline fluids, which also produced Mn- and Fe-rich apatite. We conclude that hydrothermal apatite from potassic alteration zones reflects the chemistry of fluids associated with porphyry mineralisation, and may be used to assess the mineralisation potential of such systems.

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Evolving the genetic godel for the Cononish Au deposit: from prospect to mine

Calum Lyell¹, Adrian Boyce¹, Darren Mark¹, Jonathan Cloutier², Chris Sangster³

¹SUERC, Rankine Venue, East Kilbride, G75 0QF (c.lyell.1@research.gla.ac.uk)

²Irvine Building, St Andrews, KY16 9AJ (jc301@st-andrews.ac.uk)

³Upper Tyndrum Station, Tyndrum, FK20 8RY (chris.sangster@scotgoldresources.com)

The Cononish deposit consists of a complex of near vertically dipping, gold- and base-metal-bearing quartz veins (≤ 6 m across), which strike NW-SE over 1km. Whilst the veins cross-cut the Neoproterozoic Grampian and lower-Appin Group units of the Dalradian Supergroup, the mineralization is dated around 408Ma [1].

The deposit has a published resource of 198koz Au, and 851koz Ag. Since 2016, the first significant commercial extraction of ‘Scottish’ gold is being undertaken on a stockpile amassed during the construction of a 1.2km development adit. 10 gold rounds produced on-site from this extraction achieved a typical ~ 3 premium per ounce compared to the spot price. Final planning permission for full-scale mining is likely to be accepted by early 2018: this will be Scotland’s first significant gold mine, and one of only two active British metal mines. Thus, this NERC project represents a timely opportunity to undertake research with CASE partners Scotgold Resources Limited, to refine the fundamental controls that form and locate gold mineralisation.

The planned research programme centres on the existing adit and extensive drill core record. Building on the many observations regarding ore paragenesis made over two decades ago following mine discovery [2], this research will evolve the current models of ore emplacement, and create a new structural, mineralogical and textural framework focused on the deposit. The revised framework seeks to inform and improve on-site geometallurgical processing, with gold hosted in electrum, being largely refractory ($\sim 75\%$) and associated with tellurides and as inclusions in pyrite [2].

The study will also explore the apparent genetic link between Cononish gold genesis and the nearby (~ 10 km) Etive granite igneous complex – dated around the age of mineralisation [3]. This will involve using fluid inclusion, stable isotope (H, O, C and S) and high-precision Ar/Ar geochronology of both, and their associated minor vein and intrusive developments.

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Late- to post-magmatic alteration of syenitic rocks of the Ambohimirahavavy Complex: Insights into fluids potentially mobilising REE

Eva Marquis¹, Kathryn Goodenough², Guillaume Estrade³, Martin Smith¹

¹School of Environment and Technology, University of Brighton, BN2 4GJ
(e.marquis@brighton.ac.uk)

²British Geological Survey, the Lyell Centre, Research Avenue South, Edinburgh, EH14 AAP

³Géosciences Environnement Toulouse, Université Toulouse 3 Paul Sabatier, France

Heavy rare earth elements (HREE: Gd-Lu) are critical metals, particularly Dy which is widely used in magnets. However, their known resources are restricted to deposits associated with peralkaline igneous rocks and regolith-hosted 'ion adsorption type' REE occurrences located in temperate to tropical climates [1]. Challenges in the processing of peralkaline rock deposits have resulted in the dominance of regolith-hosted REE deposits as the main source of HREE and yttrium to the global market. Although these deposits supply much of the HREE only a few occurrences in south-eastern China are strongly enriched in HREE and Y (*i.e.* $\sum\text{HREE} + \text{Y} > 50\%$ of the total REE oxide (TREO); [2]). In these rare cases the parental rocks are HREE-enriched granites, in which the HREE are proposed to have been concentrated during the last stages of granite crystallisation and autometasomatism [2]. This late stage alteration has also led to the development of degradable REE-bearing minerals, which easily release REE into the regolith. Although late magmatic alteration is a consistent feature for the development of HREE-enriched granites in southern China, there has been little investigation into the characteristics of the fluid phases associated with this alteration.

The Tantalus Rare Earths AG prospect, in northwest Madagascar, is currently unique as it encompasses both of these deposit types, with regolith profiles containing REE developed upon alkaline to peralkaline igneous and volcanic parent rocks of the Ambohimirahavavy Complex [3]. Major intrusive rocks of the complex include alkali feldspar and nepheline syenites, which form the main ring dyke and a marginal dyke swarm comprised of quartz microsyenite and peralkaline granite sheets [4].

Results from our ongoing-research project investigating the pre-conditions for the formation of this regolith-hosted REE mineralisation will be presented. Focussing on the late- to post-magmatic alteration of the ring dyke syenites, we will provide examples of key mineral assemblages and reaction textures, and present preliminary characterisation of the alteration fluids. Petrographic observations in the syenites indicate that alteration of REE minerals and REE mobilisation occurs at late stages in the magmatic evolution of some of the syenites at Ambohimirahavavy. In some cases, such as within the alkali feldspar syenites, this results in the development of REE-fluorcarbonates, which are amenable to breakdown during weathering; however, within the nepheline syenites typical late-stage REE-minerals include zirconosilicates and REE-phosphates that are relatively resistant to dissolution at low temperatures [2, 5]. Thus, the late- to post magmatic mineral assemblages have important implications for the release of REE into the regolith, and hence for the grade of the deposit.

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Magmatic and hydrothermal end member volcanogenic massive sulphide (VMS) deposits: Implications for selenium enrichment

Andrew J Martin^{1*}, Iain McDonald¹, Christopher J MacLeod¹, Katie McFall¹, Hazel M Prichard¹ and Gawen R T Jenkin²

*MartinAJ4@cardiff.ac.uk

¹ School of Earth and Ocean Sciences, Cardiff University, Park Place, CF10 3AT

² Department of Geology, University of Leicester, University Road, LE1 7RH

A magmatic input into the VMS hydrothermal system has been hypothesised to explain the enrichment in certain elements such as Se, Te, Co, Cu, Au and Bi ^[1,2,3]. Analysis of late euhedral pyrite from the South Apliki Breccia Zone of the Apliki VMS ^[4] reveals significant enrichment in Se of up to 5950 ppm with corresponding Se/S ratios of up to 9240. Se/S ratios >500 may indicate an increased magmatic component in the VMS hydrothermal system ^[5]. Sulphides from the South Apliki Breccia Zone indicate a paragenesis consistent with multiple overprinting fluid pulses, sulphide dissolution and a late magmatic component into the VMS hydrothermal system (vapour or liquid phase). This complex paragenesis is responsible for the enrichment of Se in late stage euhedral pyrite at Apliki ^[4].

The Troodos ophiolite, Cyprus hosts the type locality for mafic or Cyprus-type VMS. Regional soil geochemistry of southern Cyprus ^[7] has highlighted the heterogeneous distribution of trace elements in VMS deposits; some are enriched in Te and Se. Laser ablation ICP-MS (LA-ICP-MS) of sulphides from VMS of the Troodos ophiolite highlights distinct trace element profiles which are interpreted to represent 'end member' magmatic and hydrothermal VMS systems; the Apliki and Kokkinoyia VMS deposits.

When viewed on graben scale clear trends in Se/S ratios and trace metal enrichment in VMS sulphides have been distinguished. Three structural grabens dominate the Troodos ophiolite, from E-W they are; Larnaca, Mitsero and Solea ^[6]. Solea represents a 'full' spreading axis with underlying magma conduit whilst Mitsero is purely an extensional feature. Both grabens are associated with VMS formation. Based on trace element enrichment and Se/S ratios of VMS we have identified magmatic and hydrothermal end member deposits. Apliki and deposits of the Solea graben are enriched in Cu, Co, Bi, Te and Se and have high Se/S ratios whilst Kokkinoyia, and deposits of the Mitsero graben are depleted with Se/S ratios <640.

We hypothesise that the distribution of Se (and associated elements) is a function of increased magmatic influx; centres where spreading is accommodated through extension and graben formation are likely depleted in elements of magmatic affinity. At magmatic dominated spreading ridges end member VMS may exhibit significant enrichment in Se with the highest known Se concentrations of any mafic hosted VMS recorded at Apliki. Geochemically all VMS are expected to have compositions between the two end members; this reflects variable degrees of magmatic influx and is intrinsically linked to the structure of the spreading centre.

^[1] Chen et al., 2015 ^[2] de Rhonde et al., 2011 ^[3] Hannington et al., 1999 ^[4] Martin et al., submitted ^[5] Layton-Mathews et al., 2013 ^[6] Varga and Moores, 1991 ^[7] Geological Survey Department of Cyprus

Evidence for hydrothermal modification in the Aurora Cu-Ni-PGE prospect, Northern Bushveld Complex, South Africa

Katie McFall¹, Iain McDonald¹, Dominique Tanner²

¹School of Earth & Ocean Sciences, Cardiff University, Park Place, Cardiff, CF10 3AT, U.K.
(McFallK@cardiff.ac.uk)

²University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia

Aurora is a Cu-Ni-PGE prospect hosted in the Northern Limb of the Bushveld Complex, South Africa. The host cumulates are interpreted to represent the Upper Main Zone and intrude the dolomites of the lower Transvaal Supergroup [1]. Stratigraphically the prospect consists of peridotites and melagabbonorites (Unit 1) below gabbonorites and leucogabbonorites (Unit 2), and pigeonite gabbonorites (Unit 3) [1]. Unit 1 is intruded by coarse grained gabbonorite veins with up to 50% interstitial pyrrhotite-pentlandite-chalcopyrite+/-pyrite. Base metal sulphides (BMS) are also present in Unit 2, which contains 1–5% chalcopyrite-pyrite hosted in hydrothermal alteration, and rare pentlandite-pyrrhotite-chalcopyrite assemblages. The deposit contains pervasive, predominately talc-carbonate, hydrothermal alteration. The highest whole rock Pd + Pt concentrations (up to 6.8 ppm) are in Unit 2, and in the gabbonorite veins [1].

LA-ICP-MS of sulphides shows the BMS in Aurora have lower platinum-group element (PGE) concentrations than other Bushveld magmatic sulphides. Pentlandites from unit 2 have an average Pd concentration of 28 ppm, compared to >100 ppm in the Platreef and Merensky Reef [2,3]. Other PGEs (Ru, Rh, Os, Ir, Pt), Au and Bi are all <0.5 ppm. Unit 2 pentlandites also contain an average of 1.3 ppm Ag and 1.6 ppm Te. Pentlandites in the gabbonorite veins contain an average of 10.4 ppm Pd, 1.3 ppm Ag, 3.3 ppm Te, and <0.5 ppm of other PGEs, Bi and Au. Chalcopyrites from both units have an average of 1.6 ppm Pd, 23.4 ppm Ag, 2.2 ppm Te, and <0.5 ppm other PGEs, Au and Bi. Pyrrhotites from both units have PGE, Au, Ag, Te and Bi concentrations <0.5 ppm. Pyrites from Unit 2 contain an average of 21.6 ppm As, 0.9 ppm Pd, 4.1 ppm Ag, 1.6 ppm Te, 0.9 ppm Bi, and <0.5 ppm other PGEs and Au. This contrasts with pyrites from the veins where all PGEs, Au, Ag and semi-metals are below detection limits.

SEM-EDS analysis of 26 slides characterised 849 platinum-group minerals (PGMs), with a total area of 25630 μm^2 . 28% of PGMs studied are present in Unit 2 and 72% are in the gabbonorite veins which intrude Unit 1. 85% of the PGMs are Pd-Bi-Te minerals, with 13% Pd-Te minerals, 1% Pt-As minerals and rare Pd-As and Pt-Te minerals. The deposit contains significant amounts of Au-rich electrum (average 83 wt.% Au), hessite, altaite and galena-clausenthalite. 90% of PGMs are hosted within quartz, chlorite and talc-carbonate alteration products, with only 9% hosted within or on the edge of sulphides and 1% within silicates.

The PGE grade in Aurora is predominately in hydrothermal alteration hosted PGMs, rather than in magmatic sulphides. Assimilation of dolomite would have released water, creating a volatile phase with the potential to dissolve and/or remobilise PGEs from any early BMS liquid [2]. This is supported by the presence of fluid inclusions with halite daughter minerals in both hydrothermal quartz and magmatic plagioclase, showing a Cl-rich fluid was present during crystallisation.

