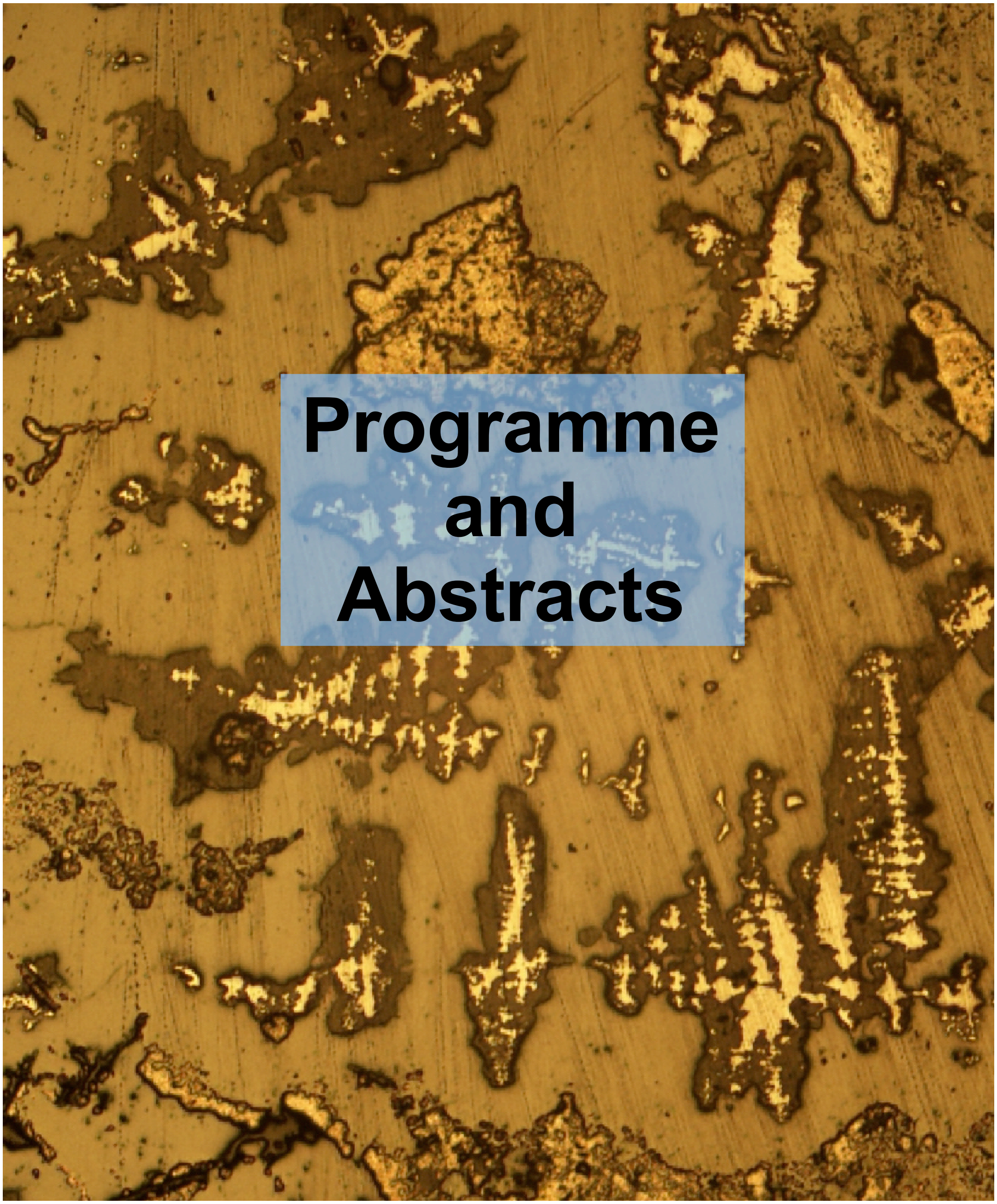
Mineral Deposits Studies Group

39th Winter Meeting
4th - 7th January 2016

University College Dublin



Programme and Abstracts

Welcome

Welcome to the 39th winter meeting of the Mineral Deposits Studies Group, 2016. The meeting will be held in the new O'Brien Centre for Science on the main Belfield campus of University College Dublin, located about 6 km southeast of Dublin city centre.

As a result of recently released major state funding in both Ireland and the UK for minerals research, this meeting should prove to be a great opportunity for new researchers to make contacts. Although many parts of the mineral exploration industry are going through a cyclical lull in activity, research now in progress should inform exploration when demand for minerals recovers. So apart from presenting the results of recent research, we have much to discuss informally about the future.

As always, there is a great diversity of topics represented in the talks and poster presentations. We have grouped talks into themed sessions, including a number of keynote presentations. The poster presentations are also arranged in a sequence that roughly parallels the oral programme.

On a sad note, the Irish minerals world was shocked by the tragic death of Dr Kerr Anderson this past summer. Kerr had a successful career in mineral exploration. His most recent success, as Managing Director of Ormonde Resources, was in winning $100m funding for the mining of the Barruecopardo tungsten project in Spain, announced on the stock market last June. From an academic perspective, he will be remembered for the seminal paper on the Navan Zn-Pb deposit in Economic Geology (Anderson et al., 1998), which is by far the most cited paper on the deposit. This paper came out of his PhD research at the University of Strathclyde under the supervision of Mike Russell. At the meeting, we remember Kerr Anderson by naming a session on Irish-type ore deposits in his honour. We are delighted that Matt Mawson, President of the Irish Association for Economic Geology, has agreed to chair the Kerr Anderson session.

Overleaf, our sponsors are acknowledged. Their support, particularly at such a challenging time for the industry, is greatly appreciated. It allows us to offer student registration at low cost and in doing so makes a big difference to the quality, reach and impact of the conference.

We hope you enjoy the meeting.

Julian Menuge, Renata Barros, Steve Hollis and Sarah Procter
MDSG 2016 Organising Committee

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PROGRAMME

Monday 4th January

18.30 – 20.00 **ICEBREAKER RECEPTION** sponsored by Boliden Tara Mines Ltd
Ground floor of Science East, O'Brien Centre for Science

Tuesday 5th January

08.15 **REGISTRATION**
Ground floor of Science East, O'Brien Centre for Science

All talks take place in the O'Connor Theatre, Science Hub, O'Brien Centre for Science

Session 1 – Critical metals and rare metal deposits (Chair: Stephen Daly)

08.50 **Welcome and conference information**

09.00 ***Keynote*: Gus Gunn (British Geological Survey)**
The future availability of critical metals: facts, fiction and fixes

09.40 **Richard Shaw (British Geological Survey)**
Petrogenesis of rare-metal pegmatites in high-grade metamorphic terranes: a case study from the Lewisian Gneiss Complex of Northwest Scotland

09.55 **Renata Barros (University College Dublin) STUDENT**
Understanding the origin of rare element pegmatites associated with the Leinster Granite in southeast Ireland

10.10 **Jörg Nessler (Technical University Bergakademie Freiberg) STUDENT**
New Drilling Results of disseminated Sn-W Mineralisation at the Zinnwald / Cínovec deposit, eastern Erzgebirge, Germany

10.25 **Victoria Honour (University of Cambridge) STUDENT**
Distinguishing hydrothermal and magmatic processes in the formation of rare earth element (REE) deposits: the Ditrău Alkaline Complex (Romania) as a case study

10.40 **Katie McFall (University of Southampton) STUDENT**
The origin and distribution of critical metals (Pd, Pt, Te & Se) within the Skouries Cu-Au porphyry deposit, Greece

10.55 Tea and coffee sponsored by Midland Valley Exploration in poster display area

Session 2 – Deposits hosted in mafic intrusions (Chair: Dave Holwell)

11.25 ***Keynote*: Judith Kinnaird (University of the Witwatersrand)**
Peripheral platinum: the Bushveld gives you the edge

12.05 **Hannah Hughes (University of the Witwatersrand)**
Lamprophyric dykes in the Bushveld Complex: The lithospheric mantle and its metallogenic bearing on the Bushveld LIP

12.20 **Dominique Tanner (University of Cardiff)**
What can we learn from the trace element composition of silicate minerals in the Bushveld Complex?

12.35 **Bartosz Karykowski (University of Cardiff) STUDENT**
The Monchegorsk Layered Complex - a natural laboratory for mineral deposit types associated with layered intrusions

12.50 **Jonathan O'Callaghan (University of Western Ontario) STUDENT**
Reconstructing the Geochemical Signature of Sudbury Breccia, Ontario, Canada: Implications for Exploration Models

13.05 **Heather Carson (Laurentian University) STUDENT**
Partial assimilation of oxide-facies iron formation – A new model for the genesis of the Black Thor Intrusive Complex, McFaulds Lake, Ontario

13.20 Lunch in Pi Restaurant, O'Brien Centre for Science

Session 3 – Kerr Anderson session on Irish-type deposits (Chair: Matt Mawson)

14.00 ***Keynote*: John Ashton (Boliden Tara Mines Limited)**
The Giant Navan Carbonate-Hosted Zn-Pb Deposit: Exploration and Geology: 1970-2015

14.40 **Freya Marks (Midland Valley Exploration)**
Controls on the formation of a large Zn-Pb Irish-type deposit: evidence from the Navan halo

14.55 **Stephen Daly (University College Dublin and iCRAG)**
A role for the lower crust in the genesis of the Irish Zn-Pb orefield?

15.10 **Danijela Mavric (Trinity College Dublin) STUDENT**
Metal Distribution in Deciduous Trees around Navan Pb-Zn Ore Deposit, Ireland

15.25 **Ann-Kristin Kalveram (Trinity College Dublin) STUDENT**
Geochemistry to explain element transport at Ballinalack, Ireland

15.40 **Julian Aldridge (IOM3)**
IOM3 Membership: the benefits to joining

15.45 Tea and coffee sponsored by Midland Valley Exploration in poster display area

Session 4 – Sediment-hosted and exhalative deposits (Chair: Sarah Gleeson)

16.15 ***Keynote*: John Güven (University College Dublin and iCRAG)**
Geology and controls on mineralisation at the Lisheen Zn-Pb orebody

16.55 **Maria Boni (Università Federico II, Napoli)**
The Zn-Nonsulphides district (with potential) of Bongarà (Northern Peru): a first look

17.10 **Roisin Kyne (University College Dublin and iCRAG)**
Genesis and Structural Architecture of the CSA Cu-Ag Mine, Cobar, NSW, Australia

17.25 **Koen Torremans (University College Dublin and iCRAG)**
Controls on ore mineralisation at the Nkana Cu-Co deposit, Zambia

17.40 **Steve Hollis (University College Dublin and iCRAG)**
2.7 Ga plume associated VMS mineralization in the Eastern Goldfields Superterrane: insights from the Ag-Zn-(Au) Nimbus deposit

17.55 Poster session

18.40 – 19.00 Coaches depart to St Helen's Radisson Blu Hotel

19.00 Drinks reception and conference dinner, St Helen's Radisson Blu Hotel

Wednesday 6th January

Session 5 – Heavy minerals and porphyry deposits (Chair: Richard Herrington)

09.00 ***Keynote*: Harald Dill (Gottfried -Wilhelm Leibniz University)**
Heavy minerals from ore guide to the deposit

09.40 **Jamie Wilkinson (Natural History Museum and Imperial College)**
Chlorite chemistry as a new exploration tool in the propylitic halo of porphyry-epithermal systems: A case study of the Batu Hijau porphyry Cu-Au system, Indonesia

09.55 **Adam Pacey (Natural History Museum and Imperial College) STUDENT**
Propylitic Alteration and Metal Mobility in Porphyry Systems: A Case Study of the Northparkes Cu-Au Deposits, NSW, Australia

10.10 **Lisa Hart (Natural History Museum and Imperial College) STUDENT**
Element mobility during propylitic alteration in porphyry ore systems: a case study of the Oyu Tolgoi deposits, Mongolia

10.25 **Yannick Buret (ETH Zürich) STUDENT**
From a long lived upper crustal magma chamber to rapid porphyry copper emplacement: The geochemical record of zircon crystals at Bajo de la Alumbrera (NW Argentina)

10.40 **Vartan Simmonds (University of Tabriz)**
Re-Os age of molybdenites from the Sungun porphyry Cu-Mo deposit, NW Iran, and its temporal relationship with similar occurrences in the Lesser Caucasus and Central Iran

10.55 Tea and coffee sponsored by Midland Valley Exploration in poster display area

Session 6 – Epithermal and skarn deposits (Chair: Koen Verbruggen)

11.25 ***Keynote*: John Clifford (Consultant)**
Cerro Negro Epithermal Au-Ag Deposit, Argentina: Discovery Case History

12.05 **Giuseppe Arfé (Università Federico II, Napoli) STUDENT**
Mineralogy of the supergene alteration in the Capricornio Au-Ag epithermal vein system, Antofagasta region, Chile

12.20 **Dan Smith (University of Leicester)**
Host rock effects on epithermal Au-Te mineralisation

12.35 **Gülcan Bozkaya (Pamukkale University)**
Fluid inclusion and LA-ICP-MS data on mineralizing fluids of the Bizmisen Iron Deposit (Erzincan, Central Anatolia), Turkey

12.50 **Helena Toman (Natural History Museum, London)**
All This is Yours: The Natural History Museum's Ore Collection

13.05 Lunch in Pi Restaurant, O'Brien Centre for Science

13.35 **MDSG Annual General Meeting**

Session 7 – Tectonics and technology (Chair: Frances Cooper)

13.50 **Gerry Stanley (Geological Survey of Ireland)**
The Geological Survey of Ireland: Your source for minerals and geological information on Ireland

14.05 **Alan Vaughan (Midland Valley Exploration)**
Neoproterozoic basement structures control New Guinea deep structure

14.20 **Nicholas Gardiner (University of Oxford)**
Myanmar: Tethyan Tectonics and Metallogeny

14.35 **Warren Pratt (Specialised Geological Mapping Ltd)**
A classification of styles of orogenic (shear zone) gold mineralization, with examples from Scandinavia

14.50 **Christopher Yeomans (Camborne School of Mines) STUDENT**
Using radioelement distributions to classify a composite granite batholith in the South West England Orefield

15.05 **Charlie Moon (Camborne School of Mines)**
Geochemical exploration for tin deposits in Cornwall, England: recent developments using portable XRF for large scale surveys and TellusSW regional surveys

15.20 **Paul Stenhouse (SRK Consulting)**
Real-time drill core orientation as an aid to effective and dynamic decision making: An example from the Ferensola Gold Project

15.35 **Licia Santoro (Natural History Museum, London)**
Assessment of Automated Mineralogy in Characterising Zn-Pb nonsulphide ore

15.50 Announcement of student prizes

16.00 Tea and coffee sponsored by Midland Valley Exploration in poster display area

POSTERS

Posters are assigned board numbers so that they run in a sequence of themes that roughly follows the sequence of oral presentations.

1 **Liam Hardy (University of Brighton)**
MDSG field trip to Portugal

2 **Liam Hardy (University of Brighton) STUDENT**
Geochemical and mineralogical controls on the distribution of rare earth elements in the laterites of Serra de Monchique, Portugal

3 **Éimear Deady (British Geological Survey)**
REE placer deposits and alkaline volcanic: a case study from Aksu Diamas, Çanakli, Turkey

4 **Humphrey Knight (Camborne School of Mines) STUDENT**
Ore fluid characteristics of antimony deposits in South West England: new insights into ore genesis in Wadebridge-Port Isaac and Herodsfoot

5 **Akmaral Baisalova (SIGS, Almaty) STUDENT**
Titanium silicates from the Verkhnee Espe rare metal deposit in East Kazakhstan

6 **Liam Bullock (University of Aberdeen) STUDENT**
The geological and microbiological controls on the occurrence, mobility and concentration of Se and Te in coal and black shales

7 **William Holyman (University of Birmingham) STUDENT**
Investigating the relationship of the Bodmin Moor Granite, Cornwall, to hydrothermal mineralisation

8 **Charlie Moon (Camborne School of Mines)**
Contrasting Styles of Antimony Mineralisation in the Variscan of South West England

9 **Gregory Smith (University of Birmingham) STUDENT**
The relationship between emplacement and mineralisation in the Land's End Granite, Cornwall

10 **Charlotte Brooks (University of Birmingham) STUDENT**
Stratigraphy of the Lower Basalt Formation, Antrim Lava Group, Northern Ireland

11 **Grace Howe (University of Leicester) STUDENT**
Assessment of the Ni-Cu-PGE sulfide potential of magmatic intrusions surrounding the Munali Ni-sulfide deposit, Zambia

12 **Chloe Mitchell (University of Leicester) STUDENT**
Comparison of the style and nature of breccia-hosted Ni-sulphide mineralisation within the Munali intrusion, Zambia

13 **Hannah Stephenson (University of Cardiff) STUDENT**
Sulphide mineralogy, geochemistry and textures at the Flatreef deposit, northern limb, Bushveld Complex, South Africa

14 **Zeinab Adeyemi (University of Leicester) STUDENT**
Quantitative characterisation of low temperature hydrothermal alteration of magmatic Ni-Cu-PGE sulphide ores

15 **Michael Convery (SUERC, East Kilbride) STUDENT**
Was the Randalstown Fault a feeder zone to the world-class Navan Zn-Pb Deposit, County Meath, Ireland?

16 **Giuseppe Arfé (Università degli Studi di Napoli Federico II) STUDENT**
New C- and O-isotopic compositions of smithsonite from Skorpion and Rosh Pinah Zn-(Pb) deposits (Namibia): preliminary results

17 **Nicola Mondillo (Natural History Museum, London)**
A reanalysis of the Kabwe Zn-Pb nonsulphide ore (central Zambia): preliminary results

18 **James Bowen (University of Leicester) STUDENT**
Base Metal Associations in Orogenic Gold Deposits, Block 14, Northern Sudan

19 **Adeline Dutrieux (University of Southampton) STUDENT**
What is the geological fate of the seafloor massive sulphide deposits?

20 **Emily Fallon (University of Bristol) STUDENT**
The distribution of trace elements in a range of deep-sea sulphide ore deposits and their impact on seafloor mining

21 **Manuel Keith (University of Leicester)**
Systematic variations in the trace element and sulphur isotope composition of pyrite with stratigraphic depth in the Skouriotissa VHMS deposit, Troodos ophiolite, Cyprus

22 **Robert Knight (University of Southampton)**
Initial results of batch reactor experiments to determine sulphide oxidation rates and trace metal release under seafloor conditions

23 **Christopher Yeats (CSIRO, Perth)**
Actively forming Kuroko-type VMS mineralization at Iheya North, Okinawa Trough, Japan: new geochemical, petrographic and $\delta^{34}S$ isotope results

24 **Iain Stobbs (University of Southampton) STUDENT**
Blue Mining: What drives hydrothermal systems and how does it vary over time?