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Paleosurface exploration using hyperspectral short-wave infrared imagery

Jo Miles^{1,3}, Stephen Grebby², Jonathan Naden³, Graham Ferrier⁴

¹University of Bristol, School of Earth Sciences (Jo.Miles@bristol.ac.uk)

²University of Nottingham, Faculty of Engineering

³British Geological Survey, Keyworth, Nottingham, NG12 5GG

⁴University of Hull, School of Environmental Sciences

Satellite imagery, such that acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), aids hydrothermal ore deposit vectoring and discovery by determining the type and distribution of alteration minerals exposed on the surface. However, satellite imagery does not always provide the spatial or spectral resolution required to map specific mineral species. In contrast, airborne hyperspectral scanners measuring the short-wave infrared (1100–3000 nm; SWIR) range of the electromagnetic spectrum are capable of resolving pixel (<2 m) to sub-pixel detail, therefore providing insight into subtle mineralogical variations within zones of hydrothermal alteration.

Emergent volcanic islands can preserve paleosurfaces from both the marine and terrestrial hydrothermal environment, resulting in widespread and intense, often overprinted alteration. The island of Milos, Greece, provides the ideal place to explore the economic potential and preservation of shallow submarine (<500 m) paleosurfaces. Previous analysis of ASTER imagery distinguished three alteration zones localised to the west of the island: silicic, advanced argillic and argillic¹. However, within these kilometre scale alteration zones, the mineralogical detail required to infer fluid pathways and zones of upflow is lost.

This study utilises a high resolution airborne survey flown over the island of Milos by the NERC Airborne Research and Facility in 2012 (project EM10/02). It focuses on the Specim ASIA Hawk (970–2450 nm) airborne scanner to map mineral-specific alteration from SWIR spectra. Flightlines were georectified via the Airborne Processing Library² prior to correcting for the effects of the atmosphere using the QUAC tool within the ENVI image processing software. A significant challenge in mapping mineral species is distinguishing minerals that are mixed together within one pixel. To overcome this, we compare pixels with field observations, laboratory spectroscopy measurements (ASD AgriSpec) and bulk-XRD analysis. Once mineral end-members were established, image classification techniques were used to search for similar spectral fingerprints within each image pixel.

Initial results have highlighted a widespread alunite-kaolinite traceable horizon situated above all mineralising systems on western Milos, interpreted as a steam-heated zone formed from H₂S-bearing steam condensate³. This zone is always observed below the paleogroundwater table, indicating degradation resulted in the descent of the water table. Smectite deposits are not limited to the west, however can be locally overprinted by kaolinite. Around the rootless breccia pipes at Triades-Galana, a strong ‘mica’ signature suggests increased crystallinity and hence higher temperatures in this region. This will be further investigated by clay-XRD for geothermometry and fluid upflow, which in turn might be used as a guide to determine which breccias are in situ and which were subjected to mass wasting⁴.

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Geochemistry and U-Pb zircon dating of Southern France bauxites

Mondillo N.¹, Chelle-Michou C.², Boni M.¹, Cretella S.¹, Scognamiglio G.¹, Tarallo M.¹, Arfè G.¹

¹ Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli Federico II, Napoli (Italy) (nicola.mondillo@unina.it)

² School of Earth Sciences, University of Bristol, Bristol (UK)

Karst bauxite deposits occurring in southern France (Provence and Languedoc), lie between Jurassic platform carbonates in the footwall and Cretaceous–Eocene marine to continental sediments in the hangingwall, and formed between Albian to Cenomanian [1]. Textural and geochemical features suggest that a combination of different processes contributed to the bauxite formation [1]: the deposits consisting of reworked bauxite fragments accumulated in karst depressions, have been considered of detrital origin or *allochthonous* [2], whereas the deposits with distinct mineralogical and geochemical zonation have been interpreted as derived from in-situ (*autochthonous*) alteration of the original protore [3]. Similarly to other karst bauxites worldwide [4], the nature of the protores for the French bauxites could not be immediately identified because the deposits do not directly lie above the weathered parent rock [1]. Here, we present new data on bulk rock geochemistry of Provence (Les Baux, Mazaugues, and Brignoles) and Languedoc bauxites (Bédarieux, San Chinian and Villeveyrac), and new U-Pb data of detrital zircons of the Provence deposits, aiming at: 1) identifying elements re-mobilized during the in-situ alteration of the deposits; 2) identifying the bauxite protores.

Relevant information was obtained from trace elements geochemistry, particularly from REEs, which have a total average amount of 700 ppm in most of the analysed occurrences, but are characterized by variable concentrations along the bauxite profiles (min. 200 ppm, max 1500 ppm). Maximum REE concentrations occur at different levels along the sampled profiles, and are commonly associated with positive Ce anomalies in PAAS- or chondrite- normalized patterns, and/or with the presence of supergene REE-minerals (e.g. cerianite and parisite).

U-Pb zircon dating was carried out on bauxite samples from the Les Baux and Mazaugues deposits and revealed important differences in the age spectra of the two localities. In particular:

- in both deposits, zircons record the early Ordovician (480 Ma) extension along the north Gondwana margin; the zircons of Les Baux subsequently record an unknown event at 420 Ma, while the Mazaugues ones record the continuation of the extension until 440 Ma;
- in the samples from Les Baux we detected abundant 545 Ma-old zircons, probably originated from the Velay Orthogneiss Fm., that are instead less abundant at Mazaugues.

In conclusion, trace elements geochemistry allowed evidencing REE patterns typically associated with in-situ alteration, indicating that also bauxites, which preserve textural characteristics originally related to an allochthonous character were reworked in-situ after their deposition. U-Pb zircon ages confirm that the protores of Provence bauxites are Variscan basement rocks, with some differences: at Les Baux there was a major contribution of material derived from the East French Massif Central, whereas the Mazaugues area was mostly supplied by material originated from the proto-Alpine domain.

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**The Cristal mineralization (Amazonas region, Northern Peru):
an example of supergene zinc enrichments in tropical areas**
Arfè G.¹, Mondillo N.¹, Boni M.¹, Joachimski M.², Balassone G.¹, Mormone, A.³

¹Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli Federico II, Complesso Universitario di Monte S. Angelo, 80126, Napoli, Italy

²GeoZentrum Nordbayern, University of Erlangen-Nuremberg, Schlossgarten 5, 91054, Erlangen, Germany

³INGV Osservatorio Vesuviano, Via Diocleziano 328, 80124, Napoli, Italy

*Corresponding author: boni@unina.it

The small Cristal Zn deposit is located in the northernmost part of a wide mining district, the “Charlotte Bongará Zinc Project”, which covers an area of approximately 110 km² in the Amazonas district (Northern Peru). The mineralized area consists of many Zn occurrences with mixed sulphide and nonsulphide ores. The nonsulphide ores are the product of weathering of primary sulphide bodies, genetically representing a MVT mineralization. The Zn concentrations of Bongará-Cristal are hosted in the platform carbonates of the Condorsinga Formation (Early Jurassic) in the Pucará Group. The nonsulphide mineralization consists mainly of semi-amorphous orange to brown zinc “oxides” that include hemimorphite, smithsonite and Fe-(hydr)oxides. The most significant mineralized areas are present at Esperanza and Yolanda occurrences, which were also most densely explored. In both occurrences, the supergene Zn-carbonates and silicates infill solution cavities, or replace the carbonate host rocks and/or the primary sulphides. The analyzed drillcores are mainly from Esperanza, where the zinc content associated with hemimorphite-rich layers can reach ~53 wt.% Zn (average Zn grade is around 20 wt.%). Germanium concentrations are significant at Cristal, with values around 200 ppm measured on bulk rock.

The Bongará area experienced a prolonged phase of weathering from Miocene to Recent under tropical climatic conditions. Under such a climate setting, weathering processes involved many pre-existing sulphide orebodies (e.g. Cristal, Florida Canyon, Mina Grande mines), where supergene profiles were developed under locally different conditions, mainly outlined on the basis of mineralogical and geochemical data. The mineralogy and geochemistry of the Bongará mineralized zones were mainly determined at a local scale by two factors: (1) uplift rates, and (2) host rock composition. The latter may favor the development of more (e.g. Mina Grande) or less (e.g. Cristal) alkaline supergene environments. Uplift was controlled by the activity of local faults, which allowed the exposure of sulphide protorees at variable altitudes in different periods of time and hydrological settings. Such different factors and settings may result in the precipitation of isotopically different supergene carbonates (e.g. smithsonite and calcite). Contrary to the Mina Grande deposit nearby, the development of a karst network at Cristal was quenched by a limited uplift rate, and supergene alteration did not completely obliterate the roots of the original sulphide orebody.

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Apatite chemistry in Central Chilean volcanics: implications for the application of apatite as a fertility indicator for porphyry copper deposits

Chetan Nathwani^{1,2}, Robert Sievwright², Jamie Wilkinson^{2,1}, Matthew Loader²

¹Department of Earth Science and Engineering, Imperial College London, Prince Consort Road, London, SW7 2AZ, UK (chetan.nathwani14@imperial.ac.uk)

²London Centre for Ore Deposits and Exploration, Natural History Museum London, Exhibition Road, SW7 5BD, UK

Accessory minerals provide valuable archives of the petrogenetic evolution of magmatic systems. Due to its ability to partition a broad suite of elements, apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$) has a versatile chemical composition that can act as a proxy for melt chemistry. As a result, apatite has attracted interest as both a petrogenetic indicator [1] and as an exploration tool [2]. Apatites from a spatially and temporally diverse sample set from Central Chile, studied by [3], were analysed by laser ablation inductively coupled plasma mass spectrometry and electron microprobe. These samples are unmineralised volcanic rocks that span the major porphyry copper mineralisation window in Central Chile. The aim of the study is to use apatite to track the evolution of the parental magmas of porphyry copper deposits.

One common fingerprint of ‘fertile’ magmatic arcs, is their association with high Sr/Y magmas [4], believed to be a product of wet magmas promoting amphibole crystallisation and suppressing plagioclase fractionation [5]. In this study, the evolution of Sr/Y ratios and europium anomalies (Eu/Eu*) show strong correlation both within samples and across the sample set. We attempt to resolve the origins of such trends using textural observations and modelling of melt evolution with crystallisation. Apatite trace element chemistry is found to be amenable to the syn/post crystallisation of other mineral phases.

The results of this project further demonstrate that apatite chemistry is a valuable tool for mineral exploration and as a tracer of the petrogenesis of magmatic systems.

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The IMP@CT Project: Characterising Geological Uncertainty in Small, High-grade Deposits

Luke W. PALMER¹, Richard ROETHE², Amela Imamovic², Dominic ROBERTS² and Kathryn MOORE¹

¹ Camborne School of Mines, University of Exeter, Penryn Campus, Cornwall TR10 9FE, UK (l.w.palmer@exeter.ac.uk)

² Mineco Ltd, 5th Floor, Stephenson House, Cherry Orchard Road, Croydon, CR0 6BA, UK

As world-class mineral deposits become more challenging to locate and harder to extract, there is a need to evaluate the factors that result in small, high-grade deposits being overlooked in the search for mineral resources and reserves. In conjunction, concerns regarding the criticality of strategic raw materials increase the need to find secure resources for mature industrial regions such as Europe, where opportunities to locate previously undiscovered large deposits are limited. The IMP@CT (H2020) project seeks to facilitate mining of small deposits in Europe by developing sampling, mining and processing options that can operate on short timescales and require a reduced capital expenditure, decreasing business risk.

An understanding of the characteristics of mineral deposits is key to successful exploitation. In this context, geological uncertainty may be termed a situation where geometry, grade distribution, mineralogical variation and metallurgical properties are imperfectly understood. Best practice methods of orebody characterisation are ill suited to small high-grade deposits as they fail to capture short-range variation and increase geological uncertainty by applied assumption [1].

The IMP@CT project aims to investigate appropriate low-cost methodologies that improve characterisation of small, high-grade deposits and incorporate measures of geological uncertainty into deposit models and understanding. An applied geometallurgical approach, entailing sampling (for grade and metallurgical recovery), mapping and in situ analysis of mineralisation, is shown to provide detailed information that can accurately inform downstream processes for two applicable case studies in Bosnia; the Olovo Lead mine and the Gorzde Antimony prospect.