25 **Maria Judge (Geological Survey of Ireland)**
Mapping Marine Minerals in Europe

26 **Simon Large (ETH Zürich) STUDENT**
Rapid ore formation at the Ok Tedi Au-Cu porphyry-skarn deposit

27 **Robert Sievwright (Imperial College London) STUDENT**
Diffusion and partition coefficients of minor and trace elements in magnetite at 1150°C as a function of oxygen fugacity: Implications for understanding the petrogenesis of porphyry ore-forming magmas

28 **Simon Tapster (NIGL, Keyworth)**
A zircon perspective on magma dynamics leading to porphyry copper deposit formation

29 **Jo Miles (University of Leicester) STUDENT**
Multi-element trends during supergene enrichment of porphyry copper ore

30 **Eloise Harman (Natural History Museum, London)**
Epidote Chemistry in Contrasting Hydrothermal and Metamorphic Environments

31 **Benjamin Francis-Smith (University of Leicester)**
The Role of Dolerite in focussing Cu-rich, Au-poor, IOCG-style mineralisation in the Cloncurry Minerals District, Australia: Implications Towards a Genetic Model and Future Exploration

32 **C. Ozturk (Ankara University)**
Specifying ore mineral types and determining the transformations in ore minerals using confocal Raman spectroscopy: Dumluca iron ore deposit, Sivas, Turkey

33 **Alla Dolgopolova (Natural History Museum, London)**
The Sekisovka gold-telluride deposit in Eastern Kazakhstan: tectonics and magmatism

34 **Anthony D'Angelico (University of Leicester) STUDENT**
Orogenic gold mineralisation in northwest Iberia: role of meta-sediment source as a control on location, geochemistry and mineralogy

35 **Reimar Seltmann (Natural History Museum, London)**
Geochemical and petrological study of the gabbro and granodiorite rock series hosting the Vasilkovskoe gold deposit (North Kazakhstan)

36 **Molly Brady (University of Birmingham) STUDENT**
Investigating the relationship of mineralisation to Palaeozoic igneous activity within the Dolgellau Gold Belt, North Wales

37 **Marshall Vice (University of Birmingham) STUDENT**
Investigating erosion of the Dolgellau Gold Belt, mid Wales, through sediment collected from the Mawddach River and Mawddach Estuary

38 **Christopher Herron (University of British Columbia) STUDENT**
Defining the Carbonate Stable Isotope Alteration Footprint of the Cortez Hills Carlin-type Au Deposit in North-Central Nevada, USA and Applications to Mineral Exploration

39 **Gawen Jenkin (University of Leicester)**
Gold and by-product recovery of critical elements from gold ores using deep eutectic solvent ionic liquids: *BRIO*

ABSTRACTS

Abstracts of all talks and posters are arranged in alphabetical order of first author. For multi-authored presentations, the presenter's name is underlined

Quantitative characterisation of low temperature hydrothermal alteration of magmatic Ni-Cu-PGE sulphide ores

Zeinab Adeyemi[1], David A. Holwell[1], Shaun Graham[2], Ben Tordoff[2]

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Magmatic Ni-Cu-PGE sulphide deposits are a major source of Ni, Cu and PGE. These deposits are formed when a mafic/ultramafic PGE-rich magma becomes sulphide saturated and an immiscible sulphide liquid separates from the magma. As the sulphide liquid begins to cool, the first phase to crystallise is monosulphide solid solution (mss), into which Ni and the IPGE (Iridium-Platinum Group Elements; Os, Ir, Ru), will partition, at temperatures of around 1000°C [1]. At 900°C, intermediate solid solution (iss) forms from the Cu-rich residual sulphide liquid. The majority of the PGEs are incompatible in both mss and iss and begin to concentrate with other trace elements, such as Te, Bi, As, and form discrete platinum group minerals (PGMs) [1]. Mss and iss recrystallize at low temperature to pyrrhotite (Po), pentlandite (Pn) and chalcopyrite (Cpy) and subsequently most magmatic Ni-Cu-PGE sulphides contain this relatively consistent primary magmatic sulphide mineralogy.

In a number of deposits, such as the Grasvally-Norite-Pyroxenite-Anorthosite (GNPA) member, northern Bushveld, South Africa, and the Lac des Iles deposit, Ontario, Canada, another sulphide assemblage has been recognised; pyrite (Py), millerite (Mill) and chalcopyrite [2]. This assemblage has been interpreted to be a secondary assemblage and the result of the low temperature hydrothermal alteration of the primary Po-Pn-Cpy assemblage, where pyrrhotite alters to pyrite and pentlandite alters to millerite [2].

This alteration of the sulphides not only alters the sulphide mineralogy, it also upgrades the metal tenors of the sulphides. The texture of the rocks changes during alteration, which makes processing the variably altered ores potentially more challenging than processing the primary magmatic ores.

Samples from the GNPA member are used as a case study, with a fully quantitative energy-dispersive x-ray spectrometry (EDS) analysis, using Zeiss' SIGMA VP SEM equipped with Mineralogic Mining Analysis Engine, identified five progressive stages of alteration; (1) Po-Pn-Cpy (2) Po-Py-Pn-Cpy (3) Py-Pn-Cpy (4) Py-Pn-Mill-Cpy and (5) Py-Mil-Cpy. We are able to fully quantify the elemental balance through each stage for the first time. During each stage there is a net loss of Fe, with the amount of Fe in total sulphide decreasing from 54 wt% in stage (1) to 37 wt% by the final stage (5). The resulting Fe is lost to the surrounding silicates (tremolite and actinolite).

References

[1] Holwell, D., and McDonald, I. (2010) A review of the behaviour of platinum group elements within natural magmatic sulfide ore systems. *Platinum Metals Review, **54**, 26-36.*

[2] Smith, J., Holwell, D., and McDonald, I. (2011) The mineralogy and petrology of platinum-group element-bearing sulphide mineralisation within the Grasvally Norite-Pyroxenite-Anorthosite (GNPA) member, south of Mokopane, northern Bushveld Complex, South Africa. *Applied Earth Science: Transactions of the Institutions of Mining and Metallurgy: Section B, **120**, 158-174.*

New C- and O-isotopic compositions of smithsonite from Skorpion and Rosh Pinah Zn-(Pb) deposits (Namibia): preliminary results

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The Skorpion and Rosh Pinah Zn-(Pb) deposits in southern Namibia, approximately 40 km north of the Orange river, are only at a 15 km distance from one another [1,2]. Skorpion is the largest Zn nonsulfide mineralization ever discovered, and is derived from the oxidation of a VMS-type sulphide protore [1]. It mostly consists of Zn-oxidized minerals (sauconite, smithsonite, hemimorphite, tarbuttite). Rosh Pinah is a typical sediment-hosted Zn massive sulphide mineralization. The original oxidized interval at the surface was of limited extent; it has been currently almost completely removed. The secondary minerals at Rosh Pinah are: smithsonite, hemimorphite, Cu-oxidized phases and Fe-oxy-hydroxides [2]. The isotopic composition of Skorpion smithsonite, already published by previous authors [1], showed that the supergene alteration of the sulphide protore resembled typical weathering processes.

Here are presented the first results of a more comprehensive C- O-isotopic study aimed to compare the deep oxidation process that occurred at Skorpion, with the more limited weathering present in the Rosh Pinah area. A batch of 20 smithsonite and calcite samples from the Skorpion deposit and 10 gossanous samples from the uppermost levels of the Rosh Pinah mine have been analyzed. $\delta^{13}C$ and $\delta^{18}O$ isotopes of carbonates have been measured in permil (‰) versus V-PDB and V-SMOW standards, respectively.

The samples from Skorpion occur mostly as cavity fillings and crusts, which consist of mm-sized euhedral crystals. Smithsonite is characterized here by $\delta^{13}C$ values strongly variable between 0.13 ‰ and −9.14 ‰V-PDB, and by a small range of $\delta^{18}O$ compositions (from 27.96 to 29.94 ‰V-SMOW). Calcite shows more limited variations: $\delta^{13}C$ compositions are generally positive (from −0.02 to 1.55 ‰V-PDB), and the $\delta^{18}O$ values slightly lower than those of smithsonite (from 25.39 to 27.05 ‰V-SMOW). The analyses of the Rosh Pinah samples produced scattered results. $\delta^{18}O$ compositions vary to a very large extent (from 18.68 to 26.55 ‰V-SMOW), due to the occurrence of tiny dolomite inclusions in the smithsonite crystals. The $\delta^{13}C$ compositions, as in Skorpion, cover a negative realm (−5.87 to −2.73 ‰V-PDB).

The negative values of $\delta^{13}C$ in the smithsonites from both deposits point to the involvement of surficial waters and organic matter in mineral formation. Ongoing investigations on the Rosh Pinah samples will define the “uncontaminated” $\delta^{18}O$ composition of smithsonite, to trace a possible similarity with Skorpion smithsonite.

References

[1] Borg, G., Kärner, K., Buxton, M., Armstrong, R., and Van Der Merwe, S.W. (2003). Geology of the Skorpion supergene zinc deposit, southern Namibia. *Economic Geology, **98**, 749-771.*
[2] Alchin, D.J. and Moore, J.M. (2005). A review of the Pan-African, Neoproterozoic Rosh Pinah Zn-Pb deposit, southwestern Namibia. *South African Journal of Geology, **108**, 71-86.*

Mineralogy of the supergene alteration in the Capricornio Au-Ag epithermal vein system, Antofagasta region, Chile

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The Capricornio epithermal Au-Ag vein system is located within the so-called "Chilean Paleocene-Eocene metallogenic belt", 60 km straight to ENE from Antofagasta, in the physiographic Central Depression, between the Coastal Cordillera and the Domeyko Cordillera. The mineralization consists of multiple epithermal quartz-adularia-carbonate veins, extending from the surface to ~ 400 m in depth. The veins are hosted in Cretaceous volcanic rocks, belonging to the Paradero del Desierto Formation. The hypogene ore association at Capricornio is represented by the Au-Ag alloy (electrum, containing on average 60 wt% Au), Ag-sulfoarsenides, Ag-sulfoselenides, Ag-sulfoantimonides, Ag-sulfosalts and acanthite, as well as by base metal sulfides including galena, pyrite, chalcopyrite, sphalerite, and bornite. The hypogene mineralization is deeply weathered, down to a depth of 200 m.

The surficial oxidized blanket (0-150 m depth) is underlain by a secondary covellite-chalcocite-bearing zone, which exhibits a variable thickness, never exceeding 50 m in each of the veins. The oxidized zone has been identified because base metal sulfides have been replaced by several other metallic minerals: (oxy-hydroxy)chlorides (atacamite, pseudoboleite, cumengeite, herbertsmithite), chlorocarbonates (phosgenite), chloroiodates (seeligerite), chlorophosphates (pyromorphite), chloroarsenates (mimetite), and halides (iodargyrite). In this zone gold still occurs as electrum, but after the remobilization of Ag in the process of supergene alteration, it is slightly enriched in Au, up to a maximum of 78 wt% Au, occurring together with Fe-oxy-hydroxides. Gold has been also locally re-mobilized and may occur as veinlets of native gold.

The major Ag-bearing mineral in the supergene zone is iodargyrite. The abundance of Ag-halides, together with the higher Au contents of electrum in this zone, compared with the electrum present in the hypogene zone, suggests a weathering-related Ag remobilization. Silver has not been leached from the deposit and has been locally re-precipitated as Ag-oxidized compounds. The abundance of Ag-halides in the uppermost part of the supergene zone suggests a large availability of halide ligands during weathering. This is not a surprise considering that Cu- and Ag- halides commonly occur in several supergene blankets of porphyry Cu deposits in the Atacama region. The Chilean Paleocene-Eocene metallogenic belt hosts other important epithermal gold deposits, such as El Peñón [1], and Faride [2], where the supergene alteration had a strong role in increasing the ore grade.

References

[1] Warren, I. (2005). Geology, geochemistry, and genesis of the El Peñón epithermal Au-Ag deposit, northern Chile: Characteristics of a bonanza-grade deposit and techniques for exploration. *Unpublished Ph.D. thesis, New Zealand, University of Auckland, 428 p.*

[2] Camus, F. and Skewes, M.A. (1991). The Faride epithermal silver-gold deposit, Antofagasta region, Chile. *Economic Geology, **86**, 1222-1237.*

The Giant Navan Carbonate-Hosted Zn-Pb Deposit: Exploration and Geology: 1970-2015

J.H. Ashton[1], R.J. Blakeman[1], J.F. Geraghty[1], B. O'Donovan[1], A. Beach[2], D. Coller[2], M. Philcox[2], A. Boyce[3] and J. Wilkinson[4]

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The Navan Orebody is a world-class carbonate-hosted Zn-Pb deposit mined by the Boliden Group. It is currently the largest Zn mine in Europe producing ca. 2.5mtpa at grades of 7.0% Zn, 1.4% Pb using underground open stoping methods. This presentation will describe the exploration history of the orebody and current geological syntheses. The deposit was discovered in late 1970 by Tara Exploration and Development Ltd. The discovery, like many Irish Zn-Pb deposits was largely the result of shallow soil trace element geochemistry. The size of the Navan discovery, estimated in the early 70s as nearly 70Mt @ 10.1% Zn and 2.6% Pb, was unprecedented in Ireland and Tara's early days involved significant legal and political difficulties, not least the loss of the near-surface Nevinstown section of the orebody due to actions by third parties. Nevertheless, development started in 1974 with production starting in 1977 and since that time, despite isolated production breaks, near continuous production at rates of 2 to 2.6Mt has been realised. The total mined tonnage now exceeds 87Mt. At the end of 2014, JORC classified Mineral Resources comprised 11.0Mt @ 6.3% Zn, 2.1% Pb and Ore Reserves stood at an additional 15.3Mt @ 6.6% Zn, 1.5% Pb. It is estimated that the total pre-mining resource, as currently known, was in excess of 112Mt @ 7.9% Zn, 1.9% Pb.

Surface exploration drilling has progressively extended the orebody laterally and down-dip (to the SW). This has discovered several new extensions of which the South West Extension (SWEX) is the most significant, comprising nearly 30Mt of resources. This work was largely driven by geology and has employed extensive use of navi-drilling to gain multiple daughter intersections from initial vertical mother holes, thus reducing drilling time, costs and environmental impact. Numerous campaigns of underground delineation drilling from hanging-wall drifts have upgraded Inferred to Indicated Resources, often with attendant discovery of new resources, not identified by first-pass surface drilling. Lastly, additions have been made at the northern and eastern parts of the orebody including the purchase of resources at Nevinstown and Liscartan.

Currently, underground and exploration drilling continue to add resources but at quantities less than the depletion rate and a step-change in discovery is needed to significantly extend mine life. Since the 70s the vast amounts of drilling and underground data, together with research work by university students and consultants, have greatly improved our understanding of the geology at Navan. This knowledge has led to the recognition of enhanced exploration potential at depth and the application of deeper penetrating geophysical exploration techniques, including 2D seismic and EM surveying, to the search for new resources.

The orebody comprises stratabound sulfide lenses hosted by Lower Carboniferous shallow-water carbonates of Tournasian age. The deposit is focused along an early east-northeast-trending, northwest-dipping, extensional relay fault system within the horst-like footwall crest of a major tilt block. This was controlled by a large, southeast-dipping extensional fault that developed during the early stages of rifting of the Dublin Basin (late Tournasian). Footwall uplift on this structure resulted in gravitational instability, promoting further southeast-dipping faulting and low angle tectonic slides that eroded the crest of the tilted footwall block, including the pre-rift host rocks and earlier faults. The culmination of this slide event was marked by the deposition of submarine debris flows and fault talus deposits. The switch from early faulting with northwest throws to faulting with sustained southeast throws created an asymmetric horst and augmented fracture permeability. These basin-margin processes were superseded by the widespread deposition of calc-turbidites in the Dublin Basin from the late Tournasian to the Visean. Many structures were subsequently inverted by reverse and wrench tectonism of probable Variscan age.

The key influence of fluid mixing in ore deposition is highlighted by several lines of evidence. Fluid inclusions reveal a large spread in both fluid salinity and temperature with a weak inverse correlation from low temperature, high salinity to high temperature, low salinity. This is consistent with mixing between shallow-sourced hypersaline brines and deep-sourced, less saline hydrothermal fluids. $\delta^{34}S$ values in sulphide reveal two partially mixed populations; the lower values (~ -26 ‰ to -4 ‰) are the result of bacterial reduction of Lower Carboniferous seawater sulphate, while the higher grouping (~ -4 ‰ to 16 ‰) represents "hydrothermal" sulphur transported by the metal-bearing fluid. The bulk $\delta^{34}S$ signature of the deposit has a mean value of -13.6 ‰ ± 2, implying that more than 90 % of the sulphide was derived through bacteriogenic reduction of seawater sulphate. $\delta^{34}S$ values in sulphate are relatively homogenous with a mean of 23.1 ‰ and derivation from Lower Carboniferous seawater is inferred. Whilst sulphur isotope data indicate the dominance of sulphur sourced from near-surface fluids, Pb isotope values are dominated by sourcing from the underlying basement. Geochronological and palaeomagnetic studies yield a single K-Ar age of 366±11 Ma and an average of 327±3 Ma, respectively. However, geological evidence, including dislocated, rotated sulphide clasts entrained within the Chadian debris flows, suggests ongoing mineralization coincident with that event.

It is proposed that the Chadian-Arundian extensional regime that focused normal faulting and gravity sliding at Navan produced episodic periods of excess pressure in a deep fluid reservoir that forced heated, buoyant, metal-bearing, sulphur-poor fluids from the basement into the limestones over a prolonged time-span. The related development of small, localised basinal areas in half-grabens on the sea floor, allowed locally sourced dense, sulphur-enriched brines to pond, encouraging microbial communities including sulphur-reducing bacteria to thrive. Resultant H_2S-rich fluids penetrated into the fracture-enhanced porosity of the area during on-going tectonism and mixed with the basement-sourced fluids to precipitate sulphides in a strongly cyclical process. Mixing of the sulphide-rich surface brines with the basement-sourced, metal-bearing fluids was the key process in ore deposition. Thus major Lower Carboniferous faulting created a special combination of stratigraphic, tectonic, hydrological and microbiological factors that formed an exceedingly efficient trap which created the world-class Navan Zn/Pb deposit.

Titanium silicates from the Verkhnee Espe rare metal deposit in East Kazakhstan

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The Verkhnee Espe deposit (48º03'– 48º10'N, 81º26'– 81º29'E) is spatially related to two small oval outcrops of alkaline granites at the northern exo-contact of the large Akjailyautas granite massif in the northern part of the Tarbagatai mountain range (Eastern Kazakhstan). Due to small size of both intrusions this deposit is ideal to study fenitisation processes and rare metal mineralisation using geochemical, mineralogical and petrographic characteristics. The mineral composition comprises more than 120 minerals [1], including some very rare and new mineral species [2-5].

Titanium silicates of the deposit include: astrophyllite group minerals (astrophyllite, kupletskite, tarbagataite and varieties of astrophyllite); bafertisite group minerals (bafertisite, camaraite, jinshajiangite); titanite, natrotitanite, narsarsukite, lorencenite, neptunite etc. We present here their physical and optical properties, chemical composition and structural parameters, as well as genesis of titanosilicate minerals.

Titanium minerals are interesting study objects as indicators of fenitisation processes. Among them there are minerals, which are formed only under certain conditions during metasomatic alteration. Under changing thermodynamic and geochemical conditions, they become unstable and decompose with partial removal (where mobile elements such as sodium, potassium, calcium etc. are depleted first) or with complete removal of selected elements from the former mineral. During partial element removal, the newly formed minerals are represented by metacrystals of quartz, microcline, albite, and titanium oxides (ilmenorutile, rutile, anatase etc.). In the case of complete removal of elements from the crystal, the crystal chambers are filled inward from the walls, mainly with microcline. This occurs in places, where there is a carbonaceous material, such as tuffs with plant detritus.

Due to their structural features, phyllotitanosilicates are good ion exchangers. Their capacity to change a chemical composition depends on the compositional contrast at the contact with the host environment. This results in occurrence of unusual mineral compositions, including the calcium analogue of astrophyllite – tarbagataite [5], and the sodium-yttrium-rare earths analogue of titanite – natrotitanite [4].

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Understanding the origin of rare element pegmatites associated with the Leinster Granite in southeast Ireland

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Rare element pegmatites are important sources of strategic metals such as Li-Cs-Ta and are represented by a large diversity of chemical signatures. The mechanisms to form such unusual rocks are still being debated. We investigated whole rock and mineral geochemistry of spodumene (Li-pyroxene) pegmatites and associated rocks in southeast Ireland to understand better how this type of deposit is formed.

The Leinster Pegmatite Belt is formed by NE-SW dykes intruding both the eastern margin of the S-type Tullow Lowlands pluton and Lower Palaeozoic metasedimentary rocks. The three rock types in these dykes are: spodumene pegmatite, intimately spatially associated aplite, and spodumene-free pegmatite. They consist of spodumene (only in spodumene pegmatites), quartz, albite, Li-muscovite, K-feldspar and accessory minerals including spessartine, beryl, cassiterite and phosphates. Ages of emplacement for both granite and pegmatites are around 400 Ma [1, 2]. Extreme fractional crystallisation of Leinster Granite magma has been proposed as the origin of the Li-rich pegmatitic fluids [2, 3].

Whole rock geochemical data from three drill cores show that pegmatites are enriched relative to granite in Li (450 ppm in granite/3500 ppm in pegmatite), Rb (250 ppm/600 ppm), Nb (7 ppm/30 ppm), Ta (2 ppm/30 ppm); depleted in Sr (200 ppm/15 ppm), Ba (350 ppm/20 ppm); and similar in Cs (70 ppm). LA-ICP-MS major and trace element data for Li-muscovite and garnet show that aplites carry the highest concentrations of most incompatible elements, spodumene-free pegmatites the least. No well-defined fractionation trends from granite to pegmatites, or within pegmatites dyke lithologies, are observed. Li- B- and Rb-rich minerals (tourmaline and Li-mica) form in the narrow (up to 10 cm) country rock contact zones adjacent to spodumene pegmatite, indicating some loss of magmatic fluid from the crystallising magma.

Models envisaging extreme fractional crystallisation of granitic magma fail to explain the scatter on chemical plots and the absence of clear fractionation trends. The more evolved pegmatites should present the higher concentrations of incompatible elements, but spodumene pegmatites with high Li content do not have the highest Rb, Cs or Ta. This indicates that extensive fractional crystallisation of Leinster Granite magma is probably insufficient to form the spodumene pegmatites. Given the age similarities in this granite-pegmatite system, it is likely that they were formed in the same event but from different source rocks.

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The Zn-Nonsulphides district (with potential) of Bongarà (Northern Peru): a first look

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The Bongarà complex of deposits (Cementos Pacasmayo, Cia. Minera Pilar del Amazonas S.A.) consists of a stratabound Pb-Zn Nonsulphide/Sulphide mineralization located in the Amazonas District, near the Yambrasbamba village (Peru) [1]. The deposits (Mina Grande, Mina Chica, and Rio Cristal) are hosted by Mesozoic limestone (Toarcian) of the Pucarà Group (Condorsinga Fm.), locally dolomitized and brecciated. The primary mineralization in the property is considered a MVT, similar to the San Vicente deposit in Central Peru. There are multiple distinct ore concentrations scattered over a large area; the mineralization appears to be open-space filling and/or manto replacement associated with karstification. At Bongarà the primary sulphides are very scarce: generally only galena in veins and clasts has been detected in outcrop throughout the property. Few other sulphides (mainly sphalerite) occur in the deepest morphological areas, and have been locally found in drill cores (Rio Crystal). The economic value of the mineralization is currently considered as related to the concentrations of nonsulphide Zn minerals [2]. A mineralogical, petrographic, and geochemical study of the Bongarà complex of deposits is being conducted by our research group on samples collected on site.

The Mina Grande deposit consists of several partly exploited mineralized areas, where the ore, located in the carbonate successions, consists of masses of nonsulphides (mainly hydrozincite>>smithsonite) mixed with brown soil. The economic mineralization is concentrated in karstic cavities and earthy-looking mantos. The mineralized body is 1.5 km long, 0.4 km wide, and extends to depths of 20 to 60 m below surface. The zinc "oxides" form a residual cap along the crest of an anticlinal structure [1]. This mineralization can be classified as belonging to Type 3 (residual in karst cavities) among the supergene nonsulphide deposits [3].

The mineralization in the Rio Cristal prospect is probably the most extensive area of zinc mineralization occurring at Bongarà to date. Diamond drilling has encountered both near-surface primary base metal sulphides (only in traces), and oxidized mineralization at depths of over 50 m down-hole, with grades of up to 20 to 30% Zn. The mineralization occurs in a sigmoidal zone, approximately 1.5 km long by 0.5 km wide. Several sub-horizontal manto-like bodies have been detected, which dominantly consist of masses of orange-brown and white zinc "oxides", which include smithsonite, hydrozincite, cerussite and Fe-hydroxides.

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Base Metal Associations in Orogenic Gold Deposits, Block 14, Northern Sudan

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Sudan is a relatively new gold producer, and has contributed to the 45 Moz of gold discovered within the Arabian Nubian Shield (ANS) in the last two decades [1]. Orca Gold Inc.'s 2.2 Moz resource of Galat Sufar South ("GSS"), which was announced in 2013 [2], is a structurally controlled orogenic gold deposit, but contains high levels of base metals (copper, lead and zinc), which is unusual in a classic orogenic-type system [3]. A possible hypothesis for this is that the base metal enrichment with the gold relates to hydrothermal reworking during metamorphism and deformation of base-metal-rich syngenetic VMS mineralisation within the volcanosedimentary pile. Confirming a potential link between orogenic and VMS-type mineralisation would allow a better understanding of the fluid events relating to the ANS, and may mean that base metal enrichment could be used as an exploration tool for gold mineralisation. The aim of this project is thus to assess a possible linkage between base metal-enriched orogenic gold mineralisation, and nearby VMS mineralisation.

The first objective is to make use of Orca Gold Inc.'s data set, to clarify the relationship between base metals and gold across the prospect. Secondly, samples have been collected from both orogenic gold and VMS-style areas, and are being subjected to petrography, fluid inclusion and S-isotope analysis. This will show the location of gold in relation to the base metals, significant from a metallurgical stand point, which could have an economic impact for Orca Gold Inc. The final objective will be to identify the number of fluid phases, their timing, and which fluids were responsible for bringing in each type of mineralisation.

Geochemical data have not shown a statistically significant correlation between base metals and gold across GSS or other prospects. Analysis of anomalous zones reveals high grade gold can be associated with moderate-high lead and zinc, but base metal and gold rich zones do occur independently. At the Wadi Doum prospect gold enrichment is almost always present with high lead and zinc, however base metal-rich zones are numerous. This could be evidence that the orogenic fluid was free of base metals, and simply deposited gold in base metal-rich zones. Early stage microscopy shows chalcopyrite deposited with gold at GSS, but no evidence thus far of gold with lead and zinc. Further analyses will reveal the true association between gold and base metals in Block 14, and the potential effects on gold recovery for Orca Gold Inc.

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Fluid inclusion and LA-ICP-MS data on mineralizing fluids of the Bizmisen Iron Deposit (Erzincan, Central Anatolia), Turkey

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The Bizmişen (Erzincan) iron deposit is located in Central-Eastern Anatolia, where the local geology consists of Palaeozoic sedimentary rocks, ophiolites and magmatic intrusions. There are various mineralization styles, such as Pb-Zn or Fe-Cu skarns, Fe-Fluorite mineralization, Au, Au-Cu, and Mo-Cu deposits, whose age range is from late Cretaceous to Eocene. The Bizmisen skarn-type iron deposit is one of the most important operating mines (a total reserve of 23.8 Mt of magnetite ore grading 53% Fe) in the region. Skarns occur at the contacts of Paleocene-Eocene plutonic rocks (diorite, quartz diorite) with the Upper Triassic-Upper Cretaceous crystallized limestones, Upper Cretaceous ophiolitic rocks and Campanian-Maastrictian volcano-sedimentary suite. Mineralization is found in different geological settings: (1) Endo-skarn lenses within plutonic rocks, (2) Ore bodies at contacts between plutonic rocks and crystallized limestones, (3) Lenticular veins at contacts between ophiolites and ophiolitic mélanges and granitoids, (4) Stratiform ore bodies extending from contacts with the diorites through the volcano-sedimentary suite. The main ore mineral is magnetite, but hematite, maghemite, limonite, pyrite and chalcopyrite are also observed. Calcite, which occurs as coarsely-crystalline, granular and veinlets, is the most prevalent gangue mineral, and is formed in two stages during metallogenesis. Additionally, quartz, barite and gypsum are also present. At the contacts between plutonic rocks, limestones and ophiolitic rocks, endoskarn alteration was observed in the diorites, represented by calcite, dolomite, garnet, epidote, diopsite, scapolite and tremolite/actinolite. Clay alteration zones (argillic zone) around the ore bodies consist of several types of clay minerals, such as smectite, kaolinite, chlorite, illite and mixed-layered illite-smectite. Talc, serpentine, chlorite, mixed layered chlorite-smectite and smectite-vermiculite minerals were also found within the pores of ore minerals.

Microthermometric study of fluid inclusion assemblages (FIAs) was conducted in gangue minerals from different mineralization stages. In the ore stage, quartz FIA's have salinities from 9 to 6 wt.% NaCl and homogenization temperatures of 210 to 220°C. In calcite-hosted FIAs, (late stage of mineralization) temperatures are from 350° to 250°C and the salinity is greater than 9 wt.% NaCl. LA–ICP–MS was used to determine the composition of these fluids and indicates the possibility of fluid mixing as alkali and alkaline earths are well correlated over a large range of concentrations. In addition the trace elements, Fe, Mn, Cu, Zn and Pb show a similar degree of correlation that corresponds with that of the major elements in the fluid. Fluids where the K and Ca are highest have the highest concentrations of metals. Based on a salinity of 8 wt% NaCl equiv. the average composition is (in ppm), Na 23248, K 6044, Cu <500, Zn 350, As<230, Mo<93, Ba 230 and Pb 255. The low concentrations of Cu, Zn and Pb in the fluid are consistent with the lack of these metals in the mineralized skarns. fluid. The ratio of Fe/Mn, which is redox sensitive, indicates the fluid with higher trace elements and K, etc., is more oxidised. The data indicate that at least two distinctly different fluids are associated with the mineralization at the Bizmisen deposit.

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Investigating the relationship of mineralisation to Palaeozoic igneous activity within the Dolgellau Gold Belt, North Wales

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The Dolgellau Gold Belt represents an area of Palaeozoic mineralisation, associated with the Harlech Dome in North Wales. Recent work on gold–quartz veins at the Clogau Mine in this area has increased understanding of the relationship between these veins and local greenstone sills, suggesting that mineralisation is controlled by both igneous and tectonic factors [1]. This study investigates the orientations of an extensive set of largely barren veins within the Dolgellau Gold Belt. These are analysed alongside local host rock structures and igneous intrusions to provide a preliminary understanding of the wider structural framework within which mineralisation occurred. A further aim of the study is to use Anisotropy of Magnetic Susceptibility (AMS) to investigate micro-fabrics within some of these mineral veins. These fabrics will potentially provide insight into deformation and fluid flow within the veins and thus greater understanding of the processes operating during mineralisation.

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Stratigraphy of the Lower Basalt Formation, Antrim Lava Group, Northern Ireland

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Volcanic components of the British and Irish Paleogene Igneous Province (BIPIP) crop out on the lsles of Mull and Skye, Scotland and, on the Antrim Plateau, Northern Ireland. The Antrim Plateau represents the largest onshore remnant of the BIPIP which is dominated by the Antrim Lava Group, a group of basic flood basalts erupted in two distinct episodes and includes the world famous Giant Causeway. Although this classic piece of British and Irish geology (indeed global geology given the UNESCO World Heritage status of the Giant's Causeway) has been studied and analysed in detail, it is principally exposed along coastal sections, with scattered inland exposures. Because of this, the detailed stratigraphy of the Antrim Lava Group (beyond formation level) remains poorly defined and the architecture and extent of the flows is poorly known. This stratigraphy comprises of the Lower Basalt Formation and Upper Basalt Formation, which are separated by laterites of the Interbasaltic Formation, which includes the locally occurring Causeway Tholeiite Member.

Recent research has been focused on the Interbasaltic Formation but categorising and mapping variations in the Lower and Upper Basalt Formations has been largely neglected. Hitherto the Lower Basalt Formation was considered internally consistent despite having a geographical extent of over 3500 km^2 and a variable thickness, which in areas has been recorded up to 531m.

The lack of robust and detailed stratigraphical information for the unexposed parts of the Antrim Plateau presents a significant hindrance to exploration that relies on information about the location and distribution of feeder systems (dykes, sills and plugs). This study aims to develop a detailed stratigraphy of the Lower Basalt based on cores located northwest of Island Magee and a field section from Browns Bay. Published logs of this interval have rarely included detail on the igneous facies and simply have attempted to recognise weathered flow tops.

The focus of this study is on the lowermost 160m of the basalts and producing detailed graphical logs. From this it is clear that there are complex internal variations both vertically and laterally. The basalts were formed by a series of tabular and compound flows most of which can be correlated laterally across the area. By identifying and characterising the geometry and morphologies of these flows, it is possible to break the Lower Basalt Formation down into three smaller lower and upper units consisting of tabular basaltic lava flows and the middle unit of much smaller compound flows.

Ultimately, the aim is to generate a robust stratigraphic model for the Lower Basalt Formation that can be applied elsewhere on the plateau to correlate key flows at the base of the Antrim Lava Group. By mapping these flows across the area it may be possible to locate mineralogical important feeder dyke systems.

The geological and microbiological controls on the occurrence, mobility and concentration of Se and Te in coal and black shales

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The global trend in environmental awareness and search for low carbon energy sources has led to an increasing interest in certain ‘strategic elements’, including Selenium (Se) and Tellurium (Te), which are seen as essential in future green energy technologies, e.g. photovoltaic solar panels. Increasing our understanding of these elements is key to ensuring their abundant and environmentally sustainable supply as demand increases. They occur in low abundances in the Earth’s crust, but are known to be concentrated in specific geological and environmental reservoirs, with Se and Te often found in high concentrations in organic-rich sediments, such as coals and black shales.

Selective enrichment in organic sediments is poorly constrained, but may reflect a number of mechanisms including paleo-watershed chemistry, sulphur distribution, thermal maturation, late stage redox or hydrothermal imprints and microbial activity. There is some disagreement regarding the world average for Se in coal, and an overall lack of detail regarding Te in coal. The world average Se content in coals has been previously cited as 1.6 ppm [1] and 2.15 ppm [2]. The US Geological Survey carried out comprehensive chemical analyses in the world coal quality inventory (published 2010), providing possibly the best indication of Se and Te in coals. The average Se content based on the mean values of each country documented is 1.6 ppm [3]. However, the average Se based on all individual data is 2.4 ppm. This may be a more suitable value based on the data available. Data analysis indicates that Se is higher in anthracite and high ranking coals, while Te is higher in lignite and lower ranking coals. Pliocene coals contain higher Se, Te and S than older coals. Anomalously high average Se is observed in coal samples from the Republic of Korea, (8.72 ppm) and China (4.16 ppm), while China has a number of documented environmental issues associated with Se in coal, including problems affecting humans, livestock and crops [3].

As well as the potential benefits associated with Se and Te, extraction of such strategic elements can have significant environmental impacts, particularly during recovery and recycling of Se. It is therefore crucial to understand processes and conditions associated with the transport, concentration and precipitation of Se and Te in coal and black shales, providing important information on how to locate and economically develop future supplies, and assess the associated environmental impacts.

Unravelling the controls on Se and Te enrichment is critical in evaluating coal and black shale as potential resources of strategic elements, and identifying environmental threats relating to the occurrence and processing in such organic-rich deposits. This work contributes towards the NERC-funded “Security of Supply of Mineral Resources” project, which aims to detail the science needed to sustain the security of supply of strategic minerals in a changing environment.

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From a long lived upper crustal magma chamber to rapid porphyry copper emplacement: The geochemical record of zircon crystals at Bajo de la Alumbrera (NW Argentina)

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The Bajo de la Alumbrera deposit in Northwest Argentina is centred on a dacitic porphyry intrusive stock that was mineralised by several pulses of magmatic-hydrothermal fluid injection [1]. To constrain the timescales of porphyry copper formation, we dated zircons from four porphyry intrusions, including pre-, syn- and post-mineralisation porphyries based on intersection relations between successive intrusion and vein generations, using high precision CA-ID-TIMS. Based on the youngest assemblages of zircon grains, which overlap within analytical error, all four intrusions were emplaced within a few 10,000 years, which places an upper limit on the total duration of hydrothermal mineralisation. Re/Os dating of hydrothermal molybdenite fully overlaps with this high-precision age bracket. However, all four porphyries contain zircon antecrysts that span a much longer duration of zircon crystallisation of ~ 200 ka.

Zircon trace element variations, Ti-in-zircon temperatures (<750 °C), and Hf isotopic compositions (εHf = -5 to +1) indicate that the four porphyry magmas record a common geochemical and thermal history, and that the four intrusions were derived from the same composite upper-crustal magma chamber. Trace element zoning within single zircon crystals confirms a fractional crystallisation trend dominated by titanite and apatite crystallisation (e.g. decreasing Th/U, and increasing Yb/Gd ratios) within this magma reservoir. However, zircon cathodoluminescence imaging reveals the presence of intermediate low luminescent (dark) growth zones in many crystals of all intrusions, characterised by anomalously high Th, U and REE concentrations and transient excursions in trace element ratios. A return to the same fractionation trend after this anomalous excursion excludes external compositional forcing such as magma mixing. Instead we interpret the dark zones to record zircon crystallisation during a transient event of magmatic volatile exsolution. We propose that this volatile phase then migrated upwards to the apical part of the magma chamber from where it was expelled, together with successive batches of magma, to form the porphyry copper deposit within a short time-span of less than a few 10,000 years.

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Partial assimilation of oxide-facies iron formation – A new model for the genesis of the Black Thor Intrusive Complex, McFaulds Lake, Ontario

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The Black Thor Intrusive Complex (BTIC), part of the 'Ring of Fire' Intrusive Suite in the McFaulds Lake greenstone belt (Ontario) contains an aggregate thickness of 100 m chromite mineralisation, much more than in typical stratiform deposits (e.g., Bushveld Complex, South Africa). The BTIC deposit is interpreted to have formed in a magmatic conduit rather than within large layered intrusion. A fundamental problem in explaining the origin of this and other chromite-rich "conduit-type" deposit (e.g., Kemi, Finland) is how to generate such large quantities of chromite from magma that contains initially at most 3000-4000 ppm Cr. Genetic models for stratiform deposits (in-situ crystallisation with oxidation [1], pressure increase [2], and/or wholesale assimilation by felsic rocks, carbonates or iron formation [3-4], and/or physical transportation [5-7]) are still hotly debated, and cannot explain the formation of the BTIC.

We propose a model analogous to the sulfide-melting model for most Ni-Cu-PGE deposits [8, 9], involving in this case partial assimilation of oxide facies iron formation (OXIF). The silicate component can be completely dissolved, but the magma is saturated in chromite and cannot dissolve magnetite. As a result, fine-grained oxide will be transported by the Cr-rich magma where it will interact and re-equilibrate during transportation within the conduit and be gradually upgraded to chromite.