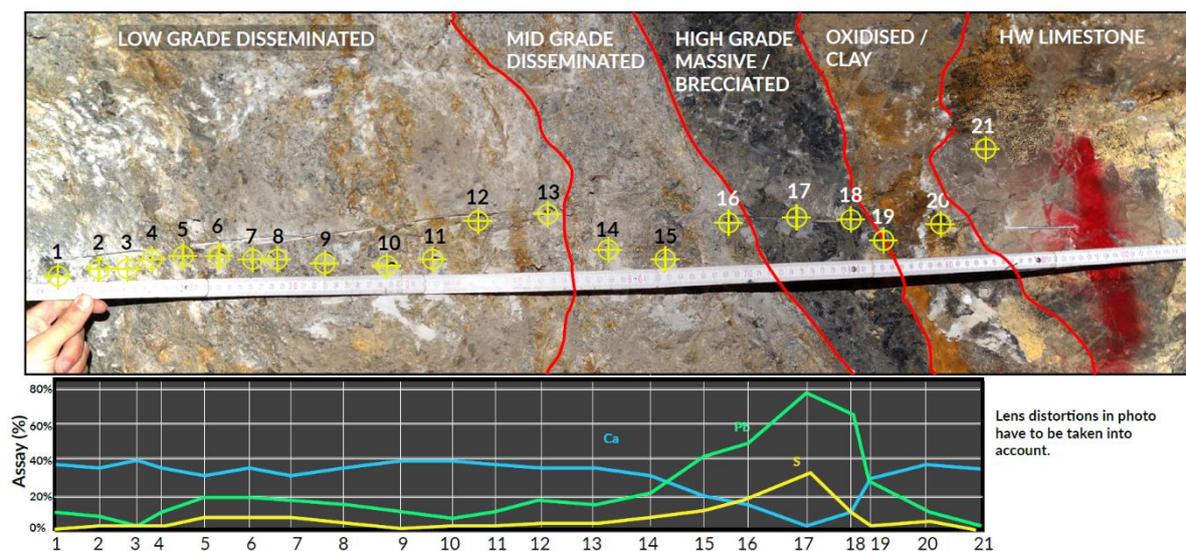


Figure 1: Example of close spaced sampling and element distribution of a high grade vein at Olovo Mine, Bosnia.

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Communicating responsible sourcing criteria to a non-specialist audience

Robert Pell, Frances Wall, Ed Loye, GeoBus

Camborne School of Mines, University of Exeter, Penryn, TR10 9FE

Over the last few years public awareness of rare earth elements (REE) has increased. This is because, owing to their unique physical and chemical properties, these metals have a remarkably large number of applications in modern technology. Growing demand for REE means that new mines will need to start producing REE in the near future. For both current and future projects, there are a number of challenges for responsible sourcing. These can be difficult to communicate to a non-specialist audience. We have been developing ‘Trumps’ style cards to convey these challenges in a clear, simple and fun way.

Twenty four rare earth projects in different stages of production were selected from around the world. Scores were calculated for deposit size, accessibility, radioactivity, environmental score, production stage, political stability and proportion of ‘rarest’ rare earth elements. Each category was calculated using data from the companies who own the projects or publicly available data from internationally recognised, peer reviewed literature. An example of a card including the explanations for each category is shown in figure 1.

Recent history has highlighted that single, high-profile issues are more likely to impact whether a project succeeds rather than a broad consideration of all responsible sourcing criteria. Examples of this are conflict minerals such as ‘blood diamonds’ and ‘coltan’ or the use of child labour in production of cobalt from the DRC. An advantage of using ‘Top Trump’ cards is that they enable players to evaluate a range of issues whilst highlighting individual issues, such as radioactivity, that are likely to provoke public concern.

It is important to communicate these complex issues in simple terms that can be understood by young and non-specialist audiences, but is equally important to allow these audiences to think for themselves about issues around responsible sourcing of raw materials. This allows them to make informed decisions about how they consume manufactured goods containing these raw materials in the future.

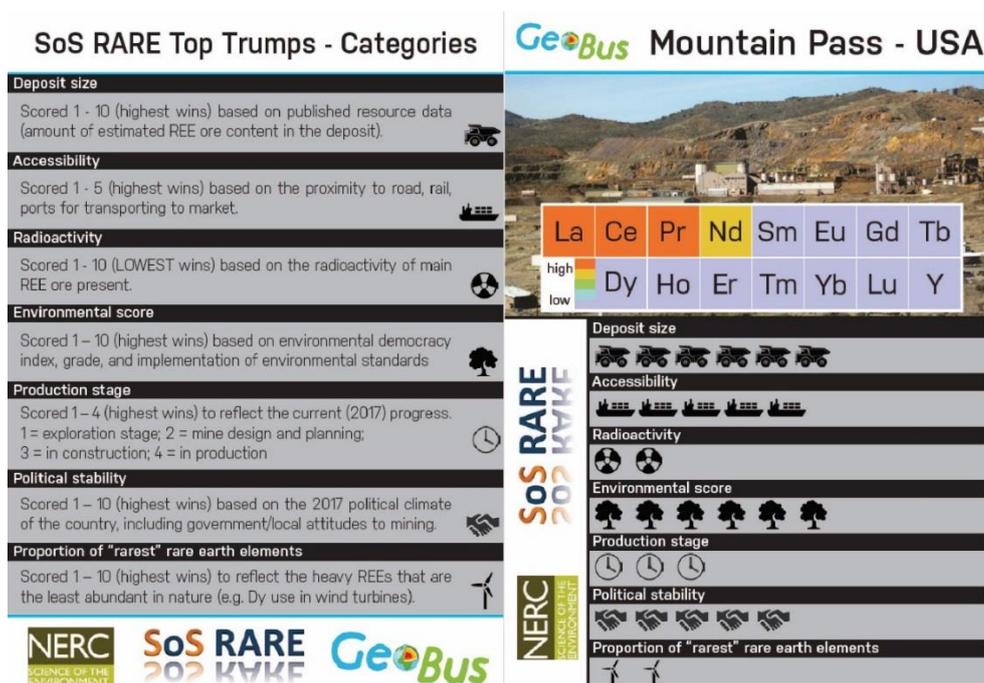


Figure 1. SoS Rare ‘Top Trumps’ categories (left) and an example of a REE project (right)

Reverse shear, horizontal shortening and lode-gold mineralisation on the Mougooderra Shear Zone, Western Australia

Jamie Price¹, Andrew Kerr¹, Thomas Blenkinsop¹, James Lambert-Smith¹,
Clinton Kuehnappel²

¹School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff.
CF10 3AT (pricejj1@cardiff.ac.uk)

²Minjar Gold Pty, 70km SE of Yalgoo, Western Australia.

The relatively unstudied Archean Yalgoo-Singleton Greenstone Belt (YSGB) is situated in the western Murchison Domain of the Yilgarn Craton, Western Australia. It is composed of several supracrustal 'greenstone' limbs (2.95-2.75 Ga^[1]) and a central sedimentary basin (Mougooderra Basin; ~2.7 Ga^[2]). The greenstone portions of the belt are dominated by mafic-ultramafic volcanic and intrusive lithologies, whereas the internal Mougooderra basin has a shale-dominated sedimentary package with subordinate sandstone, conglomerate and felsic volcanoclastic units. Deformation within the belt is characteristically heterogeneous with the development of multiple narrow, high-strain shear zones, focused primarily at the eastern and western contacts of the greenstone-bounded Mougooderra basin^[3]. A majority of the current 1.1-million-ounce lode-gold resource in the belt is directly associated with the Mougooderra Shear Zone (MSZ), located at the western greenstone-basin contact. The YSGB exhibits a distinctly arcuate shape and is bound by multiple phases of granitoid and gneissic intrusions^[3].

Detailed structural logging of drillcore intersecting the MSZ at the Silverstone deposit has been undertaken. Shear zone foliation measurements and pit observations verify that the shear zone strikes NNW with a dip of 60-70° west, such that the greenstone assemblage occupies the hanging wall and sedimentary rocks occupy the footwall. Furthermore, the vorticity vectors of a range of kinematic indicators (including sheared ocelli, pyrite porphyroblasts and SC fabrics) reveal ubiquitous 'west-side up' movement, thus indicating predominantly reverse kinematics of the MSZ. Overturning of hanging-wall units approaching the MSZ and isoclinal folding in the footwall sedimentary rocks are both consistent with dominantly-reverse shearing and horizontal shortening. With regard to mineralisation, multiple generations of veining have been identified at the Silverstone deposit, including an early quartz-carbonate phase parallel to the principal foliation, a sub-horizontal quartz-dominant vein set enriched in sulphides, and later cross-cutting carbonate veining. Sulphides present in the main ore zone at or near the sheared contact are frequently deformed, often in the principal foliation direction.

Structures observed in the MSZ are consistent with horizontal shortening, with reverse shear affecting all greenstone lithologies. The lode-gold mineralisation present along the shear zone is plausibly associated with this phase of deformation, which essentially must postdate sedimentation of the Mougooderra basin. Such horizontal shortening is compatible with intrusion-related strain, such as diapirism and/or ballooning of large granitoid bodies surrounding the YSGB. Alternatively, a later shortening event may be responsible. At this point, there is little evidence for strike-slip or transpressional strains that have been commonly associated with shear-zone hosted lode-gold mineralisation elsewhere in the Yilgarn Craton.

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**Mineralogical association and Ni-Co department in the Wingellina
(Western Australia) oxide-type laterite deposit**
Putzolu F.^{1*}, Boni M.¹, Mondillo N.¹, Pirajno F.²

¹ Dipartimento Scienze della Terra Università di Napoli “Federico II” Complesso
Universitario di Monte S. Angelo, Via Cintia 26 80126-Napoli, Italy

² Centre for Exploration Targeting, The University of Western Australia, 35, Stirling
Highway, Crawley WA 6009, Australia

*Corresponding author: francescoputzolu91@libero.it

The Wingellina property (Metals X Ltd) is a classic “oxide-type” Ni-Co laterite (168 Mt of ore at 0.98% Ni and 0.08% Co), which is derived from the weathering of the olivine-rich mafic to ultramafic layered-intrusion of the Giles Complex (Mesoproterozoic). The lateritic profile consists of a well-developed “limonitic” unit and a less voluminous saprolite horizon.

The “limonitic” ore consist of Fe- and Mn-(hydr)oxides, which are the carrier of both Ni and Co. The Fe-(hydr)oxides are common also in the lower saprolite horizon. At Wingellina, the Mn-(hydr)oxides display a high mineralogical variability. The lithiophorite-asbolane intermediate compound is the most widespread Mn-(hydr)oxide. This mineral is the main Co-host in the “limonite” zone, and has also a significant Ni content (Co and Ni average values: 7.92 and 8.49 wt% respectively). Less abundant compared to lithiophorite-asbolane, but still ore-bearing Mn-(hydr)oxides consist of romanèchite (average Ni and Co values: 1.63 and 0.89 wt%), ernienickelite (7.75 and 1.66 wt%), manganite (1.12 and 0.48 wt%), and birnessite (1.57 and 0.49 wt%). The Ni enrichment in the Fe-(hydr)oxides can be triggered either by sorption on the (hydr)oxides surface, or by substitution of Fe³⁺, whereas the Co sequestration is mainly related to sorption process under pH values ranging between 8 and 10. In general, also the Mn-(hydr)oxides show a high degree of chemical affinity both for Ni and Co, which is due to the sorption of these metals onto the Mn-(hydr)oxides surface. In the case of the lithiophorite-asbolane intermediate, the main trigger for Co and Ni enrichment is the replacement of Al by Ni- and Co-rich asbolane-type layers in the gibbsite-like octahedral sites of lithiophorite.

The “saprolitic” horizon occurs as a massive and poorly developed unit. The ore mineralogical association consists of hydrous Mg(Ni)-silicates and of subordinate Mg(Ni)-bearing clays. These species do not contain Co, and display a lower Ni enrichment (max 5 wt%) compared to that of the Mn-(hydr)oxides. The limited development of the saprolite unit can be due to the tectonic stability of the Australian shield during the lateritization process, which likely prevented the efficient migration of fluids towards the lower zone of the weathering profile and caused a limited Ni-enrichment of the Mg-bearing phyllosilicates (e.g. Freyssinet et al., 2005; Golightly, 2010; Butt and Cluzel, 2013).

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Late Caledonian post-subduction gold mineralisation and lithospheric delamination in the Southern Uplands-Down-Longford Terrane of Britain and Ireland.

Rice, S. P., Cuthbert, S. J. and Hursthouse, A.