This contamination process is recorded in partially equilibrated xenoliths and xenocrysts. OXIF underlying the intrusion contains ~55-60% SiO_2 and 27-45% FeO, whereas OXIF xenoliths in the feeder of in the intrusion contain <25% SiO_2 and >50% FeO, suggesting selective loss of silicate components. Rare relict magnetite xenocrysts are zoned with Fe-rich cores to Cr-rich rims, suggesting partial upgrading of magnetite to chromite, opposite to chromite grains typically found in the BTIC chromitite horizons that have Cr-rich cores and Fe-rich rims.

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Cerro Negro Epithermal Au-Ag Deposit, Argentina: Discovery Case History

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Between March 2005 and July 2010 geologically directed drilling, funded by Andean Resources Ltd – a junior Australian mineral exploration company, resulted in the discovery of 2.54 Moz gold and 23.5 Moz Ag in three low-sulphidation veins in the Cerro Negro district of southern Argentina.

The veins are hosted by Late Jurassic volcanic and probable intrusive rocks of the Deseado massif.

Basic geological studies and systematic drill testing, implemented by a dedicated exploration team, are the essential ingredients in the success of the program.

Andean was purchased by Goldcorp in late-2010 for US $3.47 billion. Further exploration by Goldcorp, and an up-dated feasibility study, provided the basis for a development decision.

Mine construction followed with a design capacity of 450,000 ounces of gold per annum. Commercial production was achieved in January 2015.

The presentation will provide a background to the exploration program, discuss the activities and results, and suggest the key elements that led to its success.

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Was the Randalstown Fault a feeder zone to the world-class Navan Zn-Pb Deposit, County Meath, Ireland?

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The Navan orebody is a world-class carbonate-hosted Zn-Pb deposit that exceeded 110 Mt (million metric tonnes) @ 8.0 % Zn and 2.0 % Pb prior to mining depletion. The mine is operated by Boliden Tara Mines Limited, produces 2.5 Mt per annum and is Europe's largest zinc producer. The Pale Beds, a Lower Carboniferous carbonate platform sequence, hosts 97% of mineable ore and is divided into five broadly stratiform lenses in the Main Mine area with the stratigraphically lowest lens (the 5-lens) having by far the highest grade, tonnage and greatest lateral extent, reducing in tonnage and extent up-sequence to the 1-lens [1]. Whilst the 5-lens in the Main Mine records an average Zn:Pb ratio of 4:1, markedly higher than that at Silvermines and Tynagh at 2.6 and 0.8, respectively [3], Davidheiser-Kroll [3] identified a distinct, relatively high Pb area to the southwest of the Main Mine, producing a Zn:Pb ratio clustering around 0.75-1.75, interpreted to be caused by slow, horizontal ore fluid (of evolving Zn:Pb ratio) migration along fault-controlled fractures, trending up-dip to the northeast: that is, fed from the SW. The observation of elevated Pb in proximity to major fault zones at Navan is consistent with those in other Irish-type ores [2].

A weakly mineralised extension of the Pale Beds sequence of the Navan deposit is identified immediately west of the Randalstown Fault; a regional dextral reverse fault accommodating a throw of at least several hundred metres, dipping 70-90°. Whilst the Main Mine has been intensively drilled since 1977, this area west of the Randalstown Fault has lesser geological resolution. This work project will deliver a new geological and petrographic analysis of traverses across the Randalstown Fault, which will provide a basis for fluid inclusion thermometry, S isotope geochemistry and trace element analyses to determine the relationship of the fault to the Main Mine and its potential as a feeder fault to existing or new mineralisation. For example, Blakeman et al. [4] have shown that detailed S isotope analyses can discern faults through which hydrothermal fluids have flowed through tell-tale positive $\delta^{34}S$ values. Our aim is to determine whether the area of interest represents an influx zone (i.e. that the Randalstown Fault acted as a feeder zone to the deposit) for new mineralisation, or whether it simply represents a dextrally displaced, weakly mineralised extension of the 5-lens.

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A role for the lower crust in the genesis of the Irish Zn-Pb orefield?

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Current models[1] for the genesis of Irish Carboniferous-hosted Zn-Pb mineralization point to shallow Lower Palaeozoic basement within the Iapetus Suture Zone as the main metal source. However several lines of evidence, e.g. He[2], S[2,3] and Os[4] isotopes, and the possible role of contemporary volcanism[5] all point to deeper, possibly mantle, source(s). In this talk we argue that hydrothermal fluids extracted Zn (and potentially other metals) from the lower crust at depths > 20km.

Fortunately, the Iapetus Suture Zone in Ireland is uniquely favoured to evaluate this issue because of the presence of high metamorphic grade (lower crustal) xenoliths. These were carried to the surface from ~22-28km depths mainly by Lower Carboniferous alkali basaltic lavas and diatremes[6,7,8]. They provide the only possible direct samples of the lower crust and are of appropriate age.

Xenolith geochronology provides no support for significant volumes of Precambrian rock in the deep crust. Instead an early Ordovician age is likely. U-Pb geochronology demonstrates that the xenoliths experienced high temperature (>700°C) metamorphism at ~390Ma, 381-373Ma and ~362Ma. Sm-Nd garnet dating shows that the lower crust remained hot or was re-heated to ~600°C at ~341Ma during Lower Carboniferous volcanism.

Pb isotopic analyses of K-feldspar in xenoliths from localities 35km apart across the basement strike correspond closely to galena Pb isotope contours[9] while Sr and Nd isotopic analyses of gangue calcite[10] also provide a strong match with lower crustal xenolith values. While Zn contents of the xenoliths (and indeed many common rock types) permit them to be metal sources, the mineralogy and texture of the xenoliths provide an enriched template and a plausible extraction mechanism. Zn values determined *in situ* in modally-abundant biotite and garnet show dramatic depletion during retrograde alteration, providing a metal-release mechanism.

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Orogenic gold mineralisation in northwest Iberia: role of meta-sediment source as a control on location, geochemistry and mineralogy

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Castromil and Serra da Quinta are two orogenic gold deposits located in northwest Portugal, along the eastern flank of the NW trending Valongo anticline [1]. The deposits are structurally controlled by a NW-SE trending fault, which lies adjacent to an intrusive margin between Silurian meta-sediments and the Castello de Paiva granite [2]. Collectively, the Castromil and Serra da Quinta deposits comprise the Lagares project, currently undergoing exploration drilling by Medgold Resources Corp. Although previous work on the prospect has produced models for gold deposition and concentration, the source of sulphur, gold and other base metals is undefined.

This research project will aim to test whether the composition of mineralisation is controlled by fluids sourced from meta-sediments. The counter-hypothesis is that the mineral assemblage is controlled by other factors, such as variations in precipitation conditions, different pulses of fluid, or by fluids sourced from the granite host. In addition, other orogenic gold deposits within northwest Iberia; Limarinho and Leiranco, which have no spatial association to meta-sediments, will be compared and contrasted in terms of mineralogy and potential fluid sources. This will subsequently provide constraints for future exploration targets and drilling strategies along the granite/meta-sediment interface.

Comparisons between each deposit are being made analysing mineralised and unmineralised meta-sediments and granites. Reflected and transmitted light microscopy has been utilised to observe ore mineralogy and identify the location of gold. The mineral assemblage is pyrite and arsenopyrite with lesser galena, sphalerite and pyrrhotite. Minor phases of bismuthides and antimonides have also been identified using scanning electron microscopy (SEM). Geochemical data of mineralised core provided by Medgold Resources shows a clear association between Au and pathfinder elements As, Bi and Sb. This is significant as these gold proxies may be correlated to values in the meta-sediment geochemistry to define a potential source rock. Further work will characterise the fluid chemistry using fluid inclusion microthermometry. Sulphur isotopes will also be examined in primary biogenetic sulphides found within meta-sediments and will be compared to sulphides in the mineralised ore zones.

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REE placer deposits and alkaline volcanic: a case study from Aksu Diamas, Çanakli, Turkey

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The Çanakli deposit, part of the Aksu Diamas project in Turkey and owned by AMR Mineral Metal Inc., is a potentially important source of European Rare Earth Element (REE) supply. It has an inferred resource of 494 million tonnes at about 0.07% TREO (total rare earth oxide). The deposit is hosted in Quaternary sediments situated in a topographic low in Mesozoic limestones. The heavy minerals occur in lenses and are disseminated within channelised debris flows. They are thought to have originated from repeated phreatoplininan eruptions of Plio-Quaternary age, related to the alkaline Gölcük volcano, located approximately 20 km north-west of the deposit. It is notable that any future extraction of REE from Çanakli would be as a by-product of magnetite production.

Preliminary scanning electron microscopy analysis of the heavy mineral concentrates confirms the presence of REE-bearing minerals such as allanite and chevkinite. Allanite was also found in the samples from pyroclastic flows from the Gölcük alkaline volcano. Platevoet *et al*., (2014) describes the Gölcük magma as having a possible carbonatitic component and a strong enrichment in the REE. This supports the possibility that Gölcük may have been a potential source of the heavy minerals found at Çanakli. The intense H_2O variations in the magma, described by Platveot *et al*., 2014 [1], were responsible for the explosive nature of the eruptions at Gölcük and the extensive development of ash clouds, from which REE-bearing minerals and magnetite are considered to have been deposited.

If the currently accepted model is true, that the Çanakli REE deposit solely resulted from the accumulation of air-fall tuff borne minerals, in a topographic depression, with no additional concentration processes, then this is a new type of deposit. In order to verify this, further work is required to understand the mechanism of transport, deposition and degree of subsequent reworking by debris flows. Improved understanding of the origin of this deposit could have an impact on future targeting of REE-bearing deposits globally.

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Heavy minerals from ore guide to the deposit

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Heavy minerals (HM) also nicknamed "heavies" are minerals with a specific gravity of greater than 2.9 g/cm^3. They are studied in sedimentary rocks, of which they usually make up <2% by weight, excluding special sites of HM accumulation which are called placer deposits. To harness these HM in the field of genetic and applied economic geology they must be separated and concentrated from the less dense trash or gangue minerals, commonly by heavy liquid processing, magnetic separation, jigging and panning, or flotation. This can be done at a laboratory scale prior to EMPA, SEM-EDX/WDX combined with MLA and more sophisticated methods such as those from geochronology, or at an industrial scale in a wet rubble beneficiation plant.

HM can be subdivided into two principal groups, relating to the site and process of their formation. Autochthonous HM develop in a host rock environment during supergene and hypogene processes whereas allochthonous HM derive from a source rock only subjected to chemical and mechanical alteration on transport and deposition. Another classification is based on geogenic (rutile, "Coltan", cassiterite) and anthropogenic processes (amalgam derived from gold processing, fayalite as a smelting residue). Geogenic HM concentrations may constitute economic deposits, or in other circumstances act as guides to locate economic deposits from their clastic halos. Anthropogenic haloes may help locate ancient smelting sites.

Examples of allochthonous HM used to locate mineral deposits include: cassiterite and topaz (e.g. highly-fractionated Sn granites), columbite s.s.s (e.g. pegmatites and alkaline magmatic rocks), spinel (sapphire and ruby deposits) gold (e.g. Au deposits), platinum-group minerals (e.g. PGE-bearing ultrabasic rocks). Their resistance to chemical weathering and mechanical abrasion during transit, the hydraulic conditions and the interstices for entrapment in specific environments are crucial in determining distance of transport and the settling of HM at a proximal or distal position relative to the source deposit. Ultrastable to stable HM may shelter less resistant HM forming armored relics and so may give rise to labile minerals far from the provenance area. HM whisper, but HM aggregates can tell a story about the genesis of the source deposit. This is also true for morphological studies of stable and ultrastable HM, e.g. zircon, monazite, gold and PGM. Anthropogenic HM can only be used for modern-day stream sediments (e.g. Au-Hg alloys, Pb-Ba slags, stolzite, plattnerite) and often give an overview of what "element cocktail" might be expected in the catchment area of a drainage system.

Autochthonous geogenic minerals have a role mainly in so-called paleoplacers. Deep-seated and lithified older placer deposits, e.g., Witwatersrand, South Africa, Blind River Area, Canada, and Serra de Jacobina, Brazil are the main targets. Typical minerals such as sulphides (e.g. sphalerite, galena), sulphates (e.g. barite, celestite), ferroan carbonates (e.g. siderite) or fluorite formed in situ by diagenetic and hydrothermal processes. Alteration of HM during deep burial provokes corrosion and etch pits observed on the surface of HM and newly formed secondary HM species that furnish clear evidence for the effect of intrastratal solutions during diagenesis on deep burial. Infiltration of hydrocarbons may inhibit alteration or complete dissolution of HM, as it may also for lighter minerals (see e.g. the conversion of aragonite into calcite). The value of these minerals lies mainly in the field of hydrocarbon exploration. Heavies newly formed during supergene processes are common to mining and smelting residues where they may locally be identified in stream sediments (pyromorphite, schneiderhoehnite, P mimetesite, sewardite).

Terrain analysis, consisting of the integration of applied sedimentology and geomorphology backed by remote sensing, is important in seeking both primary deposits and placers. Terrain analysis forms a pre-stage and allows for a rough classification of what type of placer deposit is to be expected. Placer deposits occur in clastic host rocks of the following terrigenous depositional systems:

- saprolite and residual deposits (residual and eluvial placers)
- alluvial and fluvial environments of deposition
- coastal environment of deposition
- aeolian environment of deposition

Residual and eluvial (plus colluvial) placer deposits may host accumulations of cassiterite, gold, chromite, magnetite, ilmenite. etc., that possess a high resistance to weathering and may concentrate immediately above a bedrock source by the chemical decay and removal of lighter rock-forming materials.

Alluvial fans are conical, lobate, or arcuate accumulations of sediments that have a focused source of sediment supply, usually an incised canyon or channel from a mountain front or escarpment. As the stream widens and the gradient decreases at the exit of the canyon, the water flow slackens and HM tend to be deposited whilst other minerals are winnowed away. Braided and sandy meandering drainage systems proximal to the source area are prospective areas in the search for placer deposits.

Linear terrigenous shoreline and point source (delta) depositional systems in a microtidal regime have proved to be the most productive environments with respect to HM concentrations. Washover fans are excellent traps for HM in microtidal coastal plains sheltered by barrier islands. HM accumulations need to be preserved due to subsequent wave and wind action. The interrelation of transgression and regression accompanied by wind action is decisive for the built-up of HM concentrations in a coastal environment.

Placer deposits constitute a major proportion of world production of gold, tin, tantalum, titanium, zircon and monazite. For practical usage a tripartite subdivision of placer deposits based on the density of HM can be given:

(1) placers containing HM of densities >6.8 mainly hosting gold, platinum, cassiterite (dominated by fluvial-alluvial mineral sands)
(2) placers containing HM of densities in the range 4.2 to 6.8 mainly hosting ilmenite, rutile, zircon, monazite (almost exclusively concentrated in coastal mineral sands)
(3) placers containing HM of densities 2.9-4.2 mainly hosting diamond, ruby, sapphire in fluvial and coastal mineral sands which locally are subject to aeolian reworking.

The Sekisovka gold-telluride deposit in Eastern Kazakhstan: tectonics and magmatism

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The Sekisovka deposit is located in the Rudny Altai region, 40 km north-east from the East Kazakhstan regional capital, Ust Kamenogorsk. The Rudny Altai is part of the fragments of the ancient palaeo-continent that drifted in the Palaeo-Asian ocean, which subsequently amalgamated into a single formation during Hercynian collision. The Sekisovka deposit is characterised by: (1) gold-sulphide bearing mineralised zones and stockworks in the igneous rocks of the Zmeinogorsk complex; (2) zones of dislocation and extreme deformation characterised by cataclastic to mylonitic rock textures that are characteristic of the ore field; (3) north-western striking ore-controlling faults; and (4) occurrence of fluid-explosive breccias (including both hydraulic fracturing and breccia pipes) with diorite, gabbro and plagiogranite fragments cemented by propylitic and beresitic altered groundmass hosting the gold-telluride mineralisation [1].

Breccia ore bodies have an elongated shape of 40x100m to 120-500m in size and traceable depth beyond 950m, open at depth. Auriferous hydrothermal mineralisation is represented by sulphides occurring in veins and breccias. Mineralisation is hosted in large tabular orebodies, stockworks, medium size veins and lens-hosted, small veins, pipes and dykes, and occasionally traced also in isolated lenses or veins. The variability of intersecting magmatic units, the complex morphology of ore bodies and rapid changes in alteration style reflect a turbulent magma-fluid system evolving in shallow (sub-volcanic) crust level where pressure fluctuations triggered mineralisation pulses. Gold is irregularly distributed and embedded in the cementing mass of the explosive hydrothermal breccias and tends to concentrate at the geological boundaries between breccias and igneous rocks. Estimated JORC-compliant probable reserves are 2.26 Moz, whereas both indicated and inferred resources amount for 5.14 Moz [1].

Following types of magmatic rocks are identified that can be combined in two series: (1) gabbro-diorite (gabbro, gabbro-diorite, diorite) and (2) plagiogranite (granodiorite, plagiogranite, granite). Both magmatic series are represented by sub-alkaline varieties, exhibiting features of volcanic arc granites (VAG) that are enriched in Rb, Th, Pb and K and strongly depleted in Sr, P and Ti. Formation of gabbro-diorite and plagiogranite magmas is supposedly related to dehydration melting of mafic substrate of a plunging oceanic lithospheric plate in the subduction zone or lower crustal melting as a result of thickening continental crust during accretion-collision [3].

U-Pb zircon crystallization ages for the plagiogranite pluton hosting Sekisovka gold deposit are 368.4±4.2 Ma, similar to intrusions of the adjacent Zmeinogorsk complex, whereas age of leucogranite porphyry dike with abundant pyrite is 304.5±2.6 Ma [2].

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What is the geological fate of the seafloor massive sulphide deposits?

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As part of the EC-funded '*Blue Mining'* project, I aim to investigate the chemical processes of alteration of extinct seafloor massive sulphide deposits as a result of exposure to cold and oxygen-rich seawater passing through them. For this, I will analyse sediments, metalliferous precipitates and pore fluids, recovered during seafloor drilling and coring. The project focuses on the extinct seafloor massive sulphides (eSMS), which may provide some of the valuable metals (Mn, Cu, Pb, Zn, Ag, Au, As, Sb and rare earth metals) for industries. The target of the study is an area of extinct massive sulphide deposits in the TAG area of the Mid-Atlantic Ridge at 26°N. Two cruises are planned in summer 2016: first to survey the eSMS locations with AUV's, and then sample (using an ROV, gravity corer, and recovering up to 55 m long cores with the RD2 seafloor drilling rig) the relict SMS mounds in the MIR and Alvin zones.

Following the cessation of high-temperature, reduced and sulphidic hydrothermal fluid discharge, SMS deposits undergo conditions different from their formation settings: *i.e.* exposure to low-temperature, oxidised, basic to neutral and metal-poor seawater. During this maturation process, numerous redox-driven and pH-driven reactions can take place between the water, the sulphide and the surrounding rock and sediment. For example, supergene alteration processes occurring between the deposits and pelagic sediment carbonate caps; dissolution, migration and chemical substitution within the deposits; alteration and replacement of the sub-surface basaltic basement; and the impact of microbial activity on SMS such as sulphide oxidation, sulphate reduction, pH modification and trace metal mobilisation.