49, Walkerston Avenue, Largs, U.K. (sam.rice.geo@gmail.com)

Post-subduction porphyry gold deposits are a relatively recently recognised and poorly documented deposit type that could be greatly significant in Phanerozoic orogens globally¹. The Southern Uplands-Down-Longford Terrane (SUDLT) within the British Caledonides is comparable to Phanerozoic orogenic belts globally that host a range of syn-orogenic gold deposit types and provides a firm geological framework in which to investigate the tectonic, magmatic and metamorphic processes behind gold mineralisation during the onset of soft continental collision². Gold occurrences in the SUDLT exhibit similarities with orogenic, intrusion related and post-subduction porphyry gold deposits². The terrane is predominantly composed of Upper Ordovician and Silurian very low metamorphic grade turbiditic metasedimentary rocks intruded by the late Caledonian Trans-Suture Suite (TSS) of calc-alkaline ultra-potassic, mafic to granitic igneous rocks³. Gold is found within, proximal to and remote from known intrusions and predominantly occurs as a lattice constituent of arsenopyrite and pyrite within quartz veins and related potassic alteration haloes. Fluid inclusion data indicate that gold was deposited by low salinity mesothermal (~330°C) carbonic fluid of mixed magmatic-metamorphic origin consistent with Caledonian orogenic conditions and shallow crustal depths $\sim \leq 5$ km. Mineralisation is commonly associated with transverse ~NW-SE- and ~N-S-trending fractures constrained to between 418 and 410 Ma. The host structures were subsequently reactivated during Late Palaeozoic, Mesozoic and Cenozoic times and host younger base metal deposits (Pb-Zn, Cu, Sn, Sb). Gold is associated with the early, dioritic I-type metaluminous oxidised magmatic phase of TSS magmatism that straddles the Iapetus Suture but predates the later emplacement of S-type granitic magma.

Melting to produce TSS magma is best explained by delamination of the partially subducted Avalonian sub-continental lithospheric mantle (SCLM) following the termination of Iapetan subduction. The SUDLT therefore provides an important new case study of post-subduction gold mineralisation in a soft continental collision zone. SCLM delamination is considered inherently likely to occur during soft continental collision. A systems approach⁴ indicates that soft collision and SCLM delamination provide the four critical elements of the mineralising system: 1) a metasomatically fertilised mantle source; 2) transient geodynamics; 3) favourable lithospheric architecture for the effective rapid transfer of mass and heat energy from subcrustal to upper crustal levels and 4) a low degree of crustal thickening and exhumation favours the preservation of upper crustal mineral deposits.

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Cobalt recovery from Katanga ores (DRC): the importance of mineralogical evaluation

L. Santoro¹, St. TshipengYav², E. Pirard³, A. Kaniki²

1Natural History Museum, (l.santoro@nhm.ac.uk)

2University of Lubumbashi, (Tshipeng@sgs.com),

3University of Liege (eric.pirard@ulg.ac.be)

Cobalt in the Congolese Copperbelt mines is commonly recovered from Co-oxi-hydroxides (i.e. heterogenite, asbolane) by acid-leaching under reducing conditions. However, most operations face a limit in the leaching yields of cobalt, which usually do not exceed 80%. The main aim of this work was to investigate the causes of the poor recovery, in order to reconcile the Co recovery with processing techniques. Several concentrate samples from different mine plants of Katanga Copperbelt (Kalukuluku, Mutanda, Mabaya, Kamwali and Fungurume) were selected and subjected to a full mineralogical characterization by Optical Microscopy (OM), X-Ray Diffraction (XRD), automated mineralogy and Scanning Electron Microscopy by Energy Dispersive Spectroscopy (SEM-EDS) prior and after leaching tests. OM and XRD results were used as background information to build a mineral list for mineral identification during automated mineralogy analyses by Mineralogic Mining System (Zeiss Ltd.). Automated mineralogy allowed obtaining mineral maps, modal mineralogy, chemical assays and Co deportment for each specimen prior and after leaching. Mineral maps of the leached samples were useful to observe the occurrences of poorly leached Co-bearing particles which were further investigated by SEM-EDS and X-mapping. The results showed that heterogenite (rarely associated with asbolane) is the main cobalt mineral in Katanga. Mineralogic Mining System was able to discriminate between pure heterogenite, and Si-Al-K-bearing heterogenite, asbolane/heterogenite, Heterogenite+Fe-oxi-hydroxide and Co-bearing mixed phases, which resulted more refractory to leaching. The comparison between modal mineralogy of pre- and post-leached samples indicates a decrease, but not a full leaching of these Co phases: chemical assays and Co-department, in fact, still reveal the presence of low Co% within Co phases listed above (Table 1). SEM-EDS and X-mapping on single particles of some specimens corroborated the results obtained by Mineralogic.

Table 1

	KALUKULUKU	MUTANDA	MABAYA	KAMWALI	FUNGRUME
Co content	0.02%	0.22%	5.18%	2.11%	0.05%
Co-bearing mixed phases	87.49	16.70	33.12	22.46	85.47
Heterogenite		57.83	32.15	27.18	1.14
Si,Al,K-bearing heterogenite	12.5	18.59	32.68	42.61	12.63
Heterogenite+Fe-oxi-hydroxides		6.88	1.21	4.15	0.76
Asbolane			0.83	3.6	

The poor recovery of cobalt was ascribed to the mineralogical complexity making the routine processing strategy poorly effective. More attention must hence be placed during the processing stages of Co-ores, in order to avoid inappropriate leaching conditions, inappropriate pulp density and liberation issues caused by the occurrence of Co-bearing phases refractory to leaching treatments.

Structural and geochemical approaches to understanding orogenic gold mineralization

James Shaw¹, Georgian Manuc¹, Taija Torvela¹, Rob Chapman¹

¹School of Earth & Environment, Ores and Mineralization Research Group, University of Leeds, Leeds LS2 9JT
(eejis@leeds.ac.uk, eegma@leeds.ac.uk)

It has long been recognised that the so-called orogenic gold deposits are strongly structurally controlled on all scales. However, an overarching genetic model has proven elusive because the deposits commonly show a variety of metal and fluid sources, pressure-temperature environments, and structural configurations. A multitude of questions remain, related to the source of the ore fluids and metals, and how these are influenced by both large-scale and local-scale structural evolution. A fundamental question is: why do deposits along the same orogenic trend differ in terms of their geochemically-determined fluid/metal sources, structural setting, and timing of the mineralization? In this poster, we will briefly discuss some of these fundamental issues, and how the two new PhD projects by JS and GM will aim to further our understanding of the nature of these differences and what controls them.

The Caledonides of the British Isles and their equivalent terranes in North America provide an excellent base for these studies, owing to the wealth of data. For example, the Irish and Scottish Grampian terranes are well known for their gold occurrences, with the development of economical orogenic gold mineralizations at e.g. Curraghinalt and Cavanacaw in Northern Ireland. This can further be utilized with recent detailed geological mapping by the Geological Survey of Northern Ireland and the geological and geophysical data available from the Tellus program, which has generated a state-of-the-art geochemical and geophysical database.

The investigation will take two main approaches. One will involve a detailed deposit-scale structural study of Dalradian Resources' Curraghinalt deposit, in collaboration with the Geological Survey of Northern Ireland (JS). The work will involve the construction of 3D-4D models based upon data collection and analysis through fieldwork (both underground and surface), microanalytics, drill core analysis, and from the Tellus database. This will be integrated with a more regional-scale study on the physiochemical differences of gold mineralization occurrences found throughout the Grampian terrane, with a possibility to extend the area to include a comparison study of Newfoundland (GM). The approach addressing structural and geochemical differences between deposits will use geochemical characterisation of the mineralizations and of the different vein generations, which will then be mapped onto a structural evolution model and/or fracture network modelling at all scales, including terrane-scale (using Midland Valley's MOVE).

We anticipate that the outcomes of this study will provide new global understanding of gold localization in orogenic belts, and of the causes of differences between deposits along the same trend. Furthermore, as existing published models for orogenic gold are based heavily on world-class Late Archean deposits (e.g. Yilgarn Province, SW Australia and Abitibi Belt, Canada), we hope to establish a genetic model that takes into consideration the often significantly different structural setting of Phanerozoic orogenic gold deposits. For example, unlike Archean orogenic gold deposits, many Phanerozoic orogenic gold deposits are not necessarily associated with crustal-scale, terrane bounding transpressive structures.

Characterisation of lithium minerals in granite-related pegmatites and greisens by SEM-based automated mineralogy

Beth Simons¹, Gavyn K. Rollinson¹ and Jens C. Ø. Andersen¹

¹ Camborne School of Mines, University of Exeter (J.C.Andersen@exeter.ac.uk)

Because of the use in high-capacity energy storage systems, lithium is an important commodity for global sustainable development. However, the determination of lithium in minerals is problematic, primarily because of the low energy and intensity of x-ray emission of the metal, and it is therefore difficult for industrial clients to obtain reliable data on the content and distribution of lithium in their ores. In this paper, we present a new method for the characterisation of lithium minerals using SEM-based automated mineralogy (by QEMSCAN). Although lithium is not detected, the use of ratios between other elements can be employed to determine the major lithium minerals. The method provides accurate information on the department of lithium between different mineral hosts, and can be combined with LA-ICP-MS determinations of lithium within the constituent minerals to assess metal department.

For this study, a method was developed for Li-prospects at Cínovec (Czech Republic), Gonçalo (Portugal) and the Kaustinen pegmatite field (Finland). The most abundant lithium minerals across all the deposits are polyolithionite-trilithionite ($\text{KLi}_2\text{Al}[\text{Si}_4\text{O}_{10}][\text{F},\text{OH}]_2 - \text{K}[\text{Li}_{1.5}\text{Al}_{1.5}][\text{AlSi}_3\text{O}_{10}][\text{F},\text{OH}]_2$), zinnwaldite ($\text{KLiFe}^{2+}\text{Al}[\text{AlSi}_3\text{O}_{10}][\text{F},\text{OH}]_2$), spodumene ($\text{LiAlSi}_2\text{O}_6$), petalite ($\text{LiAl}[\text{Si}_4\text{O}_{10}]$), lithiophilite-triophylite ($\text{Li}[\text{Mn},\text{Fe}]\text{PO}_4$) and amblygonite-montebrazite ($\text{LiAl}[\text{PO}_4][\text{F},\text{OH}]$), which typically occur with quartz, alkali feldspars, plagioclase, muscovite and topaz. Significant minor and trace minerals include beryl, apatite, tourmaline, columbite, and cassiterite.

The lack of capacity to detect Be and Li by x-ray analysis requires database development for automated mineralogy to be carried out in collaboration with optical identification of the mineral hosts. The x-ray spectra for each mineral were explored to determine any characteristics which would be unique for each mineral. Given the distinct P-K α x-ray signal and the absence of Ca-K α and Ce-L α , database development for the phosphate minerals was straightforward. For the silicate phases, in contrast, careful consideration of the Al:Si ratio in combination with the detection of other key elements allow for the recognition of beryl, spodumene and petalite. The lithium micas, however, could not be uniquely identified from their Li-absent equivalents between localities, and required bespoke characterisation for each individual occurrence (variations in Al:Si, F:OH, and Li:K substitutions).

Confirmation of Li contents requires LA-ICP-MS to ensure that appropriate consideration is given to vacancies and non-stoichiometric variability before true metal departments can be calculated. Although the method presented here is universal, the sensitivity of the method is instrument specific, deposit sensitive and requires bespoke calibration of the database to ensure accurate results.

Acknowledgments

This project is a contribution to the EU Horizon 2020 project “FAME – Flexible and Mobile Processing Technologies” – grant # 641650. QEMSCAN is a registered trademark of ThermoFisher Scientific.

Trace elements and ore formation in the Troodos and Parys Mountain VMS systems: A link to modern SMS deposits?

Joshua Smiles¹, Manuel Keith¹, Daniel J. Smith¹

¹School of Geography, Geology and the Environment, University of Leicester, LE1 7RH,
(js778@student.le.ac.uk)

Seafloor massive sulphide (SMS) deposits are typically rich in base metals, such as Fe, Cu, Zn and Pb, and their formation is genetically linked to active hydrothermal vent systems [1]. These deposits are thought to be analogous to ancient volcanogenic massive sulphide (VMS) deposits. This study aims to identify if ancient VMS deposits can be used as analogues for SMS deposits. For this study, two genetically distinct, previously mined VMS systems were chosen. The Troodos VMS deposits are hosted within the 90 Ma Troodos ophiolite, which formed in a sediment-starved, supra-subduction environment [2]. The 436 Ma Parys Mountain mineralisation formed within a back-arc during subduction of the Iapetus ocean as part of a sediment-covered hydrothermal system [3]. These ancient systems will be compared to data from modern SMS systems, including the deposits in the Escanaba Trough on the Gorda Ridge, and the TAG mound on the Mid-Atlantic Ridge.