Geochemical analysis on sulphides and metal-rich sediments will be performed to determine the primary mineralogy (presumably and mostly Cu, Zn, Fe sulphides) and the secondary mineralogy after weathering (presumably and mostly Fe, Mn oxyhydroxides, oxides, amorphous silica and metal-enriched clays) as well as on pore fluids to interpret the transport and the transformation of metal in the sediments overlying the deposits. *In situ* environmental data (pH, temperature, redox potential, conductivity) will be acquired by downhole logging during the drilling. These data will be combined with flow through experiments where sulphides will react with deep-sea pelagic sediments under a controlled permeable flow of oxygen-rich seawater. These data will elucidate the nature, conditions and rates of metal mobilisation as SMS deposits mature.

We will also explore how the distal sedimentary record incorporates authigenic metalliferous particles, and why they are hence reliable indicators for determining the history of hydrothermal activity and the metal budgets in a typical slow-spreading ridge segment.

The distribution of trace elements in a range of deep-sea sulphide ore deposits and their impact on seafloor mining

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Acid rock drainage is a natural weathering process that is often exacerbated by mining activities, common in onshore sulphide ore deposits, which can lead to considerable environmental impact. A similar 'weathering process' occurs at seafloor massive sulphide (SMS) ore deposits. In contrast to the onshore situation, the expected consequence in the marine environment is often considered to be oxide formation, negligible metal release and minimal net acid generation due to the high buffering capacity of seawater and low solubility of iron at near neutral pH. However, no dissolution studies exist that emulate the true composition range of sulphide ore deposits that either sit passively on the seafloor or are actively mined in this colder, more saline, and alkaline environment. In particular, these deposits will include a variety of minerals, and it is the interaction of these minerals and inclusions in regards to galvanic cells that can subsequently increase the dissolution of metals into the water column[1,2]. Whilst this galvanic dissolution has the potential to occur naturally on the seafloor, both the exploration and extraction phases of deep sea mining have the potential to agitate and expose a high surface area of fresh sulphide minerals to seawater and exacerbate this natural effect[3]. Any heavy metal release that is not balanced by subsequent oxidation and precipitation has the potential to produce toxicity for benthic ecosystems, bioaccumulation and dispersal through currents.

The present work has sought to provide a pilot investigation on the deep sea weathering of sulphide minerals, by identifying the mineral phases, trace elements and potential galvanic couples that may arise in sulphide samples from various tectonic settings.

Samples have been analysed using EMPA and LA-ICPMS in order to identify the range of trace elements and toxins that may be contributed to the water column, especially heavy metals and environmental toxins (e.g. Fe, Cu, Zn, Pb, Co, Ni, Cd, As, Sb, Sn). Our observations raise important questions about which ore deposits could have more or less environmental impact during any mining activity.

These observations will be used to design oxidative dissolution experiments at deep-sea conditions utilising the natural sulphide ore deposits characterised here. Furthermore, observations will allow for elucidation of the natural weathering process and the economic value of residual deposits.

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The Role of Dolerite in focussing Cu-rich, Au-poor, IOCG-style mineralisation in the Cloncurry Minerals District, Australia: Implications Towards a Genetic Model and Future Exploration

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The Cloncurry Minerals District is situated in the northern region of the Eastern Fold Belt, part of the Proterozoic Mt Isa Inlier in NW Queensland, Australia, and is host to a plethora of Iron Oxide-Copper Gold (IOCG) deposits. Due to the enigmatic nature and broad classifications of these deposits there is still a high level of controversy surrounding their formation. The dolerite-associated Great Australia-Taipan-Mongoose-Magpie (GATPMM) deposits are situated in close proximity to Cloncurry, and are thought to represent a Cu-Co-carbonate-rich, Au-poor 'end-member' style of IOCG mineralisation that has not been documented elsewhere in the district.

The GATPMM deposits are analogous with regards to their paragenetic sequence, structural setting and mineralisation styles, and are characterised by their mineralogically simple, carbonate-magnetite rich, chalcopyrite-dominated mineral assemblages. Mineralisation is strongly structurally controlled, typically located at structural jogs/flexures, and displays associations with doleritic material, either within various fault-hosted dolerite intrusions or within structurally bound basaltic to gabbroic textured meta-volcanics. The western GATPMM-style deposits are all situated within or directly adjacent magnetic highs, in close proximity to the crustal-scale Cloncurry Fault.

This host-rock affiliation is considered to be the result of dolerite having both a rheological and chemical control on Cu-Au mineralisation. The relatively fine-grained and homogenous nature of these dolerite intrusives resulted in the early focussing of brittle-type deformation, aiding in the multi-stage development of these dilatational sites. These early stages of 'ground preparation' allowed the migration of metal-bearing fluids, promoting fluid mixing and decompression – processes further encouraged by ongoing deformation within these dilatational zones. Ore textures show brittle-type deformation occurring pre-, syn- and post-mineralisation. The exposure of oxidised fluids to pre-existing Fe^{2+} (of metasomatic and indigenous origins), contributed to driving down the solubility of Cu-Au bearing complexes, precipitating chalcopyrite *en* masse to form the Cu-rich deposits of the GATPMM. The reasoning behind the low levels of gold mineralisation within these deposits is explored here, and proposes that the physiochemical actions of bismuth are responsible for Au attaining saturation at depth.

These dolerite-associated deposits offer an attractive reward to exploration efforts, being Cu-rich and in close proximity to existing mine infrastructure. This study has highlighted that these bodies are confined to magnetic highs, with affinities towards structurally and chemically complex dilational sites. The genetic model proposed here also highlights the ability of the Liquid Bismuth Collector Model (LBCM) to act as a chemical polarizer for ore fluids, aiding the development of the characteristic, Cu-rich, Au-poor deposits of the western Cloncurry District.

Myanmar: Tethyan Tectonics and Metallogeny

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Myanmar (Burma) is perhaps the world's most prospective but least explored minerals terrain, being extraordinarily endowed in a diversity of mineral resources, and hosting important known deposits of tin, tungsten, copper, gold, zinc, lead, nickel, silver, platinum group elements, jade and gemstones. Myanmar lies at a crucial geologic juncture where the main Tethys-related suture zones swing south around the Eastern Himalayan Syntaxis into Southeast Asia, with the consequence that the region has experienced an increasingly oblique collisional geometry over the recent history of orogeny. An understanding of both the genesis of Myanmar's mineralization, and of its minerals potential, can only be fully realized with an understanding of its tectonic history. Myanmar, however, remains geologically enigmatic, in part due to its relative political and scientific isolation over the past half century. There remains considerable uncertainty around the configuration, nature and timing of major Tethyan-related tectonic events within Myanmar, which renders discussions on Myanmar's metallogenesis somewhat equivocal.

We review the range of known mineral deposits found within Myanmar and propose a model that places them within a new space-time construct that summarizes Myanmar's Mesozoic-Cenozoic geological history. We argue for a simple tectonic scenario: the subduction and suturing of the Neo-Tethys and the ensuing Himalayan Orogeny, and present a metallogenic model for Myanmar that accommodates the genesis of nine major metallotects within this orogenic framework. We apply a mineral systems approach to this model to make large-scale observations regarding the progression of orogeny and concomitant mineral deposit genesis. Finally, we present new zircon U-Pb, Hf and O isotope data that both inform on the crustal evolution of Myanmar during the Cenozoic, and hint at the controls on Cu-Au versus Sn-W magmatic-hosted metallogeny.

The future availability of critical metals: facts, fiction and fixes

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Mankind is using larger quantities of metals than ever before. It is undeniable that this trend will continue, at least in the short and medium terms, and it is equally certain that over the same timescale recycling alone will not be able to meet global demand for metals. We will therefore continue to be reliant on mining to provide the majority of the supply we need. The security of future metal supply and scare stories forecasting the imminent depletion of metal resources have received considerable recent attention. However, the voice of the geologist in this debate is seldom heard and often ignored by the 'resource pessimists'. It is essential that all sides of the argument are understood because of the serious implications for corporate and government policy.

The terms 'resources' and 'reserves' are fundamental to the assessment of supply security: 'resources' refers to the amount of metal in the Earth's crust that is, or may become, of potential economic interest as the basis for the extraction of that metal, whereas a 'reserve' is that part of the resource that is fully geologically evaluated and is commercially and legally mineable. The ultimate fate of a mineral reserve is either to be physically worked out or to be made non-viable, either temporarily or permanently, by a change in circumstances, most commonly economic, regulatory or social. Published estimates of global 'resources' and 'reserves' are poorly constrained and subject to continual revision. As a result they are unreliable indicators of the future availability of metals. Nevertheless some authors, ignoring these definitions, have applied the 'peak' concept to model the depletion of metal resources and future production trends. This approach is not only seriously flawed but also fails to acknowledge the real causes of variations in production and consumption. Declining production is generally driven by falling demand rather than by dwindling resources.

Although it is broadly agreed by geologists that physical exhaustion of primary metal resources is unlikely, the restriction of access to these resources threatens future supply security. A wide range of continually changing above-ground factors - economic, environmental, social, legal, ethical and logistical, to name but a few - determines whether resources in the ground can be extracted. The concept of 'criticality' has been introduced to identify which metals might be particularly susceptible to scarcity, for whatever reason. Appropriate strategies can then be developed for each commodity to manage that risk and mitigate its implications.

Assessment of criticality is, however, far from simple, with a wealth of methodological approaches and terminology. Not surprisingly, there is no single or fixed list of critical raw materials. The European Commission defines criticality in terms of two variables, economic importance and supply risk. While economic importance is readily quantified, the supply risk is a function of several variables the most important of which reflect the concentration of raw material production in a few countries with poor standards of governance and environmental regulation. The supply risk for the critical raw materials is further increased by a lack of effective substitutes and low recycling rates.

Thirteen metals or groups of metals (Be, Co, Cr, Ga, Ge, HREE, In, LREE, Mg, Nb, PGM, Sb and W) are currently classified as critical to the EU economy. Several of these are derived largely as by-products of the extraction of major industrial metals, such as copper, aluminium and zinc. The markets for some of these metals are very small with global production of only a few tens, hundreds or thousands of tonnes. They are typically used in tiny quantities that are essential to the function and performance of specialised high-technology devices.

If we are to deliver a high-technology, low-carbon economy the demand for these metals will continue to escalate. For example, Co, Ga and In are indispensable to clean energy generation and energy storage technologies. We, therefore, need to be able to maintain adequate and secure long-term supplies of these metals to ensure that modern technological development is not constrained by lack of raw materials. However, it is virtually impossible to predict how much of these critical metals we will need in the future. Demand continually changes in response to diverse factors, such as available technologies and products, consumer preference and government policy. At times of rapid technological change forecasting becomes increasingly problematic. In general we use existing data and past experience to predict demand, but for most critical metals such information is lacking. The limited available research has served chiefly to highlight the problems involved and to confirm that future demand for the low-carbon sector alone will significantly exceed current levels of global production for several metals.

There has been relatively little previous research on many technology metals because they had little practical use in the past. Consequently we know little about how they are enriched in the crust, where to explore for them and how to extract them from ores. To assure their future availability it is essential to invest in adequate and timely research that addresses their complete lifecycle. We also need reliable resource estimates for every mineral raw material of interest in order to conduct well-founded material flow analyses and criticality assessments to inform long-term planning and policy making in relation to future minerals supply.

Geology has a major role to play in improving knowledge of the resource base and identifying new reserves. The refinement of mineral deposit models and the identification of new classes of ore deposit will enable us to evaluate the potential of terranes that have hitherto been little explored and to re-evaluate terranes previously assessed for other metals. The acquisition of new baseline datasets, comprising geological, geochemical and geophysical data, will stimulate exploration in areas previously regarded as unprospective and in well-explored regions. For example, the regional geochemical and geophysical data from the Tellus project in Northern Ireland provided a major boost to exploration, chiefly for precious and base metals. However, the Tellus geochemical data also provide new insight into the potential for critical metals. For example, the distribution of REE, PGM, Te, Co and Ga highlight a number of areas considered as potential long-term targets for exploration. Given the declining success rate of global exploration and the increased discovery depth in recent decades there is a requirement for new techniques to detect deposits under cover. These need to be complemented by improved laboratory techniques for the accurate determination of the critical metal abundance and distribution in rocks, ores and waste streams.

Given increased future demand it is likely that the minerals industry will turn its attention to more extreme and technically challenging environments. For example, the resource potential of seafloor deposits is largely untested. Fe-Mn crusts and nodules and massive sulfides are known to be enriched in several critical metals which need to be systematically assessed to determine their viability and sustainability relative to land-based deposits.

The requirement for major programmes of research to better understand the life cycles of critical metals and to assure their availability is well established. The role of the geoscientist is vital because without geology there can be no exploration and associated expansion of the resource base to supply future generations.

Geology and controls on mineralisation at the Lisheen Zn-Pb orebody

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The Lisheen Zn-Pb orebody, County Tipperary, Ireland is a Lower Carboniferous carbonate-hosted sulphide deposit. It was discovered in 1990 using a combination of geological deduction, geochemistry and to a lesser extent geophysics. Mining of the Lisheen resource, 23Mt @ 13.3% Zn and 2.3% Pb, began in 1999 and finished in 2015.

The orebody is broadly stratiform occurring at or near the base of the Waulsortian Limestone Formation, a 200m thick massive biomicrite, which is regionally dolomitised. The underlying lithology is the medium-bedded, Argillaceous Bioclastic Limestone (ABL or Ballysteen Formation) within which, some 90m below its contact with the Waulsortian, is a 70m thick cleaner oolitic member (Lisduff Oolite). Lisheen consists of a number of separate orebodies of varying sizes each localised on the hanging-wall side of a ~200m displacement, north-dipping extensional fault. These faults together form an ENE-trending, left-stepping, en-echelon, fault system that displays a classic ramp-relay geometry and forms part of a bigger mineralised trend of faults (Rathdowney Trend) that includes the Galmoy orebody and a number of smaller deposits.

The ore is largely developed by replacement of a hydrothermal alteration dolomitic breccia, black matrix breccia (BMB), which occurs at or near to the base of the Waulsortian but only on the hanging-wall side of the extensional fault system. Minor replacement mineralisation also occurs in the ABL at its contact with the Waulsortian. In the structural footwall the Lisduff Oolite is locally mineralised where faulted and in proximal juxtaposition with the Waulsortian. The ore consists of massive and disseminated pyrite, sphalerite and galena. Other minor minerals of Cu and Ni including tennantite, chalcopyrite and niccolite also occur especially in oolite-hosted ores and in areas proximal to major extensional faults. The mineralisation exhibits a wide range of textures including: complete and partial replacement of BMB, delicate replacement of host rock lithologies, multi-phase sulphide breccias, and cavity-filling with both colloform and laminated, precipitated sulphides.

Faulting appears to exert a major control on mineralisation. The thickest ore is developed adjacent to the main extensional faults. Mineralisation progressed northwards from these faults along the Waulsortian\ABL contact aided by a network of small-displacement, low-angle extensional structures that are widely developed there. It is possible that these structures developed in response to the rheological differences between the massive Waulsortian and the bedded ABL lithologies. Fault controlled oolite-hosted ore in the structural footwall exhibits mineral assemblages, distributions and textures that strongly suggest that it provided a route for mineralisation to enter the Waulsortian. Once there Zn\Pb ratios together with Cu and Ni distribution indicate that they flowed northwards. As they did so their potential for carbonate replacement reduced with the resulting ore being poddy and becoming increasingly restricted to the fault conduits. The BMB, which predates the sulphide mineralisation, has a similar but broader distribution. It is thought that it formed as hydrothermal, dolomitising solutions accessed the Waulsortian via the same fault conduits as the later sulphide mineralisation. This augmented the permeability of the fault and host-rock alike through dissolution and hydraulic fracturing and is therefore an important precursor to mineralisation. In the oolite there are large amounts of dark, hydrothermal dolomite much of which has precipitated from solution

and deposited as a sediment in large dissolution voids filled with disaggregated lithologies, drop-stones and numerous phases of sulphide which commonly display brecciated textures.
In the main Waulsortian-hosted ore, sharp hanging-wall ore contacts and banded sulphides within heterogeneous breccias indicate a strong fluid control on mineralisation. The mineralising fluids appear to have been dense metal-bearing brines that occupied permeability generated by faults, BMB and remnant primary permeability at the base of the Waulsortian. Bound by the impermeable ABL below they are largely responsible for the general stratiform geometry of the orebodies. This stratiform geometry persists in the ore hanging-wall across faults that have generated displacements in the ABL below and strongly suggests that the mineralisation is post-faulting. Further evidence for this is seen in the oolite orebody where mineralisation has replaced through fault breccias, associated with the major controlling extensional faults, into the hanging-wall block ABL.

There is evidence of significant dissolution due to mineralisation. This is most obvious in the oolite ore where collapse breccias, restites and drop-stones are present in the hanging-wall of the mineralisation. The BMB in the ore hanging-wall displays geometries consistent with stoping and collapse into the regionally dolomitised Waulsortian above. Also in the Waulsortian there is a notable thinning where ore is thickest. This relationship is best seen in the immediate hanging-wall of the major structures where the ore is thickest. This dissolution together with extensional faulting developed at its contact with the ABL may be responsible for the widespread generation of irregular veins of coarse, white crystalline dolomite (White Matrix Breccia) seen in the Waulsortian.

Dextral transpression related to the Variscan orogeny appears to be largely post-ore at Lisheen. There is some evidence however, of fold flexure and thrust-related mineralisation (possibly remobilised) particularly of zinc and lead. The presence of strong northwest-trending control particularly on zinc-rich, iron-poor ores, also seen in the K-zone at Galmoy, may be related to this or be some part of an as yet unresolved episode in the extensional fault history. Many of the original extensional structures at Lisheen have been inverted, complicating the original ore\fault geometry. A late, clearly post-ore, period of sub-vertical, northwest-trending, dextral wrench faulting is common throughout the mine. Together with accommodating NNW and N-S structures they are deeply karstified and responsible for much of the water ingress into the mine workings.

Geochemical and mineralogical controls on the distribution of rare earth elements in the laterites of Serra de Monchique, Portugal

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Current European manufacturing relies heavily on imports from China for unprocessed rare earth elements (REEs) and rare earth oxides (REOs). It has been suggested that the EU holds viable reserves of REEs that, with adequate research, could satisfy 10% of EU demand, by the recycling of mine waste from bauxite production (red muds) alone [1]. Focus has been turned to the potential for similar 'South China type' laterite deposits being exploited in the EU, but limited exploration and understanding of EU laterite formations currently makes them unattractive to investment [2].

Following early work by Bernard-Griffiths [3] into the REE content of the Cretaceous Serra de Monchique Nepheline-Syenite intrusion, this project examines the clay mineralogy and geochemistry of a selection of pedogenic profiles, logging their variations in mineralogy, bulk chemistry and specific REE content and comparing them to currently producing regions in Southern China. Investigation is under way using a five stage sequential leach-ICP-MS method to identify REE hosting minerals and mineralogical hosting phases, supported by XRD analysis of mineralogy and clay structures.

Initial results indicate similarities in clay hosted REE distributions through laterite profiles to other researched formations in Madagascar [4] and China [5], where specific organic rich (acidic) soils and biogenic profiles of tropical (rainforest) environments were presented as a key factor for REE mobilisation during pedogenesis. Serra de Monchique has a unique climate, with similar seasonal rainfall and cycling, but is not a rainforest, nor in a tropical region. It is therefore hypothesised that classic REE distribution models may also be applied to non-classic environments for this deposit type, supporting the hypothesis of Herrington [6] that 'China-type REE hosting ion-adsorption clay profiles' could exist across Europe in novel and previously unresearched environments.