Fieldwork and examination of hand specimens has shown that the Troodos VMS deposits are hosted in extrusive lava unit of the Troodos ophiolite. The Parys Mountain mineralisation occurs at the contact between shales and rhyolites. Bulk ore XRF data showed that the Troodos VMS ores are rich in Cu, Zn and Au whereas the Parys Mountain ores are Pb-, Zn- and Ag-rich. Scanning electron microscopy revealed that galena is the main host for Pb in both systems and contains zones rich in Ag and Sb. Pyrite grains in the Parys Mountain ores show both oscillatory and sector zoning of As, possibly reflecting changes in fluid composition. Chalcopyrite and sphalerite usually occur together and in association with disseminated and massive pyrite or as individual disseminated phases in the wall rock and quartz veins. Rutile bearing Nb- and REE-rich monazite has been found in the Parys Mountain ores, likely responsible for their REE enrichment compared to the Troodos samples. Electron microprobe and LA-ICP-MS will be carried out to investigate the zoning patterns in pyrite and galena from the Parys Mountain and the Troodos VMS samples. This will help us to better understand the trace element distribution (e.g., Te and Au) between different sulphide phases and their main incorporation mechanisms, which can provide information on the ore-forming processes. The ultimate aim of this study on ancient onshore VMS deposits is to predict the geometallurgy, potential by-products and to identify toxic trace elements that may be released during potential future submarine mining operations of modern SMS deposits.

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Petrogenesis and geochronology of evolved granites in the Cornubian Ore Province: insights into dynamic magmatism and Sn-W Mineralization

W.D. Smith¹, J.R. Darling², D.S. Bullen and R.C. Scrivener

¹ Smithwd1@cardiff.ac.uk

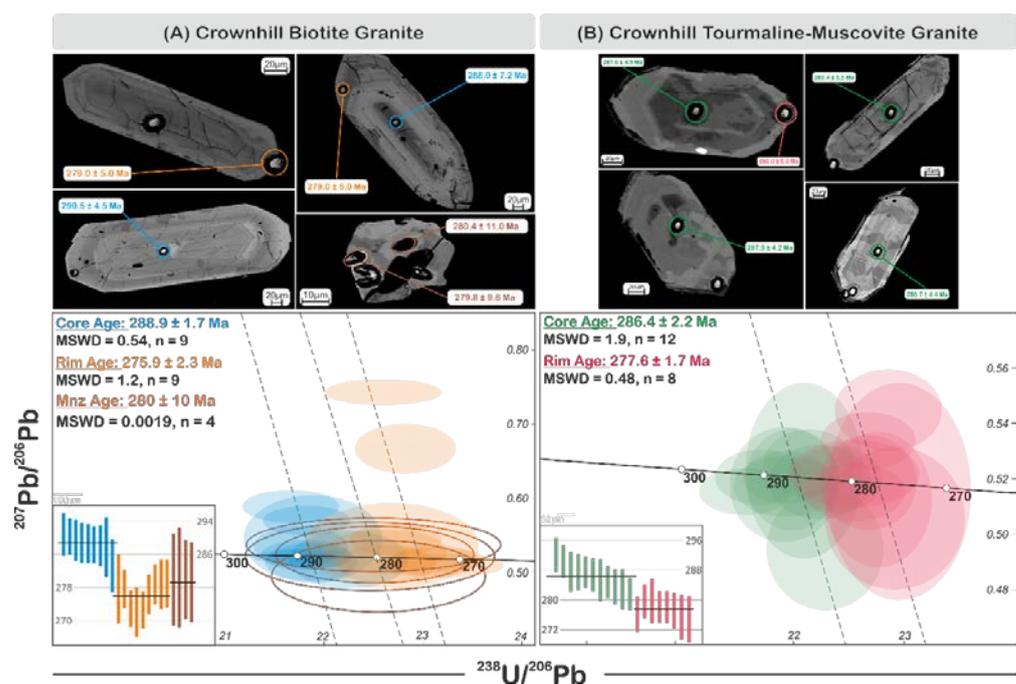
² james.darling@port.ac.uk

***for Poster Presentation**

The understanding of dynamic granite magmatism and magmatic-hydrothermal ore-forming processes in the Cornubian Ore Province is limited by an incomplete magmatic record and its relationship with hydrothermal processes and mineralization. The opening of the Drakeland's Mine, Hemerdon (2015), has renewed interest in unravelling felsic magmatism and associated fertile, hydrothermal systems. Directly adjacent to the Sn-W muscovite granite at Hemerdon lies the Crownhill Intrusion, comprising biotite and tourmaline-muscovite granite. No modern analytical work has been applied to this intrusions and this study provides the first whole-rock and accessory phase geochemical dataset together with U-Pb LA-ICP-MS geochronological record of Crownhill. All granite samples analyzed are peraluminous ($A/CNK > 1$) and reveal fractionation trends between biotite and tourmaline-muscovite granites due to decreasing Ti and HFSEs and increasing Al and LOI, owing to the metasomatic replacement of biotite by tourmaline and the effect of secondary muscovitization.

Polyphase zircons from Crownhill granites yield 288.9 ± 1.7 Ma for resorbed cores (e.g. Hemerdon, Bodmin and Carnmenellis), whereas oscillatory-zoned rims produce 275.9 ± 2.3 Ma (Dartmoor, St Austell and Land's End). Trace element analysis of zircons reveal rims with greater incompatible elements concentrations, including REEs, over their core-counterparts.

A decoupling is observed between wolframite and cassiterite, where cassiterite occurs in association with interstitial metasomatic tourmaline within tourmaline-muscovite granites and wolframite occurs as isolated crystals within the groundmass of muscovite granite. Cassiterite crystallized within boron-rich fluids exsolved from a second phase of magmatism, where nucleation of ore minerals was perhaps induced by the liberation of sequestered Sn from biotite during tourmalinization. As the granites underwent the magmatic-hydrothermal transition, exsolved borosilicate fluids promoted the remobilization of ore minerals, causing them to appear spatially, and temporally associated.



Constraining Gold Placer Sources at a District Scale using Placer Gold Geochemistry and Inclusions. An Example from the Atlin Placer Camp, British Columbia.

Carl P. Spence-Jones¹, Robert J. Chapman¹, David A. Banks¹, Graham W. Mcleod¹.

¹University of Leeds, LS3 9ET, UK (C.Spence-Jones@leeds.ac.uk)

World class placer gold camps, such as Barkerville and Atlin in BC and Whitehorse in the Yukon, have a discrepancy in the size of hard rock vs placer gold inventories. Two hard rock styles of gold mineralisation are known in the Atlin Camp: Gold vein occurrences associated with carbonisation (Listwanite) alteration of ophiolitic ultramafic units and visible gold in quartz-feldspar veins hosted within metasediments [1]. While numerous occurrences are reported the known hard rock reserves have a clear discrepancy in contained gold to the placer resources, the ultramafic Yellow jacket deposit contains 2500 Ounces compared to the 750,000 Ounces of gold estimated to have been produced from placers to date [2].

A total of 805 placer gold grains were collected from 12 localities across the camp and analysed by scanning electron microscopy and microprobe techniques at the University of Leeds. The Ag concentration of the gold alloys are consistent displaying a normal distribution, within each sample population, around a mean of ≈ 21 wt % Ag (maximum and minimum values of 45 and 0 wt % Ag). The distributions include notable “steps” in composition, produced by numerous grains of similar compositions separated by larger jumps in composition, indicating multiple sources/ generations of mineralisation that are geographically widespread occurring in all the drainages sampled.

Mineral attachments/ inclusions found on and within the gold grains provides further constraints on both vein mineralogy and the host lithologies. The most common attachments are quartz, feldspar and base metal sulphides, interpreted as co-forming vein phases. Complex poly mineral “lithic” inclusions are also observed to be preserved within the grains, these indicate an association to mafic igneous/ meta-sediments.

This evidence suggests that ultramafic hosted veins do not represent the original source of the placer gold in the Atlin camp and outlines the insights that placer gold provides on a camp scale. The mineralisation is interpreted to result from a camp wide mineralising event with multiple distributed fluid pathways. This is supported by the lack of significant economic ore discoveries, especially within the ultramafic units, produced by conventional exploration.

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An Early Magmatic Fluid Pulse at Cononish Gold Deposit? Tellurium Enrichment and Implications for the Genesis of Gold Veins in Orogenic Belts.

Carl P. Spence-Jones¹, Gawen R.T. Jenkin², Adrian J. Boyce³, Nyree J. Hill^{2,4},
Christopher J.S. Sangster⁴

¹School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
(C.Spence-Jones@leeds.ac.uk)

²Department of Geology, University of Leicester, Leicester, LE1 7RH, UK

³Scottish Universities Environmental Research Centre, Rankine Avenue, Scottish
Enterprise Technology Park, East Kilbride, G75 0QF, UK

⁴Scotgold Resources, Upper Station, Tyndrum, Stirlingshire, FK20 8RY, UK

Tellurium enrichment is reported in many orogenic gold deposits [1]. Fractionation of Te from Se and S could offer insight into source/pathway processes of auriferous fluids. The Cononish gold deposit, Scotland, is hosted within Dalradian Supergroup metasediments. The gold veins have a Te/Au of ≈ 2.4 making it enriched in tellurium relative to the majority of orogenic gold deposits, that have Te/Au ratios <1 .

The veins at Cononish contain gold alloys of variable silver content which increases from ~ 20 to 80 wt.% through the paragenesis, correlating with decreasing silver telluride (hessite) abundance. This covariance indicates the Au–Ag alloy composition was controlled by the Te activity of the ore fluids, which decreased through time. This fluid evolution is also observed as an increase in pyrite $\delta^{34}\text{S}$ from 1.9‰ to +11.4‰ through the paragenesis.

These findings provide constraints to the genetic model of formation of the Cononish deposit. They reveal that the deposit formed from a fluid with an early low- $\delta^{34}\text{S}$ and high Te+Au+Ag that progressively evolved towards a high $\delta^{34}\text{S}$ –low Te fluid through the formation of the gold bearing veins. The high $\delta^{34}\text{S}$ of the later fluid suggests it can only be a metamorphic fluid sourced from nearby SEDEX horizons. The early fluid that deposited most of the gold could be metamorphic fluid from other units in the stratigraphy, or magmatic in origin. Two observations taken together suggest it is most likely that this fluid was magmatic; the age of the mineralisation is identical to the last stage of crystallization of nearby granite batholiths, and the fluid has a S–isotope signature consistent with a magmatic source. Tellurium in some orogenic gold deposits may relate to magmatic input.

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What lies beneath? Understanding the Platreef mineralisation on farm Turfspruit, northern limb, Bushveld Complex.

Hannah Stephenson¹, Iain McDonald¹, and Danie Grobler².

¹ School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3YE, UK
(StephensonHG@cardiff.ac.uk)

² Platreef Resources, 2nd Floor, 82 on Maude, 82 Maude Street, Sandton 2198, South Africa

The northern limb of the Bushveld Complex, is actively being explored and mined for Ni-Cu-PGE deposits. Mining has focused on the Platreef mineralisation, a 30-100 m thick pyroxenite hosting a base metal sulphide (BMS) orebody dipping $\approx 40^\circ$ at the surface. Current mining of the Platreef is performed by open-pit bulk extraction methods on the world's largest PGE mine, Anglo Platinum's Mogalakwena complex. Underground development of the Platreef is taking place on the farm Turfspruit, located 8 km SE of Mogalakwena, by Ivanplats Pty Ltd.

The nature of the PGE mineralisation on Turfspruit varies moving down-dip (westwards) and can be broadly split into three styles: the near-surface Platreef (0-300 m depth); the Flatreef (700-1000 m) and the deep-Platreef (> 1000 m). A summary of the characteristics of the mineralisation events, as observed from core logging of four drill holes covering 4 km surface distance in the down-dip direction, is presented in Table 1. These are referenced to a baseline event, labelled 0, observed in all drill holes; + and – indicates additional events stratigraphically above and below this baseline, respectively.

Table 1: Summary of the principal characteristics of the mineralised intercepts using a 2 g/t COG.

Note: the prefix refers to the drill hole collar and position on Turfspruit as follows: ATS (Platreef), 233 ('normal' Flatreef), TMT ('thick' Flatreef) and UMT (deep-Platreef).