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Epidote Chemistry in Contrasting Hydrothermal and Metamorphic Environments

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The unique crystal structure of epidote group minerals allows the incorporation of a wide variety of major, minor and trace elements. Variations of these elements are a result of the environment in which epidote formed, either by magma crystallization, metamorphism or as a secondary mineral in hydrothermal alteration systems. Samples from a variety of settings, some associated with mineralization, were analysed to explore the natural variability and potential controls on the chemistry of epidote. Compositions were determined using SEM EDS analysis and laser ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS).

It was found that epidote chemistry varied markedly both between and within samples. Within individual samples, epidote compositions differed between vein and replacement types, with vein epidote generally containing lower concentrations of trace elements such as the transition metals and REE reflecting the relative importance of local sourcing from minerals undergoing replacement and advection of trace elements in fluids. Differences in epidote chemistry between environments is attributed to bulk rock compositional controls and the composition of either the precursor mineral being replaced by epidote, and/or to competition for trace elements with phases co-precipitating with epidote. For example, epidote hosted by felsic igneous rocks is generally lower in Ti and V relative to intermediate and more mafic compositions and epidote replacing garnet is interpreted to have acquired its HREE-enriched pattern from the precursor mineral. A similar relationship may also exist for epidote replacing pyroxene, where the REE pattern of the precursor phase appears to be preserved. Conversely, epidote co-precipitating with actinolite is depleted in REE and displays a pattern similar to an inverted amphibole distribution, suggesting that competition for REE by the amphibole controlled partitioning into the associated epidote. The chalcophile elements are the most diagnostic of a given style of mineralization, potentially providing a fingerprinting tool. In particular, Sn, As, Sb and Ga are low in epidote from mineralized relative to unmineralized settings and skarn samples, and Pb is low in epidote from the (limited) porphyry samples studied. These results indicate that epidote trace element chemistry is complex and more work is required to fully constrain the controls of compositional variations in nature.

Element mobility during propylitic alteration in porphyry ore systems: a case study of the Oyu Tolgoi deposits, Mongolia

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Porphyry deposits are characterised by metal sulphides and oxides, precipitated from hydrothermal fluid exsolved during cooling and crystallisation of stocks or dykes intruded from crustal magma chambers [1]. Large volumes of rock within and surrounding these porphyry intrusions become altered by these fluids as they migrate outward and potentially mix with circulating external fluids. Propylitic alteration forms the outermost halo and is typically characterised by the assemblage epidote–calcite–chlorite ± albite, actinolite, pyrite and prehnite [2]. Although it is the weakest and most subtle imprint of hydrothermal activity, it affects the largest volume of rock, often extending several kilometres from the mineralised core. In principle, this makes it useful for exploration because it represents an extensive geochemical footprint. However, until recently, there were few tools with which to interpret the intensity of propylitic alteration, and even how to distinguish it from background regional low grade metamorphism. Recent studies have shown that the fingerprint of this weak alteration can be detected in the trace element chemistry of propylitic minerals, particularly epidote and chlorite. This is interpreted to be due to the incorporation of trace elements from the permeating magmatic fluid in response to fluid temperature, pH, fO_2 and composition gradients around the porphyry centre. Thus, the concentrations of key elements vary systematically with distance from deposits [3,4] and can therefore be used as vectors to ore that could be applied in mineral exploration.

The world class Oyu Tolgoi porphyry district of Southern Mongolia contains the largest Palaeozoic porphyry Cu-Au-Mo deposits in the world, with eight discrete deposits closely spaced along 26 km of the NNE-oriented Oyu Tolgoi trend. Hydrothermal alteration around the deposits is typical of that of intermediate-composition porphyry intrusions within basaltic host rocks, with early sodic-calcic and potassic alteration in the system core surrounded by propylitic alteration, which has been overprinted by widespread sericitic and advanced argillic alteration [5]. To date, little has been reported about propylitic alteration at Oyu Tolgoi, except that it replaces early/proximal potassic alteration at approximately 600 m, with a typical alteration assemblage of calcite, chlorite, epidote, and lesser pyrite [6]. The aim of this project is to develop a detailed model of propylitic alteration at Oyu Tolgoi, in order to understand the controls on the spatial and temporal distribution of propylitic minerals, and to explain any associated patterns in their trace element chemistry.

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Defining the Carbonate Stable Isotope Alteration Footprint of the Cortez Hills Carlin-type Au Deposit in North-Central Nevada, USA and Applications to Mineral Exploration

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A stable isotopic approach was applied to the Cortez Hills 10Moz [1] Carlin-type gold deposit (42-37 Ma) to define the carbonate alteration footprint. This deposit is located in central Nevada, USA along the Battle Mountain-Eureka Trend within the Cortez District. Carlin-type deposits are carbonate-hosted disseminated Au deposits that are dominantly confined to Nevada, USA. They commonly occur as replacement deposits that are hosted in carbonate rocks that were decarbonatized during hydrothermal alteration [2].

The goals of the study were to elucidate fluid flow processes and to define the distal alteration halo surrounding the deposit. The alteration footprint was examined at the micro (mm) - to macroscales (km) through field mapping, core logging and sampling of drill core, pulped rock, surface areas and reverse-circulation chips. These samples are combined with detailed lithogeochemistry and stable carbon and oxygen isotope analyses that were performed using the off-axis integrated cavity output spectroscopy analyzer [3].

Results from ~1400 drill hole pulped rock samples display a correlation between stable oxygen compositions and Carlin-type pathfinder elements (As, Au, Hg, Sb, Tl) that can be utilized as a vectoring tool for fluid pathways and mineralization. The most altered areas (^{18}O is 2-18‰ VSMOW) are proximal and within the ore zones and major faults. The results show that the alteration halo extends for >2 km. Alteration is focused along faults and sub-horizontally permeable strata. Fluid flow predominantly upwards and outwards is interpreted to reflect the escape of spent mineralizing fluids.

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2.7 Ga plume associated VMS mineralization in the Eastern Goldfields Superterrane: insights from the Ag-Zn-(Au) Nimbus deposit

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Economic volcanogenic massive sulphide (VMS) deposits of the Archean Yilgarn Craton, Western Australia, are restricted to zones of juvenile crust, as revealed through regional Nd, Pb and Hf isotopic variations and the geochemistry of felsic volcanic rocks. Interpreted as Archean paleo-rift zones, one such zone runs N-S through the Eastern Goldfields Superterrane (broadly coincident with the Kurnalpi Terrane) and is associated with the high grade ca. 2690 Ma Teutonic Bore, Jaguar and Bentley deposits, plus sub-economic VMS mineralization further south. To date, only small historic resources (e.g. Anaconda) and barren pyritic lenses have been recognised in the older plume-dominated lower stratigraphy of the Eastern Goldfields.

The Nimbus Ag-Zn-(Au) deposit (12.1 Mt at 52 g/t Ag, 0.9% Zn and 0.2g/t Au) is located approximately 10 km east of Kalgoorlie, near the margin of the Kurnalpi rift zone. Its origin has been contentious for a number of years, with previous models favouring seafloor/sub-seafloor VMS mineralization or a high sulfidation fault-hosted system. Compared to other VMS occurrences in the Yilgarn Craton, the Nimbus deposit is unusual in terms of its tectono-stratigraphic position, the geochemistry of its host sequence (i.e. FI-affinity felsic volcanic rocks, ocean-plateau like low-Th basalts), ore mineralogy (e.g. abundance of Ag-Sb-Pb-As bearing sulfosalts, high Hg, low Cu) and carbonate-sericite dominated alteration assemblages. Classification of Nimbus as a shallow water and low temperature VMS deposit with epithermal characteristics (i.e. a hybrid bimodal-felsic deposit) is consistent with these features and its position near the margin of this paleo-rift zone and juvenile Pb isotope values. The recognition that the Nimbus deposit is associated with 2.7 Ga plume magmatism (SHRIMP U-Pb: 2703 ± 5 Ma and 2702 ± 4 Ma) opens up new areas for VMS exploration in the Eastern Goldfields Superterrane, over a strike length exceeding 500 km. Activity associated with the Palinuro Volcanic Complex of the northern Aeolian arc, Tyrrhenian Sea, Italy, represents a comparable modern shallow marine hydrothermal system.

Investigating the relationship of the Bodmin Moor Granite, Cornwall, to hydrothermal mineralisation

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The Bodmin Moor Granite represents one of the lesser-studied intrusions of the Cornubian Batholith in southwest England. Former work suggests that the granite was emplaced as a single pulse [1], although the relationship of this granite to surrounding Cu/Sn/W mineralisation is poorly understood. This study uses the orientation of mineral veins, foliations, bedding planes, granite sheets and fold axes in the area to determine controls on mineralisation. Preliminary results allow a relationship between structure and mineralisation associated with the Bodmin Moor Granite to be developed. These results suggest that there were magmatic as well as tectonic influences on this mineralisation. The findings are compatible with former work on the Cligga Granite in Cornwall [2] and indicate that greater focus should be placed on the emplacement-related controls on Cornubian mineralisation. Planned further work includes a combined geochemistry and Anisotropy of Magnetic Susceptibility (AMS) study. This will potentially determine micro-scale flow and deformation fabrics within various types of mineral vein, thus providing further insight into the processes operating during mineralisation.

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Distinguishing hydrothermal and magmatic processes in the formation of rare earth element (REE) deposits: the Ditrău Alkaline Complex (Romania) as a case study

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Europe's rare earth element (REE) resources are under-studied, yet they have the potential to supply all of Europe's REE needs for the foreseeable future. The Ditrău complex The Ditrău complex is a Mesozoic layered alkaline intrusion (ca. 19 km diameter), in NE Romania, enriched in REE, Nb, Ta and Mo. It has the potential to contribute to, and form the basis of, a secure and sustainable European REE mining industry, ensuring supply security of such 'critical elements', a key aim of EURARE (www.eurare.eu). The Ditrău complex formed during continental rifting associated with Tethyan evolution[1]. The complex comprises layered amphibolites, alkali gabbros, diorites, syenites, nepheline syenites and alkali granites, all of which have been significantly modified post-solidification. However, there has thus far been limited study of the effects of late-stage magmatic and hydrothermal fluids on element remobilisation in the Ditrău cumulates the effects of late-stage magmatic and hydrothermal fluids on element remobilisation in the Ditrău cumulates.

New whole-rock geochemical and petrological data, combined with apatite EPMA data (focusing on REE), provide insights into the highly dynamic magmatic and hydrothermal systems of the Ditrău complex. We have correlated these data with field relationships New whole-rock geochemical and petrological data, combined with apatite EPMA data (focusing on REE), provide insights into the highly dynamic magmatic and hydrothermal systems of the Ditrău complex. We have correlated these data with field relationships to develop a conceptual model of magma chamber evolution and late-stage geochemical modification of REE by at least two phases of hydrothermal fluids. Initial magmatic processes led to the formation of titanite-rich mafic cumulates that are enriched in Ta, Nb, La and Ce. Subsequent magmatic evolution produced highly evolved magmas and late-stage hydrothermal fluids. Syenites near the roof of the complex have been pervasively altered and are cross-cut by hydrothermal veinlets bearing zircon and pyrochlore; the most hydrothermally altered samples show the greatest enrichment in Zr, Hf and HREE. The presence of fluid pathways transecting the complex that are depleted in Zr, Hf and HREE suggest that these elements were mobilised by late-stage fluids. A second hydrothermal event is represented by REE-enriched, late, cross-cutting carbonate veins hosting monazite, allanite, bastnäsite, rutile, molybdenite and sulphides (chiefly pyrite). Apatite REE patterns vary systematically: magmatic apatites are LREE-enriched with a negative linear pattern, whilst carbonate vein-hosted apatites are MREE to HREE-enriched with a concave pattern and a different REE substitution mechanism. We propose two main REE mineralising events for Ditrău: (1) magmatic REE-enrichment with a HREE hydrothermal overprint; (2) late mineralised REE-rich carbonate veins cutting the complex and extending into the surrounding country rock. These later veins may be related to a phase of carbonatitic magmatism at depth.

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Assessment of the Ni-Cu-PGE sulfide potential of magmatic intrusions surrounding the Munali Ni-sulfide deposit, Zambia

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The Munali Ni deposit and mine, southern Zambia, is an example of an economic magmatic Ni-Cu-PGE sulfide breccia deposit. Deposits such as Munali are typically hosted by mafic-ultramafic intrusions whose magmas have undergone sulfide saturation, forming in deep crustal conduits [1], which are temporal with intracontinental rift events and are spatially distributed among many of the world's craton margins. In the case of Munali, this is the southern margin of the Congo Craton along the Munali Fault [2]. These settings host some of the world's largest and well studied Ni-Cu-PGE deposits for example, Noril'sk, Siberia and Voisey's Bay, Canada. Munali, however, is relatively poorly documented, with very little academic research performed on the deposit.

Munali is a magnetite-rich deposit, comprised of a barren gabbro core with a marginal zone of sulfide-matrix, ultramafic breccias. The intrusion displays a distinct magnetic anomaly. A number of potentially similar mafic-ultramafic intrusions have been identified as magnetic anomalies with similar anomalies to the main Munali intrusion, including the Chibuku and T1B prospects, which immediately surround the main Munali intrusion along the Munali Fault. These intrusions remain untested for mineralisation but represent potentially prospective exploration targets.

Petrological and field studies have indentified 8 different igneous phases at Munali, all containing variable proportions of pentlandite, pyrrhotite, chalcopyrite and pyrite in addition to magnetite and ilmenite. Underground mapping revealed a multistage emplacement of the ultramafic units which are either structurally and/or genetically associated with mineralisation.

Initial analysis of RC hole geochemical data and subsequent down hole trace element plots from Chibuku, reveal four distinct igneous units, which display variably elevated concentrations of Ni, Cu and PGE in accordance with S. Petrologically, Chibuku contains magnetite-bearing rocks including, gabbro, poikilitic gabbro and a highly serpentinized ultramafic phases that are directly comparable to those at Munali. Subsequently, Ni-Cu-PGE mineralisation may be present at the Chibuku prospect. The T1B intrusion, however, is comprised of only one igneous phase with minor magnetite, and no elevated Ni, Cu or PGE concentrations.

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Lamprophyric dykes in the Bushveld Complex: The lithospheric mantle and its metallogenic bearing on the Bushveld LIP

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In Southern Africa, the geodynamic setting and source(s) of magmas that fed the Bushveld Complex remain unresolved – not least the controls on the metallogenic signature of this large igneous province (e.g., Pt/Pd ratio) between Northern, Western and Eastern Limbs of the complex. The Northern Limb is separated from the rest of the Bushveld Complex by the Thabazimbi-Murchison Lineament (TML), and the differences in Bushveld metallogenic 'fingerprint' N *vs.* S of the TML might signal interplay between a mantle plume (asthenospheric-derived magmas) and/or significant subcontinental lithospheric mantle (SCLM) melting. We predict that the shallow Kaapvaal SCLM keel should record the Bushveld magmatic perturbation and either reveal the SCLM as a major magmatic source or as a largely 'passive' lithospheric region which may contribute precious metals to ascending asthenospheric magma(s).

Lamprophyric parental magmas are thought to be produced by low-degree partial melting in the lithospheric mantle. Hence, spatial and temporal changes in lamprophyre composition provide insights into the geochemical evolution of the SCLM below the Kaapvaal Craton, through which the Bushveld Complex intruded. In the Western Limb, lamprophyric dykes regionally trend NE-SW to NW-SE and range in thickness from millimetres to > 20 metres. So far we have identified five main types of lamprophyric dyke but there is huge textural variation across these groups.

Lamprophyric dykes show a clear terrane-scale trace element and metallogenic signature, closely resembling that of the Bushveld Complex itself and adjacent kimberlites. For example, Pt/Pd ratios of lamprophyric samples are typically > 1, with a mean ratio of 1.79 ± 1.04 (2σ). This is significant in light of the Western Bushveld Pt/Pd range of 1.60 to 2.76. We suggest that this metallogenic signature is inherent to the SCLM source of parental magmas of the lamprophyres. Hence, there appears to be an intrinsic link between the Kaapvaal SCLM (per constituent block) and Bushveld magmatism.

On a practical level, lamprophyric dykes represent a major hazard to mining excavations and underground developments across various portions of the Bushveld Complex, particularly the Western Limb. Once exposed during operations, dykes frequently 'rot' within 24-48 hours, and this has led to multiple incidences of falls of ground and underground collapse. In addition, catastrophic blow-outs and wall rock failures caused by highly pressurised gas pockets have been documented in association with the dykes, resulting in serious injury and fatalities of mineworkers. The cause of lamprophyre decomposition is unclear although we would predict that it could reflect a specific vulnerability of certain mineral species to dissolution (e.g., carbonates or salts) or oxidation. By understanding the mineralogy and composition of the lamprophyric dykes we aim to identify the process(s) involved in their disintegration and thereby mitigate these dangerous working conditions.

Gold and by-product recovery of critical elements from gold ores using deep eutectic solvent ionic liquids: *BRIO*

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Gold ores, and concentrates from them, often contain high enrichments of scarce or critical elements such as Te, Bi and Sb, but there are few financial incentives for a company to recover these elements. They may be lost to tailings or roasted off (and so become an environmental liability), or can incur smelter penalties. Recovery of these elements, along with the gold, would add value and secure supply.

Ionic liquids are anhydrous salts that are liquid at low temperature. They are powerful solvents and electrolytes with potential for high selectivity in both dissolution and recovery. Deep eutectic solvents (DES) 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 [1].

Using a microleach technique employing an optical profiler we show that gold, as electrum, dissolves rapidly by oxidation with I_2 in DES at 50°C (at least 80x the maximum cyanidation rate at 25°C). Recovery of the gold by electrodeposition has been demonstrated [2]. In itself this is a potential environmentally-benign alternative to cyanidation for gold recovery. In addition, hessite (Ag_2Te) dissolves as rapidly as electrum, whilst native tellurium, altaite (PbTe), tellurobismuthite (Bi_2Te_3) and stibnite (Sb_2S_3) also dissolve. Base metal sulfides such as galena and chalcopyrite dissolve slowly, whereas pyrite and sphalerite are insoluble. Thus there is good discrimination in dissolution rate between the base metal sulfides/pyrite gangue and the Au, Ag, Te, Bi and Sb minerals, suggesting the potential to recover *all* these elements from gold ores.

Pyrite, and many other sulphides, are soluble by electrolysis in DES. Thus inclusions of gold and other target minerals locked within pyrite could potentially be liberated by electrolysis for subsequent dissolution by oxidation.

We are planning to develop this approach through a H2020 application – ***BRIO***: By-product Recovery by Ionometallurgy of Ore. For this we are seeking industrial partners who can supply suitable ores with potential by-products that we can test.

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Mapping Marine Minerals in Europe

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The Geological of Ireland (GSI) as leaders of EMODnet Geology WP7 Marine Minerals, have established a framework for mapping geological occurrences for 9 different types of marine mineral deposits and accumulations in European seas.

The 9 marine mineral types established, which include hydrocarbons are: aggregates, hydrocarbons, gas hydrates, marine placers, phosphorites, evaporites, polymetallic sulphides, polymetallic nodules and cobalt-rich ferromanganese crust.

A unique scheme has been devised, to capture key components of each deposit type and information relating to the source data and agency. This scheme, together with template shapefiles and explanatory task guide, was distributed to all EMODnet Geology project partners, allowing partners to format and deliver their marine minerals data in a systematically harmonised fashion.

In order to merge data sets and produce the marine minerals Web Mapping Service (WMS), partners' data were assessed for error then merged and projected using WGS 84. Polygon and point data have been created for each deposit type; polygons indicate the spatial extent of data provided, while point data – illustrated using individual mineral-type styles – demonstrate the type of mineralogical deposit and location, thus mirroring the approach to mapping deposits used by terrestrial mineral projects such as Promine and Minerlas4EU. The styles adapted to represent these data for both polygon and point adhere to INSPIRE standards. A WMS displaying each of the nine deposit types has been created and is consumed by the EMODnet Geology web portal. The WMS will continue to be updated by the GSI as partners submit updates or new data.

Geochemistry to explain element transport at Ballinalack, Ireland

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Geochemical anomalies in soil and sediment samples are often used as a tool in mineral exploration. Soil Zn anomalies have been applied with great success in the Irish Midlands contributing to the discovery of the Lisheen, Galmoy and Navan (Tara Mines) deposits. More recent developments in the field of trace-element analysis and isotope geochemistry could provide new insights into fingerprinting mineralization in surficial sediments.

Both major and trace elements can be easily mobilized during fluid-rock interaction. These element signatures are often passed on to the overlying sediments (tills) and soils with their magnitude depending on the soil mineralogy, organic matter content as well as on Eh and pH conditions. To explain the element transport, we adopted a reduced chimney model for glacial terrains (Hamilton, 1998) [1], which succeeded to explain the general patterns but did not successfully resolve the detailed processes of mobilization. Current research will provide insight into the geochemical processes generating the observed metal anomalies and will help fingerprint cryptic alteration haloes, aiding mineral exploration programs.

Here, we present the geochemical distribution of major and trace elements associated with mineralization of the Ballinalack carbonate-hosted Pb-Zn deposit, in the Irish Midlands. Typical sphalerite and pyrite trace-element signatures determined by LA-ICP-MS are reflected in the bulk geochemistry of the host Waulsortian Reef limestone. There is a contrast between the soil above the sulphide body, which is enriched in As, Mo and Sb, and the cover rocks, which are depleted in these elements. In accordance with known redox-reactions (reduced chimney model), enrichment of these elements might not take place within this particular cover rock. The results suggest that the observed trace-element signature is an indicator for complex element mobility above the Ballinalack Pb-Zn deposit.

In the future, further investigations will examine the processes of mobilization and isotope fractionation in surficial sediments, which could help to refine exploration models for the discovery of blind mineralization in the Irish Midlands.

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The Monchegorsk Layered Complex - a natural laboratory for mineral deposit types associated with layered intrusions

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The 2.5 Ga mafic-ultramafic Monchegorsk Layered Complex (MLC) is located in the centre of the Kola Peninsula in NW Russia. It comprises two separate intrusions covering an area of ~550 km^2: the predominantly ultramafic Monchepluton (~ 65 km^2) and the mafic Main Ridge Massif (~485 km^2) making it one of the largest layered intrusions on Earth [1]. The MLC occurs together with a number of other mafic-ultramafic intrusions across the Fennoscandian Shield, however, almost all of them are slightly younger, at 2.44 Ga [2]. The older intrusions occur exclusively in the Russian portion of the Fennoscandian Shield. The reason for this remains under debate.

The Monchepluton intruded Archean high-grade metamorphic basement of the Kola Group comprising metapelites, quartzites, banded iron formation and minor dioritic gneisses [3]. It is crescent-shaped and consists of six sub-massifs arranged in two branches. The NNE-trending ultramafic branch (approx. 7 km across) is referred to as "NKT Massif" and comprises Mts. Nittis, Kumuzh'ya and Travyanya. The W-trending mafic-ultramafic branch is slightly longer (9 km) and consists of Mts. Sopcha, Nyud and Poaz. The intersection of the two branches is occupied by a dunitic body hosting several massive chromite layers known as the "Dunite Block". Its stratigraphic position relative to the MLC, however, remains under debate.

The complex hosts a range of mineral deposit types including (1) contact Ni-Cu-PGE reef mineralisation at the base of the intrusion, (2) internal PGE reefs associated with layered dunite and pyroxenite as well as evolved gabbro, (3) massive Ni-Cu sulphide mineralisation in steeply dipping veins, (4) Ni-Cu sulphide mineralisation in micronorite and (5) massive chromite layers in dunite [4].

Taken as a whole, the MLC represents a natural laboratory for virtually all mineral deposit types associated with layered intrusions in a single complex. Hence, it provides a unique object of study for a holistic synopsis of petrogenetic and ore-forming processes during the crystallisation of layered intrusions.

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Systematic variations in the trace element and sulphur isotope composition of pyrite with stratigraphic depth in the Skouriotissa VHMS deposit, Troodos ophiolite, Cyprus

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The Troodos ophiolite represents one of the best-preserved fossil analogues of modern oceanic crust and includes numerous volcanic-hosted massive sulphide deposits. The actively mined Skouriotissa deposit can be separated into a stockwork ore zone and an overlying massive sulphide lens that is covered by metalliferous sediments representing the former sulphide–seawater interface. Pyrite is the dominant sulphide mineral within these ores. The trace element composition of pyrite varies systematically with stratigraphic depth (down to about 150 mbsf) probably reflecting fluid temperature variations during precipitation (Co, Ni, Se, Te, Bi and Cu) [1, 2], metal remobilization due to hydrothermal zone refining (Zn, Sb and Pb) [3, 4] and significant fluid-seawater mixing at the seafloor (Mo) [1, 3]. Massive sulphide-hosted sphalerite and euhedral pyrite formed under high temperature fluid conditions (~400°C) while the occurrence of colloform pyrite indicates lower precipitation temperatures (<400°C). Similar δ^{18}O quartz-fluid equilibration temperatures (~400°C) of the stockwork zone indicate that the Skouriotissa fluids did not cool significantly during the final 150 m of fluid ascent to the seafloor. The S isotope composition of deep stockwork pyrite (-1.4 ‰) suggests that an isotopically light magmatic volatile phase (<0 ‰) was added to the hydrothermal system of Skouriotissa and reflects degassing of supra-subduction zone magmas [5]. During further fluid ascent 33 to 40 % of conductively heated Cretaceous seawater (200-250°C, δ^{34}S=18-19‰) was added, which results in the precipitation of stockwork pyrite with positive δ^{34}S values (6.1‰) and high concentrations in temperature-sensitive elements such as Co, Ni, Se, Te, Bi and Cu. Proceeding sulphide precipitation causes a ^{34}S depletion in the remaining fluid and in associated pyrite at the seafloor (average δ^{34}S=4.8 ‰). In addition, the comparable trace element and S isotope composition of pyrite from the Skouriotissa massive sulphide lens and the active Sisters Peak black smoker from the Comfortless Cove vent field on the Mid-Atlantic Ridge (5°S) indicates that the Skouriotissa hydrothermal system has a modern analogue.

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Peripheral platinum: the Bushveld gives you the edge

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Within the layered succession of the Bushveld Complex, there are a number of horizons with elevated platinum group element (PGE) concentrations. Such layers include ~12 chromitite packages from the LG1 upwards, the Pseudoreefs and Boulder Beds, culminating in the Merensky Reef with a subsequent rapid decrease above this. Previous authors [1,2] have attributed such mineralised layers to influxes of new magma. In the Pseudoreefs, Boulder Bed, and Merensky there were pulses of more mafic magma (only mafic minerals on the liquidus) that spread across the cumulus pile that was likely to have been a source of PGE. Was this magma responsible for all the PGE-enrichments, both in the entire Layered Series and in satellite bodies?

In the last decade a number of deposits that are peripheral to the main Complex have challenged previous ideas. If the Main Zone magma did not carry PGEs, why do enriched horizons of PGE occur in the Main Zone in the far northern limb and at the level of the Pyroxenite Marker? Can this all be attributed to reworking of lower layers by Main Zone magma, which became "contaminated" (by PGE), or were there later magma pulses from a PGE-enriched magma reservoir that mixed with some Main Zone magma that account for mineralisation at the Sheba's Ridge and Waterberg deposits?

The Sheba's Ridge pyroxenite-norite-gabbronorite southwest of the eastern limb of the Complex comprises a basal zone of Marginal Zone quartz-norite sills, a Ni-Cu-PGE mineralised pyroxenite; an interfingered zone of Critical Zone pyroxenites and Main Zone norites; and an upper package of mottled anorthosites overlain by thick Main Zone gabbronorites [3]. Mineralised horizons above the Ni-Cu-PGE-bearing pyroxenite occur where the two types of magma were in contact. The Intermediate Chromitite Layer and Platchro are potentially equivalent to Middle and Upper Group chromitites of the Bushveld Complex whilst the hanging-wall mineralised norite and upper Mineralised Pyroxenite could be equated to the Merensky Reef.

At the recently discovered Waterberg project in the far northern limb of the complex, F reef PGE mineralisation occurs in a basal ultramafic zone of troctolites and minor harzburgites while an upper T reef occurs at the boundary between the Main and Upper Zone in varied lithologies that include pyroxenite, harzburgite, gabbronorite and anorthosite with an unusual metal ratio of ~50% Pd, ~30% Pt and 20% gold. Both reefs are atypical for the Bushveld Complex in terms of host rocks, stratigraphic position and metal budget and both reefs show evidence of the importance of new magma influxes in promoting mineralisation and questions the source of the PGE.

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Ore fluid characteristics of antimony deposits in South West England: new insights into ore genesis in Wadebridge-Port Isaac and Herodsfoot

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Security of supply concerns for antimony (Sb) mainly result from the concentration of production in China (about 78% of primary global production in 2013) [1]. The major source for Sb in China is the rapidly depleting Xikuangshan supergiant Sb deposit [1]. Sb is used predominantly in the manufacture of flame retardant materials and currently has no adequate substitutes. The development of improved models for the genesis of antimony-bearing deposits will permit more effective exploration and thus contribute to diversification of the supply base and improved supply security. Here we present the results of a case study on selected antimony occurrences in South West England.

The petrographic and fluid inclusion characteristics of known Sb mineralisation at Wadebridge-Port Isaac and Herodsfoot in Cornwall have been examined. Mineralisation at Wadebridge-Port Isaac, which was mined in the 19th century, contains either pyrite + arsenopyrite ± galena ± sphalerite or galena + chalcopyrite ± bournonite ($PbCuSbS_3$) ± freibergite ($(Ag,Cu,Fe)_{12}(Sb,As)_4S_{13}$). The deposits are similar in style to European Variscan, shear-zone-hosted, Sb-bearing deposits such as those in the Massif Central, France [2]. Previous work [3] concluded that the different deposit styles formed independently. However, new inclusion data presented in this study suggests that the deposits are genetically linked. Results indicate that earlier high temperature (T_h 170-280°C/T_t <450°C), CO_2-H_2O-NaCl brines (5.6-8.8 wt% NaCl equiv.) precipitated the pyrite-arsenopyrite assemblages. Subsequently, the fluids degassed and evolved, by mixing with meteoric waters, to lower temperature (T_h 107-223°C/T_t c. 190°C), mostly lower salinity (1.2-11.7 wt% NaCl equiv.) H_2O-NaCl fluids and precipitated the galena + Sb sulphosalt mineralisation.

The Herodsfoot lode is a north-striking, 1 km long, sub-vertical vein that was intermittently mined primarily for Pb and Ag from the early 1700s until 1884. It is also known for its spectacular specimens of 'cog-wheel' bournonite ore [4]. The deposit has historically been classified as a Mid-Triassic, low-temperature 'crosscourse' deposit based on little more than a shared geometry with nearby orebodies [5]. Fluid inclusion data from samples of legacy tailings at the North Herodsfoot Mine reveal that the ore fluids comprised high salinity (18-27 wt% NaCl equiv.) H_2O-NaCl-$CaCl_2$ brines that ingressed at low temperatures (T_h 83-129°C). These compositions confirm that the ore fluid at Herodsfoot lode has clear geochemical similarities with other crosscourse deposits in South West England.

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Initial results of batch reactor experiments to determine sulphide oxidation rates and trace metal release under seafloor conditions

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Rates of sulphide mineral oxidation in seawater were studied using abiotic batch reactor experiments completed under seafloor conditions. The aims of these experiments were to assess the potential for major and trace metal release during the mining of seafloor massive sulphide (SMS) deposits. Significant metal release may result in toxic concentrations of some elements in the surrounding environment. This research also has the potential to explore the weathering of SMS deposits as they move away from ridge axes, which is vital for identifying inactive deposits.

Monomineralic samples of pyrite, chalcopyrite, sphalerite, galena and pyrrhotite were reacted with synthetic seawater at temperatures of ~2°C, under circum-neutral pH (~8.2) and anoxic conditions. Monomineralic samples of pyrite, chalcopyrite and sphalerite as well as polymineralic mixtures of these three sulphides in all configurations were also run under the same pH and temperature conditions as above, however, the synthetic seawater was equilibrated with atmosphere.

These initial experiments were limited to eight-hour runs in order to determine initial oxidation rates and to assess experiment validity. During the experiments, 1 mL samples of seawater solution were regularly taken. These were subsequently analysed for a suite for elements by ICP-MS to determine rates of trace element release. The surfaces and interiors of reacted sulphides were analysed for oxidation features using a scanning electron microscope.

During the experiments hydroxides and other unknown phases precipitated from the synthetic seawater solution. These phases appear to sequester Fe, Zn and Cu in different proportions. As a result, rates of sulphide mineral oxidation cannot be determined from the concentrations of these metals in solution as they are not representative of sulphide oxidation alone. The precipitation of these mineral phases is caused by reacting sulphide minerals at a pH >5 which is known to result in hydroxide formation. Increased concentrations of dissolved oxygen likely increases the rate of sulphide mineral oxidation, but also increases the rate of oxy-hydroxide (and possibly other mineral) precipitation.

Galvanic effects are evident in polymineralic experiments with a galvanic series of chalcopyrite>sphalerite>pyrite observed. In this case chalcopyrite appears to corrode in the presence of sphalerite and not vice versa as expected, however, this is potentially an effect of a greater proportion of Zn being removed from solution and incorporated into the precipitates than Cu. Increasing the number of sulphide phases present in the experiment appears to increases the rate of oxy-hydroxide precipitation.

The release of other trace elements excluding Fe, Cu and Zn is poorly understood. There appears to be limited trace element release within the first hour of reaction with little variation occurring thereafter. It is unclear whether this is a ‘real’ feature of the experiments or an artefact resulting from the dilution of trace element concentrations; a result of using small surface area to volume ratios.

Genesis and Structural Architecture of the CSA Cu-Ag Mine, Cobar, NSW, Australia

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The CSA Cu-Pb-Zn-Ag mine, located 11km NNW of Cobar in central NSW, is one of Australia's highest grade copper deposits. Historically workers have attributed its nearly vertical pipe-like ore bodies to the intersection of two regional faults, the Cobar and the Plug Tank. While the position of the deposit is in the hanging wall of the Cobar fault and directly along strike from the Plug Tank Fault there is no evidence that these faults intersect within the deposit. Structural analysis of drill core and underground mapping in conjunction with 3D stress modeling were employed to understand the controls on mineralization within the deposit and the Cobar region. Analyses showed the presence of folding as well as orthorhombic fault arrays within the deposit which, when activated during regional compression, focused the ore forming fluids into damage zones along the intersections of these faults to form sub-vertical pipe-like ore bodies.

Structural analyses continued on from the work of Jeffries [1], who looked at the top 300 m of the deposit, showed a significant change in regional cleavage from 80º/090º at surface to 80º/264 at depths greater than 300 m. This change suggests that the hanging wall of the Cobar Fault was dragged and rotated during regional compression. Analysis of three major lineations present within the deposit showed the following: 1. Measured intersection lineation's suggest that the regional S_2 cleavage overprints early folding, 2. Chlorite stretching lineations favour a dip-slip strain history over the widely accepted transpressional regime and 3. Chlorite Slickenlines indicate late strike-slip faulting which overprints all other structural features of the deposit.

To understand the spatial location of the CSA deposit a regional stress model was constructed using Poly3D a boundary elements method (BEM) based program. The effect of the two regional faults (the Plug Tank and Cobar) on the stress fields surrounding the location of CSA were modeled by applying a horizontal σ_1 stress of 200 MPa directly EW. The σ_1 stress was calculated using twinning within calcite grains to determine the palaeostress at the time of peak mineralization. When a $\sigma_1 = 200$MPa was applied with an azimuth of 90°, dilation was achieved along the lines of intersection of the orthorhombic fault arrays allowing for the formation of the deposit.

The CSA deposit was found to form epigenetically from hydrothermal fluids migrating up areas of high strain. These areas of high strain formed as a result of regional compression responsible for the formation and activation of orthorhombic fault arrays in the hanging wall of the Cobar Fault. Boundary element modeling showed that the spatial location of the deposit is likely the result of the geometry and movement of the Plug Tank and Cobar faults in response to regional compression producing zones of dilation. Modeling has shown that these regional faults do not need to intersect to produce the deposit, but can be used as targeting tools for other areas of potential mineralization.

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Rapid ore formation at the Ok Tedi Au-Cu porphyry-skarn deposit

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High precision U-Pb zircon dating by CA-ID-TIMS enables us to determine porphyry intrusion emplacement and the timescales of associated Cu-Au mineralisation. Applying this technique at the Ok Tedi porphyry-skarn deposit, one of the youngest known deposits in the world (~1.1 Ma), could potentially yield the tightest time bracket for the formation of a giant porphyry deposit.

Several different intrusions were identified during a field visit at the Ok Tedi Au-Cu deposit and age relations were established using unambiguous cross-cutting relationships. Magnetite-sulfide skarn mineralisation is bracketed by the intrusion of pre- to syn-skarn Monzodiorite and post-skarn Monzonite while later disseminated porphyry-style Cu-Au mineralisation is centred around a barren core in the Monzonite. Porphyry mineralisation and all intrusive phases are cut by a heavily mineralised intrusive-hydrothermal breccia.

First results show that the majority of zircons are of Pleistocene age but a significant proportion is inherited with a Proterozoic age. Youngest zircon populations are the closest approximation of porphyry emplacement. At Ok Tedi they indicate rapid mineralization pulses of several 10^5 years, in accordance with recent numerical simulations [1].

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Controls on the formation of a large Zn-Pb Irish-type deposit: evidence from the Navan halo

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The Navan orebody has an estimated pre-mining size >110 Mt at 10% Zn+Pb, with an overall Zn/Pb ratio of 4. Mineralization hosted by Lower Carboniferous shallow water carbonates, termed the Pale Beds, is demonstrably epigenetic. However, subordinate mineralization hosted by submarine fault talus deposits and the lowermost overlying basinal rocks apparently formed during seafloor exhalation. It is well documented that the deposit formed by mixing a relatively hot, metal-rich hydrothermal fluid (positive $\delta^{34}S$) with cooler seawater-sourced brines carrying bacteriogenic sulfide (negative $\delta^{34}S$). >90% of ore sulfide at Navan is of bacteriogenic origin. The Navan deposit is strongly controlled by faulting that evolved during basin-margin break-up at ~345Ma. Here, we characterise the halos associated with the deposit to better understand metallogenesis, and to identify regional vectors to mineralisation.