Event	Thickness (m)	Host Lithology	Features
ATS 0	7	Pegmatoidal orthopyroxenite / harzburgite	Cr-stringer (x 2); interstitial BMS (< 10%)
233 +1	5	Feldspathic pyroxenite / norite / leuconorite	Interstitial BMS; phlogopite; chilled margins; leucocratic pegmatoids
233 0	15	Pegmatoidal feldspathic pyroxenite	Cr-stringer (x 1); interstitial BMS (< 10%)
TMT +1	12	Feldspathic pyroxenite	Interstitial BMS (10 - 20%)
TMT 0	18	Pegmatoidal orthopyroxenite	Cr-stringer (x 1); coarse-grained interstitial BMS
TMT -1	8.5	Melagabbro / para-pyroxenite / serpentinite	BMS (< 10%), phlogopite, disseminated chromite (up to 20%)
TMT -2	10	Melagabbro / para-harzburgite	Strong serpentinisation (locally up to 50%), interstitial BMS (< 10%)
TMT -3	6	Melagabbro / pegmatoidal orthopyroxenite / olivine-bearing pyroxenite	Interstitial, fine to pegmatoidal BMS (< 10%)
TMT -4	10	Norite to leuconorite and feldspathic pyroxenite	Phlogopite; increased felsic content; variable grain sizes (chilled margins and pegmatoids)
UMT +1	16	Feldspathic pyroxenite	Interstitial BMS (< 5%); quartz; phlogopite
UMT 0	5	Pegmatoidal orthopyroxenite +/- olivine	Cr-stringer (x 3); interstitial BMS (5 %)
UMT -1	5	Chromitite (1 m thick) / melagabbronorite (chromitite HW)	Disseminated and massive chromite; interstitial BMS; vari-textured

The observations, as outlined in Table 1, illustrate how the number and size of the mineralised intervals increases down dip, with the notable exception of the 'thick' Flatreef. Understanding the processes leading to these variations is undertaken using bulk geochemical and *in situ* mineralogical data of the silicate assemblage in addition to whole-rock PGE analyses.

Ti-Zr placers and weathering crusts of the Karaotkel and Satpaev deposits, Kazakhstan

Yertlek Suiekpayev¹, Yerzhan Sapargaliyev^{1,2}, Mikhail Kravchenko², Alla Dolgopolova³, Reimar Seltmann³, Askhat Azelhanov²

¹Serikbaev East Kazakhstan State Technical University (EKSTU), Kazakhstan

²LLP “Altaiskiy Geologic-Ecological Institute, JSC “NSTH Parasat”, Kazakhstan

³Natural History Museum, Earth Sciences Dept, CERCAMS, London, U.K.

The Ust-Kamenogorsk titanium and magnesium plant, one of the world's largest titanium producers, with a production capacity of more than 20% of the total world production is located in East Kazakhstan [1]. The raw mineral base of its titanium production comprises the Satpaev and Karaotkel titanium-zirconium (Ti-Zr) placers and weathering crust, which are located in the Kokpekty district of East Kazakhstan [2]. Due to low ore grade and limited reserves, the development of the mineral resource base in the region is strategically important. The Karaotkel and Satpaev deposits are located in the SW part of the Maytubek trough at the border of the west Kalba and Zharma-Saur metallogenic zones of the Greater Altai [3]. The Karaotkel deposit of Ti-Zr placers and weathering crust is confined to river valleys embedded in the Mesozoic weathering crust and alluvial gravel-sandy-argillaceous sediments of the Miocene-Pliocene age. The medium-size Satpaev deposit of Ti-Zr placers is located 16 km to the west of the Karaotkel deposit; it is represented by alluvial Neogene placer [4]. Ore placers are associated with the Karaotkel and Preobrazhensk intrusive massifs, which are represented by three independent complexes of different ages: Maksut, Saikan, and Delbegei.

The following zones are identified in the profile of the weathering crust (from the top down): (1) zone of kaolin clays, represented by bleached clay eluvium, with completely lost structure of the parent rock; (2) zone of hydro-micas - a clay eluvium, composed of clay products of chemical decomposition, but retained structure of the parent rocks; (3) zone of disintegration - a zone of tectonised eluvium consisting of weathered, highly fissured rocks bleached due to partial removal of alkalis and hydration of micas. The ore-bearing strata are clays of the Aral Formation, divided into lower and upper members. The boundary between is caused by an inter-formation break in the sedimentation of clay strata and erosion of the weathering crust.

Geological and genetic relationships were established to reconstruct the formation of the placers: (a) alluvial mineralisation is associated with covers of andesite porphyrites representing the lower member of the Maityube suite (C₂₋₃mt), the destruction of which formed the upper member of the same formation; b) during the intrusion of Late Paleozoic granitoids of the Preobrazhensk and Karaotkel massifs, extensive hornfelsification took place in the zone of contact metamorphism both in the volcanogenic and sedimentary formations of the Maityube suite (C₂₋₃mt) enriched in metamorphogenic ilmenite; c) the localization of ore minerals took place under conditions of strong chemical weathering caused by the marine transgression that began in the Meso-Cenozoic during the subsidence of the Zaisan depression. After the Oligocene the regression of the sea resulted in formation of the clays of the Aral Formation of Miocene age. All these factors contributed to the release of (Ti, Zr) minerals followed by their redeposition, establishing exploration criteria for new discoveries.

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LA-ICP-MS trace-element discrimination for mapping iron sulphides within an Irish-type Zn-Pb deposit, Lisheen mine

Oakley Turner¹, Steve Hollis², Sean McClenaghan¹, Aileen Doran³, John Güven³

¹iCRAG at Trinity College Dublin, Ireland (oakley.turner@icrag-centre.org)

²Geological Survey Ireland, Dublin, Ireland

³iCRAG at University College Dublin, Ireland

Stratiform carbonate replacement Zn-Pb mineralisation in the Irish Midlands is relatively devoid of non-economic sulphide minerals. The notable exception is pyrite, which occurs temporally and spatially throughout deposits, overlying the sphalerite-galena ore body and forms a distal halo in the hanging-wall of fluid-controlling structures.

Samples were taken from 10 vertical diamond drill holes along a section perpendicular to a major normal fault (feeder conduit) transecting the Derryville ore body at the Lisheen mine. Bulk lithogeochemistry of parent samples was undertaken at ALS Loughrea by ICP-MS using a 4-acid digestion. Polished thin sections of samples from the lowermost reef-bearing sulphides were examined by optical and SEM-BSE/EDS microscopy before undergoing LA-ICP-MS for a suite of elements (³²S, ⁵⁵Mn, ⁵⁸Fe, ⁵⁹Co, ⁶⁰Ni, ⁶³Cu, ⁷⁰Zn, ⁷⁵As, ¹⁰⁷Ag, ¹¹⁴Cd, ¹¹⁸Sn, ¹²¹Sb, ²⁰²Hg, ²⁰⁵Tl, and ²⁰⁸Pb).

Petrographic observations support multiple stages of dissolution and crystallisation involving pyrite±marcasite-sphalerite-galena. Early pyrite (Py₁) is spongy in appearance and defined as disseminated aggregated framboids. Py₁ was subsequently recrystallised into disseminated botryoidal pyrite (Py₂). These phases are further recrystallised by latter hydrothermal phases. Distal to feeder structures, LA-ICP-MS data shows these pyrite phases are deficient in elements associated with ore stage mineralisation (Zn-Cd-Cu-As-Tl) within the core. Both have elevated Co, Ni, Mn, Pb and Sb and a further central zone (in preserved framboids) identified by increased Sn. Distal, early-stage pyrite shows evidence of a later rim (Py₄) with distinctively higher As-Tl concentrations associated with minor crystals of sphalerite.

Within the ore zone, preserved early pyrite occurs as radiating agglomerated botryoidal forms, subsequently recrystallised into euhedral crystals (Py₃) with additional, fine, massive pyrite (Py₄) replacing the accompanying carbonate phases. As and Co are concentrated in the rims of, early, hydrothermally altered diagenetic pyrite similar to the distal sample; large euhedral recrystallised pyrite concentrates Mn-Cu preferentially.

Massive finely-crystalline Py₄ in the proximal sample is As-rich, yet poor in many other trace elements analysed. Bladed marcasite overgrows pyrite and sphalerite phases. Trace-element variations are less certain, Ni is preferably concentrated in pyrite over marcasite; Co and Mn contents are variable with no discernible features.

This characterisation can, with appropriate treatment of data, be applied to bulk lithogeochemical data utilising principle component analysis to map dominant pyrite stages at Lisheen mine, thus a new target discriminator in regional exploration.

Bakyrchik type gold mineralization in black shale strata and regularities of its formation

Umarbekova Z.T., Dyussebayeva K.Sh.

Satpayev University, Almaty, Kazakhstan; zama7777@mail.ru

Auriferous deposits located in black shale strata are among the most attractive targets for enhancing the resource potential of gold in the long term. Gold deposits of black shale type are hosted in carbonaceous sediments of a wide range, from Proterozoic to Mesozoic-Cenozoic. Alone in Asia more than 15 giant and large gold deposits are known for this group containing a total resource of more than 12 thousand tons of gold. A significant number of deposits are concentrated in the CIS - Uzbekistan (Muruntau, Myutenbay, etc.), Russia (Sukhoi Log, Natalka, etc.), Kazakhstan (Bakyrchik, Bolshevik, etc.). They all exhibit complex polygenic features [1].

The main ore controlling structure for the Bakyrchik deposit, together with genetically similar and structurally related objects Bolshevik, Shalabay, Kholodny Kljuch, Promezhutochnoe, Gluboky Log, Sarbas is the Kyzyl zone which according to seismic data can be traced to a depth of 3 km from the surface (5.0 to 5.5 km in the dip). Within the ore hosting Kyzyl zone are known more than 70 ore bodies; 35 of them have been explored to a depth of 160-200 m and up to 1000-2000 m in dip, with an average gold content of 8-10 g/t [2].

In the Bakyrchik gold deposit are known about 35 ore minerals that are forming five paragenetic associations. The bulk (90%) of Au is invisible under the optical microscope and contained as refractory gold in the lattice of pyrite and arsenopyrite or as micro-inclusions.

Based on the analysis of published materials on the formation of gold deposits in carbonaceous strata and using collected own data, a three-stage formation model of gold mineralization is proposed for the Bakyrchik deposit: sedimentary-diagenetic stage; tectono-metamorphic stage; intrusion-related thermal aureole (thermal-metamorphic) stage [3].

In deciphering the genesis of the black-shale hosted gold deposits, together with stratigraphic-lithological and mineralogical-geochemical constraints, interesting results were obtained on the isotopic composition of Pb, which confirm the concept of the multistage character of ore in large mineral systems due to complex and multiple mechanisms for the concentration and redistribution of complex ores. The following Pb model ages are discussed for the mineralization: 560 ± 18 and 437 ± 10 Ma that refer to Cambrian and late Ordovician – early Silurian stages of intense destruction and widespread basaltoid volcanism; 320 ± 13 Ma that corresponds to the C1-2 stage of molasse sedimentation and syngenetic mineralization; 229 ± 20 and 201 ± 28 Ma - following intense granitoid magmatism the post-collisional and intraplate stages of the orogeny during P₃-T₁ and T₂-J₂.

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Geology and genesis of the Aynak Copper Deposits, Kabul, Afghanistan

Hamidullah Waizy¹, Norman Moles¹, Martin Smith¹

¹ SET, University of Brighton (H.waizy@brighton.ac.uk)

Aynak is the largest and best known copper discovery in Afghanistan, located about 30 km SSE of Kabul in Logar province. It has been exploited for over 2400 years and the site contains remnants of an ancient settlement with old copper smelting furnaces visible at the surface and slag covers much of the deposit area. Following re-discovery of the deposit in the 1970s and extensive drilling, Soviet-Afghan geologists estimated an indicated resource of 240 million tons at a grade of 2.3 % copper in the Central and Western parts of Aynak copper deposit.

The host rocks for the copper mineralisation are a metamorphosed cyclic succession of dolomite, marls, siltstones and carbonaceous pelites of the Ediacaran to Cambrian age Loy Khwar Formation. Late Alpine folding formed an asymmetrical anticline approximately 4 km long by 2.5 km wide. The core of the anticline consists of amphibolites and gneisses of the Welayati Formation which are flanked on the limbs by the Loy Khwar Formation.

The aims of this project are to determine the origin of Aynak copper resources (Central, Western, North Aynak-Taghar), located in the Kabul Basin (District), and to describe the geochemistry, mineralogy and distribution of the copper ore in these deposits. To achieve this, a total of 92 rock specimens were collected, mainly comprising drill cores. The samples have been analyzed using XRF; optical and scanning electron microscopy; sulphide geochemistry from partial acid dissolution followed by ICP-MS; fluid inclusion microscopy for vein samples; stable isotope analyses of sulphur in sulphides and geochronological analysis using the pyrite Re-Os method. Results from these analyses have enabled consideration of the sources of sulphur and metal components in the mineralizing fluids and the processes of ore formation.

The primary ore minerals are dominantly chalcopyrite and bornite with less abundant pyrite and sphalerite, and rare cobaltite, pyrrhotite and molybdenite. Sulphides occur as bedded laminae, disseminations, cross-cutting veins, and in metamorphic segregations together with coarsely crystalline quartz, dolomite and calcite. Sulphide $\delta^{34}\text{S}$ ratios range from -14.5 to +17.3‰ in bedded and disseminated sulphides (n=35) and from -6 to +12.2‰ in vein and segregation sulphides (n=25). ICP-MS analysis of sulphide separates shows high cobalt concentrations in chalcopyrite, pyrite and pyrrhotite with nickel enrichment in some pyrites supporting petrographical interpretations that pyrite replaced pyrrhotite post-metamorphism.

The origin of the Aynak copper deposit is still under debate. According to previous researchers, the ore formed syngenetically in sediments deposited in a near-shore environment, as copper mineralization is typically bedding-parallel and largely constrained to the Loy Khwar Formation. However it is possible that the Aynak ore is instead of epigenetic (hydrothermal-metamorphic) origin, in which case the copper and associated metals could have been extracted by hydrothermal fluids from Proterozoic basic meta-igneous rocks in the crystalline basement of the Kabul tectonic block. Interpretation of sulphur isotope analyses suggests that bacterial reduction of seawater sulphate is the likely source of sulphur in the ore deposit, with some redistribution during metamorphism. This favours a SEDEX genetic model for the formation of the ore deposit, which is also constrained by geochronological analysis.

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The geometry of the precious metal bearing epithermal system, Tlamino, Serbia.

Sam J Walding¹, Gawen RT Jenkin¹, Daniel James² and David Clark².

¹School of Geography, Geology and the Environment, University of Leicester, LE17RH, UK
(sw417@student.le.ac.uk)

²Medgold Resources Corp. Novi Beograd, Serbia (info@medgoldresources.com)

The Tlamino gold project is situated in southeast Serbia, hosted within the Serbo-Macedonian Massif (SMM), a north-south belt of metamorphic rocks within the East Alpine orogen [1]. The project comprises two historical prospects, Liska and Barje, both previously explored by Yugoslav-era state companies for base metals. Liska is located 1.5 km south-southwest of and 150 m lower than Barje, the prospects are both thought to be associated with the Eocene Crnook detachment, a regional scale low angle detachment fault, striking east-west and dipping south. The area between the prospects is overlain by conglomerate, deposited in half grabens formed by listric faulting in the hanging wall of the Crnook detachment [2].

Liska is located at the base of the conglomerate cover and parallel to the surface of the detachment fault, the body of mineralized rocks are shallow dipping and lensiod shaped. Mineralized rocks at Barje are strata bound and dip gently to the south, an adit driven into the prospect perpendicular to the dip suggests mineralization may continue up dip slope. Mineralization at both prospects is hosted in a tectonic breccia, thought to have formed along the Crnook detachment. The prospects are characterised by different base metal to precious metal ratios, Liska is barren of precious metals but relatively enriched in base metals, whereas Barje is enriched in precious metals and base metal poor.

It is hypothesised that Liska and Barje prospects are genetically and temporally linked and the different styles of mineralization observed at each prospect represent the product of a single evolving fluid, with Barje prospect representing a more evolved hydrothermal fluid than Liska. It is suggested that if the two prospects are related in this way then mineralization may occur between the two prospects below the conglomerate cover, with Au content increasing towards Barje. This hypothesis will be addressed through geological mapping, petrographic studies, scanning electronic microscope analysis, and geochemical analysis.

Initial results show that Ag/Au ratios at Liska and Barje fall into very different fields, with average Ag/Au ratios of 126 and 23 respectively, suggesting either the evolution of a single fluid or two independent fluids forming each prospect. Au is not correlated with any elements at Liska, whilst Ag, Pb, Sb and Bi show strong correlations suggesting Ag may be concentrated in galena and possibly sulfosalts. Au and Ag show a good correlation at Barje and are also associated with Sb and Hg. Early Petrographic work suggests native electrum is present as a later phase in Py-Gln-Spl veining at Barje.

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Magnetite as an indicator mineral for Ni sulfide mineralisation: a case study from Munali, Zambia

Laura Ward¹, law51@le.ac.uk, David Holwell¹, Tiffany Barry¹, Shaun Graham²

¹Geology Department, University of Leicester

²Carl Zeiss Microscopy Ltd, U.K

Magmatic Ni-Cu-PGE sulfide deposits hosted by mafic-ultramafic intrusions are the most important source of Ni and PGE on the planet. Exploration for these deposits relies on geophysics to identify host intrusions, and surface geochemistry to identify anomalously concentrations of Cu, Ni, Co, Cr, As and other associated elements. One of the greatest challenges in mineral exploration is the recognition of mineralisation at greater and greater distances from the primary source, however, no indicator mineral techniques are routinely applied to the exploration for magmatic sulphides. Whilst the use of magnetite has effectively been shown to be a useful petrogenetic indicator (Dare et al 2014), and as a prospectivity indicator in porphyry systems (Pisiak et al 2017), it has not been used to identify magmatic sulfide prospectivity. Magnetite represents an ideal indicator mineral for Ni sulphide mineralisation given its ubiquity in magmatic systems, resistant properties and ability to record chemical variability under differing modes of formation. This study, through textural classification and laser ablation-ICP-MS, utilises multiple magnetite-bearing intrusions, both mineralised and barren, from the Munali Intrusive Complex, Zambia, as a pilot study to test magnetite's effectiveness as a geochemical indicator mineral.

Magnetite from mafic, ultramafic and magmatic sulfide lithologies show discernible differences in the most compatible elements in magnetite (V, Ni, Cr). We propose a new Cr/V versus Ni discrimination diagram for magnetite that can be used to indicate fractionation of parental magmas (Cr/V increases with evolution from ultramafic to mafic), and the presence of co-existing sulfides (Ni contents >300ppm). Detrital magnetite taken from overburden directly on top of known sources of economic grade mineralisation at the Munali Ni deposit replicate chemical signatures in the fresh rock, confirming that magnetite geochemistry in preserving fresh rock signatures with fidelity. Samples of overburden from areas without any geophysical or geochemical anomalies show very few mineralisation signatures in magnetite, whereas magnetite samples taken from exploration prospects with such anomalies display signatures consistent with mineralisation in fresh rock.

For the first time, mineralising signatures are confirmed to be preserved in detrital magnetite collected from soil overburdens on top of known sources of Ni-sulphide mineralisation. This demonstrates magnetite's potential as a geochemical indicator mineral in early stage geochemical exploration to identify magmatic Ni-Cu-PGE sulfide prospectivity.

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Incorporating Geological Mapping, Geological Modelling and 3D Scanning data from The Rogerley Mine, the UK's only hand specimen mine

Authors: James Williams¹, Guy Dishaw², Harri Rees³

^{1 & 2} SRK Consulting (UK) Ltd, 17 Churchill House, Churchill Way, Cardiff, CF10 2HH

³ SRK Exploration Services, 12 St Andrews Crescent, Cardiff, CF10 3DD

The Rogerley fluorite mine ('Rogerley') is the United Kingdoms' only mineral specimen focused mine, located in the Weardale mining district in County Durham. SRK was commissioned by UK Mining Ventures Ltd to undertake geological mapping (surface and underground), a 3D scan, and geological modelling of the fluorite mine workings and surrounding area.

Rogerley is located within the Northern Pennine Orefield, a 1,400 km² block of Carboniferous aged (~325 million years old) sedimentary rocks (limestones, sandstones, and shales). Mineralised veins were intruded into the Pennine Orefield during a single phase, sourced from the Weardale granite.

The majority of lead, zinc, barite and fluorite mineralisation within the Weardale region, and at Rogerley, occurs within the upper 10 m of the Carboniferous aged "The Great Limestone" unit. At Rogerley, two main types of fluorite mineralisation occur:

purple fluorite crystals associated with near vertical fissure veining (feeder structures), and, green fluorite crystals associated with near horizontal mineralisation, locally termed 'flats', which formed via the metasomatic and cavity replacement processes.

The 'flats' related mineralisation is the most abundant within the mine and has the most valuable hand specimens. Two fissure veins were previously known to occur within the immediate mine area, these are the Greenbank vein (north northwest to south southeast orientation) upon which the mine has been developed, and the Sutcliffe vein (east northeast to west southwest orientation).

A surface geological sketch map of the Rogerley area has been produced by SRK. The fissure vein structures occur within all of the units mapped by SRK. But, other than the Great Limestone unit, the other units do not appear to be as prospective for mineral specimen quality fluorite mineralisation due to the competency contrast and lack of 'flats' (dissolution cavities).

SRK identified an additional fluorite bearing vein during the surface geological mapping, located approximately 35 m to the north of, and with the same orientation as, the Sutcliffe vein, and named it the "River Catcher" vein. During the underground mapping SRK also identified sub parallel mineralised fissure veins trending in the same orientation as the Greenbank vein. The intersection points for the River Catcher and Sutcliffe veins, with the Greenbank vein set, is considered by UK Mining Ventures to be a target zone for the long term development of the mine, as the intersection between these structures may have resulted in an increased amount of jointing and fracturing of the rocks and therefore potential for mineralisation.

The underground mine extents were scanned by SRK using a handheld Zeb Revo device, an automated 3D laser scanner. This scan resulted in an extremely detailed 3D point cloud dataset, from which a wireframe mesh was built. Small mine development drives, voids and even individual timbers within the mine were captured during the scan.

A 3D geological model of the mine was built combining the Zeb Revo scan data, SRK geological mapping data (surface and underground) and Lidar (topographical) data. The model allowed an accurate distance between the current mine development and the postulated vein intersection points to be calculated, as well as identifying near mine exploration targets associated with the Greenbank vein.

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By-product elements in Iron-Oxide-Copper-Gold deposits: an assessment of resources and recoverability.

Sally Worbey¹, Dave Holwell¹, Richard Lilly²

¹ Department of Geology, University of Leicester, UK (sw422@student.le.ac.uk, dah29@leicester.ac.uk)

² Earth Sciences, University of Adelaide, South Australia (richard.lilly@adelaide.edu.au)

By-product elements are produced alongside other major commodities and they are increasingly being used in developing technologies, such as solar panels and modern electronics. Major commodities are widely reported by mines and have detailed resource figures; yet by-product elements are not routinely analysed for, reported or extracted from mine refineries, therefore we do not have reliable resource estimates for these elements. The security of supply of these elements is also an issue, as at present these elements are sourced from a limited number of countries, such as China. Similarly, the production of these by-product elements is dependent upon the production of the major commodity, which is often limited.

It has been found that the bulk quantity of by-product elements can be estimated in various deposit types, by finding a strong correlation to major elements [1]; however, this method has not yet been tested on Iron-Oxide-Copper-Gold (IOCG) deposits. IOCG deposits are ideal for by-product element resource estimation and extraction as they are enriched in a variety of base, precious and trace metals. They also have large quantities of copper sulphides, which by-product elements such as cobalt, selenium and tellurium are associated with in porphyry type deposits. Samples of high grade ore, concentrate and tailings were obtained from Ernest Henry, a world class IOCG with the aforementioned characteristics.

Preliminary results show significant Cu, Co, Sb, Ba, Bi, Se, Te and W enrichment relative to bulk continental crust values from Rudnick and Gao (2003). However, only reliable Cu/Bi and Cu/Te ratios could be calculated from average ore, bulk rock geochemistry. These ratios were used to determine the total contained Bi and Te in the ore deposit, based on the Ernest Henry resource of 87.1 Mt at 1.17% Cu [2]. The concentration factor in copper concentrate was then calculated to indicate the recoverable proportion of Bi and Te; this yielded a resource of 1710 t of Bi and 51 t of Te. World reserves are currently 370,000 t of Bi and 25,000 t of Te, [3] so the Ernest Henry deposit and other IOCG deposits could represent large under-exploited resources of by-product elements.

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Mineralogy of SEDEX-Style Mineralization in the lower Upper Dark Limestones overlying the Tara Deep deposit, Navan, Ireland

Lola Yesares¹, Julian Menuge¹, Robert Blakeman², John Ashton²

¹iCRAG and School of Earth Sciences, University College Dublin, Belfield, Dublin 4, Ireland (lola.yesares@icrag-centre.org)

²Boliden Tara Mines DAC, Navan, Co. Meath, Ireland

The Navan Orebody is a carbonate hosted Zn-Pb deposit located in the Dublin basin, Ireland. Recent exploration drilling has revealed a new satellite deposit to the Navan orebody, known as Tara Deep, with an inferred mineral resource of 10 Mt @ 8.5% Zn and 1.8% Pb. It consists of sphalerite- and galena-rich stratabound lenses hosted by the Pale Beds; the Courceyan basal limestone sequence that hosts the main Navan orebody. The Tara Deep deposit is unconformably overlain by a deep marine succession, comprising Arundian basin fill, known as the Upper Dark Limestone (UDL) [1]. In the Tara Deep area, the lower UDL includes the Thin-Bedded Unit (TBU) which comprises alternating sequences of dark mudstones, siltstones and calcarenites. Here, broad geochemical dispersion halos have been identified with a direct link to the mineralization [2] and [3].

Core samples containing sulfide mineralogy within the TBU at Tara Deep have been studied in detail. Petrographic analyses have revealed a texturally complex mineralogy composed mainly of pyrite and marcasite with subordinate sphalerite, galena, chalcopyrite, arsenopyrite, stibnite and undefined Ni-sulfosalts. Three different mineral assemblages have been identified from their mineralogical and textural features:

(1) Laminated pyrite: This represents the most abundant assemblage, which is mostly composed of 0.5-15 cm thick bedding-parallel layers of framboidal pyrite and minor interstitial sphalerite. It is found extensively throughout the TBU, progressively increasing in abundance downwards. A close association between dark mudstones and laminated pyrite suggests that distribution is controlled by high organic matter content.

(2) Hydrothermal chert: This mainly comprises 0.5 to 2 cm thick microcrystalline quartz bands rimmed by euhedral coarse Mn-rich dolomite associated with bird's eye marcasite, fine euhedral aggregates of pyrite, sphalerite, chalcopyrite and galena. The galena includes very fine exsolved Ni-sulfosalts and stibnite. This occurs systematically at higher stratigraphic levels in the TBU and a heterogeneous horizontal distribution suggests fault or fracture control.

(3) Replacive assemblage: This is pervasively distributed throughout the TBU and associated mainly with calcarenites. It occurs as late remobilizations both crosscutting, and parallel to, the bedding overprinting the early laminated pyrite. Mostly comprising marcasite and pyrite, this assemblage is accompanied by smaller and variable amounts of sphalerite, chalcopyrite and galena. Textural patterns include filling of open spaces and fossil replacement.

Laminated pyrite shows features comparable to other mineral assemblages identified in the lower UDL [2] and [3]. However, both hydrothermal chert and the replacive assemblage have not been described before.

Geological record and detailed petrographic analysis support evidence of the overlapping of diagenetic and hydrothermal multi-phase sulfide mineralization in the TBU. The close relationship between organic matter and laminated framboidal pyrite suggest that this mineralization was generated within soft sediments during early diagenesis, close to the seawater-sediment interface, under euxinic conditions. Chert may also record distal hydrothermal exhalation via sub-vertical fault pathways for ascending fluids bearing silica, Zn, Pb, Cu, Ni and Sb. Replacive sulfide textures suggest the circulation of hydrothermal fluids through the sedimentary pile during early-mid diagenesis, with sulfide deposition controlled by the secondary porosity of calcarenites and its organic material content.

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Discriminating porphyry, skarn-forming and ‘barren’ magmatic/hydrothermal systems in the Daye District, China

Fei Zhang¹, Ben J. Williamson¹, Hannah Hughes¹

¹Camborne School of Mines, University of Exeter, Penryn, Cornwall TR 10 9FE
(fz239@exeter.ac.uk)

Porphyry- and porphyry-skarn-type deposits constitute a major source of the world’s Cu, Mo, Pb, Zn, Ag and Au. They share many characteristics such as their common association with calc-alkaline porphyritic plutons [1, 2]. How porphyry-type and exoskarn deposits form is relatively well understood but two questions remain: (1) why do some calc-alkaline systems produce endoskarn- rather than porphyry-style mineralisation; and (2) why are some plutons poorly mineralised or ‘barren’. The aim of this study is to address these questions and develop mineralogical and geochemical exploration criteria for porphyry- and porphyry-endoskarn-type deposits. This will be based on a case study in the Daye district of China, the second largest mineral district in the Late Mesozoic Metallogenic Belt, both in terms of historical production and reserves. More than 90% of its Cu-Fe-Au-Mo ores are hosted in adakite-like intrusive rocks or along their contacts with Early Triassic marine carbonate rocks [3]. Many porphyry and porphyry-related skarn deposits have been documented such as the Tongshankou porphyry skarn Cu-Mo deposit, Fengshandong porphyry Cu deposit and Tieshan Fe-Cu skarn deposit [3].

This study will focus on the mineralogical and geochemical differences between magmatic-hydrothermal systems producing porphyry or endoskarn deposits, and between poorly mineralised/‘barren’ and ‘fertile’ systems. Particular emphasis will be given to assess the level of carbonate assimilation by feeder magmas at depth. A recent study has shown that mafic magmas assimilating carbonate may degas a significant amount of CO₂ in the deep crust before evolving to more silicic compositions [4]. These higher levels of CO₂ may affect the exsolution of metal-bearing fluids, fluid pressures and even sulphide precipitation. Data from the study will be compared with that from the literature for worldwide porphyry- and skarn-type systems to better constrain the formation of porphyry- and endoskarn-type deposits.

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Sources of fluids and evolution models of the Weibao skarn Cu-Pb-Zn deposit, East Kunlun Mountains, Northern Tibetan Plateau

Shihua Zhong^{1,2}, Jens C. Ø. Andersen², Reimar Seltnann³, Chengyou Feng¹, Alla Dolgoplova³, Daxin Li¹

¹ MLR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, China (S.Zhong@exeter.ac.uk)

² Camborne School of Mines, University of Exeter, Penryn Campus, Tremough, Penryn, UK

³ Center for Russian and Central EurAsian Mineral Studies, Department of Earth Sciences, Natural History Museum, London, UK

The Weibao Cu-Pb-Zn skarn deposit is located in Xinjiang Province, NW China (37°07'58" N, 91°07'08" E), at an elevation of ca. 5000 m. This deposit belongs to the Qimantagh metallogenic belt (QMB), a significant Triassic Cu-Fe-Pb-Zn (-Ag) belt in East Kunlun Mountains, Northern Tibetan Plateau (Feng et al., 2010; Zhao et al., 2013). Although it has significant economic potential, many aspects of this deposit are still unknown. In this work, fluid inclusion (FI) microthermometric and stable isotopic results are presented, aiming to (1) constrain sources of ore-forming fluids, (2) clarify mechanisms of metal precipitation, and (3) suggest a genetic model for the Weibao deposit.

The Weibao deposit comprises three ore blocks from west to east, known as Weixi, Main and Weidong. It is intimately related to Triassic intrusions occurring at Weixi and Weidong and the orebodies are predominantly hosted within carbonate rocks. Five hydrothermal mineralization stages can be identified, i.e, hydrous skarn (stage I), anhydrous skarn (stage II), Cu-Fe sulfides (stage III), Pb-Zn sulfides (stage IV) and barren quartz-carbonate (stage V) stages. Stages I and II are dominantly characterized by liquid-rich and daughter crystal-bearing FIs, with homogenization temperatures and salinities ranging from 430-560 °C and 11.5-59.8 wt% NaCl equiv, respectively. Stages III and IV are characterized by coexisting liquid- and vapor-rich FIs, with temperatures and salinities ranging from 298-442 °C and 0.4-15.0 wt.% NaCl equiv, respectively. Stage V are characterized by liquid-rich, vapor-rich and CO₂-bearing FIs with much lower temperatures and salinities (150-300 °C and 0.2-9.9 wt% NaCl equiv). $\delta^{18}\text{O}_{\text{water}}$ and $\delta\text{D}_{\text{water}}$ of FIs hosted by minerals from stage II range from 8.1 to 12.2‰ and -60 to -58‰ (relative to V-SMOW), respectively, whereas those from stage III range from 12.5 to 16.7‰ and -101.6 to -89.1‰, respectively. Stages IV and V are characterized by much lower $\delta^{18}\text{O}_{\text{water}}$ and $\delta\text{D}_{\text{water}}$ values, with $\delta^{18}\text{O}_{\text{water}}$ being 2.8 to 10.4‰ and -6.1 to -3.6‰, respectively and $\delta\text{D}_{\text{water}}$ being -107 to -83‰ and -110.5 to -91.6‰, respectively.

The systematical variation of δD and $\delta^{18}\text{O}$ of fluids from stages I to V, combined with microthermometric data, is consistent with a predominantly igneous source for the initial fluid and cooling and dilution of magmatic-hydrothermal fluids with crustal fluids. Fluid-rock interaction and cooling were predominantly responsible for skarn formation and metal precipitation. Textures suggest that fluid boiling may also have been a key mechanism for metal precipitation in the Weibao deposit.

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LA-ICP-MS evidence for coupled geochemistry of Au, Cu and As in As-pyrite from modern sea-floor massive sulphides, Kolumbo arc-volcano, Greece

E. Zygouri^{1,2}, S. P. Kiliass², T. Zack³, I. Pitcairn⁴,
E. Chi Fru⁵, P. Nomikou², A. Argyraki², M. Ivarsson⁶

¹University of Leicester, Leicester LE1, UK (ez67@le.ac.uk)

²National and Kapodistrian University of Athens, Athens 15784, Greece (kiliass@geol.uoa.gr)

³University of Gothenburg, SE-405 30 Gothenburg, Sweden (thomas.zack@gu.se)

⁴Stockholm University, Stockholm 10691, Sweden (iain.pitcairn@geo.su.se)

⁵Cardiff University, Cardiff, CF10 3AT, UK (chifru@cardiff.ac.uk)

⁶Swedish Museum of Natural History, SE-104 05 (magnus.ivarsson@nrm.se)

Pyrite from ancient hydrothermal ore deposits commonly shows coupled geochemical behaviour of Au and As, and spatial decoupling between Au-As rich areas and Cu contents [1,2,3]. Both speciation (solid solution Au¹⁺ vs. native Au⁰ nanoinclusions) and concentration of Au are thought to be strongly dependent on the incorporation of As into the pyrite structure and As contents [1, 4]. Conversely, Cu is geochemically decoupled from As in pyrite with zoned crystals exhibiting for example As, Ag, Sb, Te, Pb rich zones that are Cu poor, and distinct Cu-rich zones substantially poorer in these elements [2, 4, 5]. The pathways and processes through which this decoupling behaviour occur are key to the economic recovery of these commodities in ancient VMS deposits and require investigation of modern day SMS that have not undergone significant zone refining. Here we report primary colloform pyrite (Py1) and recrystallized subhedral to-euhedral pyrite (Py2) from the only known SMS deposit associated with thinned continental margin volcanism, Kolumbo arc-volcano, Hellenic arc [6]. The 2 generations of pyrite are enriched in Au, Cu and As {Py1 – up to: 58 ppm Au, 2wt% Cu, 9071 ppm As; Py2 up to 24 ppm Au, 1.3wt% Cu, 4297 ppm As} with positive correlations between the concentrations of these elements. We found that Au and Cu were possibly incorporated in Py1 mainly in solid solution, possibly at distortions in the lattice or vacancies caused by As substituting for Fe, and to a lesser extent in native Au⁰ species, and/or composite Au⁰, Cu-sulphide, or native Cu⁰, inclusions. Recrystallization of Py1 to Py2 led to partial expulsion of As, Au and Cu from pyrite. There is an increase in the abundance of Au- and Cu-enriched inclusions in Py2, and Au, and Cu are also enriched in secondary sulphide phases (galena: ≤60 ppm Au; Pb-Sb-sulphosalt: ≤87 ppm Au; As-sulphide: ≤171 ppm Au) and late chalcopyrite, respectively. Our results suggest that Cu may be more readily accumulated in the pyrite lattice when As and Au are present and substituted into the Fe site in pyrite. With increasing recrystallisation, Cu is preferentially expelled from the pyrite lattice into Cu rich inclusions and external secondary Cu-sulphide grains, as it has been previously documented for Au and As [7, 8]. It is likely that this coupled Au, Cu and As behaviour is due to these elements being delivered together via magmatic volatile contribution to the Kolumbo shallow-submarine hydrothermal system.

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