A Pale Beds-hosted epigenetic halo contains low-grade sulfide mineralization with Zn/Pb <1 up to 2.5 km from the orebody. The dominant sulfide is galena with a hydrothermal signature ($\delta^{34}S$ = 0 to 10‰). Locally where grades increase, higher Zn/Pb ratios tend towards those in the Navan orebody and a bacteriogenic signature is present ($\delta^{34}S$ = -25 to -5‰). This suggests that mineralization within this halo formed mainly in an environment relatively depleted in bacteriogenic sulfide. Zn isotope values ($\delta^{66}Zn$ = -0.3 to 0.4‰) within the epigenetic halo suggest that precipitation was not from fluids moving laterally away from the Navan deposit, consistent with upwelling of hydrothermal fluids over a region larger than the Navan orebody. A second halo, which apparently formed syngenetically, comprises Fe-rich with variable Mn horizons hosted by stratigraphically higher deep-water basinal limestones. In an area south of the orebody, where these horizons are more abundant, possible genetic links with adjacent Pale Beds-hosted ore-grade base metal sulfides are being investigated. This Zn+Pb mineralization has a dominantly hydrothermal sulfide signature ($\delta^{34}S$ = 6 to 16‰). However, the overlying pyrite has a bacteriogenic sulfide signature. Thus the bacteriogenic sulfide-bearing fluid did not mix with the hydrothermal fluid, thereby denying the efficient trap mechanism responsible for the main orebody. This may imply repeated hydrothermal fluid upwelling, or a restriction of bacteriogenic sulphide-bearing fluids into the Pale Beds.

In both types of halo and in the main deposit, the presence of bacteriogenic sulfide enhances the precipitation of Zn+Pb mineralization from the hydrothermal fluid. Therefore, in areas without access to these bacteriogenic sulfide-bearing fluids within the epigenetic halo, base-metal species dissipate to background levels. Similar restrictions within the Pale Beds adjacent to the syngenetic halo suggest that base-metals remain in solution until the host fluid interacts with bacteriogenic sulfide-bearing fluids at or near the seafloor, leading to accumulations of base metal sulfides within the lowermost units of the overlying basinal sediments. From a mineral exploration point of view, the syngenetic halo provides the better opportunity to vector towards high-grade base metal mineralization.

Metal Distribution in Deciduous Trees around Navan Pb-Zn Ore Deposit, Ireland

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The ability of certain plants to selectively absorb and accumulate metals makes them useful as geochemical indicators [1]. Recent studies showed great potential of using plants in mineral exploration, especially grassroot geochemistry, which lead to a discovery of a new Australian metallogenic province [2].

In this research, the trace elements of native and most common plant species in Ireland such as ash, beech, blackberry, hawthorn, oak, poplar and sycamore were determined above the sub-outcrop of the Navan Zn-Pb deposit (Ireland), currently mined by Boliden Tara Mines Limited. This area represents a sub-outcropping carbonate-hosted base-metal orebody characterised by a large shallow soil Zn-Pb anomaly. Vegetation (trees and shrubs) grows directly above mineralization, which makes it an ideal location for biogeochemical surveys.

Because biogeochemistry is not a standard exploration methodology, being influenced by a number of factors affecting sampling and analysis, (e.g. phytochemistry, seasonal variations and contamination), this study initially tested detailed sampling strategies. Seasonal sampling, sub-sampling of individual plants and comparison with control locations were investigated with the aim of testing which uptake of which trace elements into which of the higher plants might serve as an exploration tool.

Preliminary results show Cd, Zn and Pb enrichment in all investigated tree species grown in soil with metal anomalies compared to the background values from control sites. In general, the element content may originate either from soil via uptake by roots and/or by atmospheric deposition of particles. To distinguish between these possibilities, dendrochronological records of metal absorption in oak and beech will be used, as tree records stretch back in time prior to local Zn-Pb mining and its associated anthropogenic atmospheric emissions.

In further research, trace elements and stable metal isotopes will be used to track the metal signature to its source, with the aim of aiding in the exploration of blind deposits. Different type of trees will be investigated, starting from deciduous to coniferous species. In addition, this research will be used to develop new criteria for biogeochemical surveys and will try to better understand specific metal update, e.g. our pilot data imply that cadmium uptake is strongly dependent on that of zinc.

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The origin and distribution of critical metals (Pd, Pt, Te & Se) within the Skouries Cu-Au porphyry deposit, Greece.

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The Skouries deposit is an Au-Cu porphyry system in the Chalkidiki peninsular, Greece, with associated Ag, Pd, Pt, Te and Se credits (resource estimate 5.405 million oz. Au at 0.6 g/t and 1.234 million tonnes Cu at 0.43%). The deposit is hosted by a series of overprinting shoshonitic intrusions, in a metamorphic sequence including ultra-mafic xenoliths and mafic dykes. The initial quartz monzonite porphyry is associated with a quartz–magnetite +/- chalcopyrite–pyrite stockwork, cross cut by a set of syenite porphyry dykes associated with quartz–chalcopyrite–bornite veins. The final intrusive phase consists of monzonite dykes with associated sulphide veinlets, which is followed by a late vein stage containing quartz–pyrite veins, commonly with associated anhydrite. The compositions of the intrusive phases are similar, and are interpreted to share the same magma source, with their compositional evolution representing the fractionation of a hypabyssal stock.

The Pd and Pt in the deposit is hosted within telluride minerals that occur as both inclusions in chalcopyrite and as isolated grains within the quartz-chalcopyrite-bornite veins associated with the second syenite intrusion. The main platinum group minerals present are Merenskyite ($(Pd, Pt)(Te, Bi)_2$) and Sopcheite ($Ag_4Pd_3Te_4$), with minor Telargpalite ($(Pd,Ag)_3Te$) and Kotulskite ($Pd(Te,Bi)$). Gold and silver tellurides are also present as Muthmannite ($AgAuTe_2$) – Krennerite ($AuTe_2$) assemblages, with minor amounts of Sylvanite ($(Au,Ag)_2Te_4$), Empressite ($AgTe$) and Volynskite ($AgBiTe_2$) – Skippenite ($Bi_2Se_2(Te,S)$). Although microcrystals of Ag-Se bearing galena are commonly associated with vein-hosted chalcopyrite the majority of the Ag and Se appears to be hosted in accessory minerals such as Petrovskaite ($AuAg(S,Se)$), and within the telluride assemblages.

$\delta^{34}S$ values do not show much variation between veinsets, and none at all between critical metal enriched and depleted samples. $\delta^{34}S$ values of the deposit as a whole range from -3.8‰ to +1‰, with an average of -1.4‰, with only the early magnetite bearing veins (-0.1‰) and the sulphide veinlets (-3.2‰) differing. This indicates a magmatic sulphur source for all stages of this deposit. Fluid $\delta^{18}O_{V\text{-}SMOW}$ ranges from 6.4‰ to 7.4‰, and fluid $\delta D_{V\text{-}SMOW}$ of -87.5‰ to -52.6‰, consistent with a magmatically equilibrated fluid source. High levels of hydrothermal magnetite within the deposit show the fluids were strongly oxidising, and an initial fluid inclusion study has shown the fluids to be highly saline. These conditions favour hydrothermal transport of PGEs [1], and the stable isotope results suggest that the critical metals in Skouries originate from an enriched magma source. Phlogopites within the deposit have high F content (up to 3.24 wt.%), which combined with high levels of LILE suggests mantle metasomatism has occurred, probably driven by fluids derived from the down going slab [2]. This provides a possible mechanism for the critical metal enrichment observed in this deposit.

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Multi-element trends during supergene enrichment of porphyry copper ore

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Porphyry copper deposits (PCDs) that undergo supergene enrichment are attractive to the mining industry since the process transforms a low grade protore into viable ore and creates the possibility of low cost hydrometallurgical processing. The process increases Cu content by 200-800% in comparison to a non-enriched PCD which contains only primary sulfide mineralisation [1]. PCDs supply 60% of the annual world Cu production [2], as well as being considerable sources of Au, Ag and Mo.

The supergene process results in a profile of an upper leached cap, a supergene enriched zone of economic value and a lower hypogene ore that resembles primary sulfide mineralisation. However, the role of supergene enrichment in controlling the behaviour of a range of by-product elements is currently poorly known. Whether certain elements are mobilised, retained, upgraded or depleted, will determine whether they can be recovered as by-products. Bismuth, Cd & As may impact downstream mineral processing when extracted alongside Cu-ore, whereas Au, Ag, Te, Se & Sb have the potential to be viable economic by-products.

Here, we utilise samples from a supergene enriched PCD from the southwestern USA to test the hypothesis that the progressive oxidation of the Cu-bearing minerals leads to fractionation of the trace and semi-metals through differential mobilisation and secondary adsorption.

Results show that grade increases downhole within the supergene profile from a near surface Cu-poor (0.005 – 0.049%) leached cap, through an enriched zone exceeding the Cu values of the hypogene PCD (2.86 – 1.1%). Initial results suggest that the concentrations of the trace elements listed above are low (0.6 – 16.2ppm), and Sb and As are below detection limits for bulk analysis by XRF (<5ppm). These results suggest that supergene Cu ore is not particularly prospective for by-products, but is ideal for the extractive metallurgy of copper. Detailed correlation between this bulk rock geochemistry and in situ mineral analyses will identify the mineral-specific concentration of particular elements, and will have application in the process mineralogy and extractive metallurgy of different zones of a PCD, and in evaluating their potential for recoverable by-products.

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Comparison of the style and nature of breccia-hosted Ni-sulphide mineralisation within the Munali intrusion, Zambia

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Magmatic deposits which contain exploitable quantities of nickel (Ni), copper (Cu) ± platinum group elements (PGEs) are genetically associated with the concentration of sulphides in mafic and ultramafic rocks. The mafic and ultramafic intrusions which host magmatic sulphide deposits are morphologically diverse and are often associated with deep-seated, vertically extensive magma feeder conduits [1]. Magma conduits are dynamic environments in which sulphides may be upgraded in metal tenor through interaction with continuous pulses of undepleted magma. Consequently, conduits are considered to be highly prospective locations for economic mineralisation [1].

Conduit-hosted Ni-sulphide mineralisation occurs within the Zambezi Supracrustal Sequence (ZSCS) of southern Zambia. The Munali intrusion occurs along a NW-SE trending fault and comprises of an unmineralised gabbroic core (855Ma) and a marginal ultramafic breccia with massive to disseminated Ni-sulphide mineralisation [2]. Mabiza Resources' Enterprise deposit has been mined since 2011, however, the base of the intrusion has not been intersected and the emplacement history for the sulphides remains poorly understood.

Multi-phase sulphide injection during breccia formation has given rise to four intrusive sulphide phases which comprise the matrix of the breccia, these include 1) massive sulphide; 2) talc-carbonate-magnetite-sulphide; 3) apatite-magnetite-sulphide and 4) calcite-apatite-sulphide. The latest two contain apatite, which is consistent with positive Y and Sr anomalies obtained by trace element geochemistry. This suggests that apatite equilibrated late in the system and was preceded by the exsolution of an immiscible sulphide liquid which gave rise to the massive-sulphide and talc-carbonate-sulphide phases. The presence of apatite-magnetite and Fe-sulphide assemblages suggests mixing of sulphide with an immiscible Fe-Ti-P-rich silicate liquid, most likely within a dynamic magma conduit. This draws parallels with the Babbitt deposit in the Duluth Complex [3] where sulphide and Fe-Ti-P-liquids have also been suggested. Munali represents a feeder conduit with a marginal ultramafic sulphide breccia with evidence of multiple injections of sulphide, with and without associated immiscible liquids. Further work will characterise the metal tenors and ratios of each of these different phases.

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A reanalysis of the Kabwe Zn-Pb nonsulphide ore (central Zambia): preliminary results

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The Kabwe Zn-Pb deposit, in central Zambia, was discovered in 1902 and mined until 1994, when Zn-Pb massive sulphides were exhausted [1]. In total, 1.8 Mt of Zn and 0.8 Mt Pb, plus 79 t Ag, 7820 t V_2O_5, 235 t Cd and 64 t Cu were extracted from the Kabwe mine during its lifespan, leaving 1.9 Mt of Zn-silicate resources, at 13.4 wt.% Zn and 1.5 wt.% Pb, still in situ [1]. The carbonate-hosted sulphide ores originally consisted of sphalerite, galena, pyrite, chalcopyrite and accessory Ge-sulphides. Zn-silicate resources are mainly made up of willemite, generally replacing sulphides [1]. On the nature of this replacement previous authors [1, 2] consider that it may be related to either low-temperature hydrothermal oxidizing fluids (since this mineral is "usually" considered to be of hydrothermal origin), or to weathering (considering that the willemite is here associated with a "typical" supergene mineral assemblage, e.g. smithsonite, cerussite, goethite). To try to answer this question, we decided to conduct a reanalysis of the Kabwe ores, specifically focusing on the particular behaviour of trace elements contained in the original sulphide orebodies during later oxidation events. We present here the first results from the study of a batch of Kabwe ores specimens, housed in the Natural History Museum Ores collection in London.

Petrography confirmed the complex paragenesis reported in previous studies [1, 2]. In the analysed samples containing relict Zn-Pb-(and Ge-)sulphides, altered sphalerite (also when originally associated with the interstitial galena [1]), is always rimmed by thin galena layers, characterized by reaction boundaries with the Zn-sulphide. Sphalerite is also observed to be directly replaced initially by smithsonite. The first willemite generation constitutes a matrix between the galena-rimmed, smithsonite-replaced sphalerite remnants, and in this case it always hosts tiny galena inclusions. This generation directly replaces the interstitial galena and the smithsonite that was originally replacing sphalerite. This willemite is almost pure, and does not form euhedral crystals. However, a second willemite generation is developed forming well-shaped crystals of variable size (in some cases 0.5 mm hexagonal crystals in geodes). This willemite is chemically zoned, with alternating Pb-rich (up to 2 wt.% Pb) and Pb-poor bands. This entire assemblage is overprinted by minerals typical for a supergene environment: smithsonite, cerussite, hemimorphite, sauconite, pyromorphite, Pb-vanadates and Fe-oxy-hydroxides.

Ongoing LA analyses and isotopic investigations will help better definition of trace metal deportment in the sulphide and nonsulphide phases.

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Geochemical exploration for tin deposits in Cornwall, England: recent developments using portable XRF for large scale surveys and Tellus SW regional surveys

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Tin exploration has been in the doldrums since the price crash of 1985. However, price changes and projected supply deficit have resulted in the re-examination of old targets and search for new areas. This contribution details geochemical methods used in SW England where Treliver Minerals has been conducting exploration. Geochemistry has formed an important part of the programme as geophysics has proven ineffective and exposure is very poor.

The main geochemical technique has been soil sampling, either near surface or, in contaminated areas, at depth [1]. The challenge of the 2010s is to reduce costs and turnaround, if possible, by using portable XRF (pXRF) analysis. pXRF has also been used on a routine basis by Treliver Minerals in deep sampling and initial scanning of drill core for assay during geological logging.

As the utility and most cost effective method of using pXRF in soil sampling was not known, a 400 m long orientation study across the main sulphide-poor Treliver Sn soil anomaly was undertaken in 2013 using both in-situ and conventional sampling. Although patterns are very similar in all depths and methods, it was decided that pXRF on dried, disaggregated samples was most effective as sample analysis could be undertaken at leisure in a field base and samples archived for any later further analysis. This technique was used in several large semi-regional surveys, which were successfully meshed with pre-existing soil surveys analysed using wdXRF.

The 2015 release of data from the Tellus SW project [2] of the British Geological Survey and NERC have added much and brought SW England up to the standard of regional data for other Variscan tin bearing areas. Comparison of the Wolfson Atlas data with Tellus SW shows similar patterns with obvious control of Sn and W mineralisation by granites. Data for Ta and Nb as well as Nb/Zr indicate association of higher concentrations with topaz and lithium granites, which have low Th/K ratios on airborne radiometrics and some of which host commercial kaolinite deposits.

Many geologists at Treliver Minerals contributed especially Alex King, James Smith and Tom Pascoe in the orientation study; the support of Executive Chairman Mark Thompson was crucial.

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Contrasting Styles of Antimony Mineralisation in the Variscan of South West England

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Antimony deposits are well known from South West England but have produced little, perhaps 250 t [1]. Until recently no systematic geochemical survey for antimony was available but this has been rectified by the Tellus SW survey of the British Geological Survey [2].

Follow up of the Tellus SW geochemistry anomalies has located significant volumes of oxide antimony mineralisation (identified as romeite group minerals). This style has not been previously detected as no sulphides are present at surface and antimony oxides/hydroxides are not easy to detect visually. In situ (pXRF) assays indicate grades from 0.1-2% Sb which have been confirmed by conventional ICP-MS analysis.

Mapping and sampling by Pearson [3] showed the deposits are associated with previously mapped faults. Host rocks are very siliceous, isolated, blocks as well as travertines in Devonian limestones, and Permian red beds. The elemental association of Sb-As-Pb-Cs (no Au) and travertine-tufa occurrence suggest a Permian hot-spring origin. The heat source may have been distal volcanic, basinal or granitic.

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New Drilling Results of disseminated Sn-W Mineralisation at the Zinnwald/Cínovec deposit, eastern Erzgebirge, Germany

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The Sn-W-Li Zinnwald-Cínovec deposit is represented by greisen-type mineralisation hosted within the apical portion of a small granite intrusion. Similar to other granitic stocks with Sn-W mineralisation in the Erzgebirge, the Zinnwald granite intruded during the post-collisional stage of the late-Variscan (Permo-Carboniferous) magmatic evolution. These intrusions are characterised by the prominent enrichment of incompatible elements (F, Li, Rb, Cs) and the depletion of P_2O_5 [1].

The Zinnwald granite is located in the eastern part of the Erzgebirge-Fichtelberg anticline and consists of highly evolved, weakly peraluminous and variably altered albite–Li mica leucogranite of A-type affiliation. The deposit itself is characterised by laterally extensive pegmatitic veins and sheet-like, metasomatic greisen ore bodies, which are located in the apical part of the granite cupola. While the greisen veins represent the dominant source for the historically exploited Sn-W mineralisation of the deposit, the greisen bodies serve as a major resource for Li due to the abundance of Li-containing mica, named zinnwaldite. This was demonstrated recently during extensive exploration on the Li mineralisation carried out by SolarWorld Solicium GmbH (SWS) during 2011 and 2014 [2].

Albite granite has been generally considered as a barren lithological unit for Sn-W in the deposit of Zinnwald/Cínovec with only tentative indications of Sn-W mineralisation first described by [3]. Recent exploration drilling by SWS encountered a continuous succession of well-mineralised albite granite in the footwall of a lithologically distinct lithium-rich greisen ore body. The drilled thickness of the mineralised intersection is 20 m with a weighted average Sn grade of about 0.26 wt% Sn (including 4 m @ 0.39 wt% Sn) as well as elevated concentrations of W, Nb and Ta. The mineralisation is hosted by slightly to moderately greisenised, poikilitic albite granite that is mesoscopically indistinguishable from a barren equivalent of the hanging- or footwall. Cassiterite, minor columbite and scheelite as well as rare wolframite have been identified as ore minerals. The mineralisation style was encountered by several diamond drill holes defining a flat dipping mineralised zone at the eastern flank of the granite cupola, which is about 20 m in thickness and about 700 m in strike. The discovery shows that Sn-W mineralisation at Zinnwald/Cínovec is not exclusively linked to the formation of major greisen ore bodies – as was previously thought. This, in turn, may require a critical assessment of current metallogenetic models.

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Reconstructing the Geochemical Signature of Sudbury Breccia, Ontario, Canada: Implications for Exploration Models

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Sudbury breccia is a ubiquitous lithology in the footwall of the 1.85 Ga Sudbury Igneous Complex (SIC) in Ontario, Canada [1]. The breccia acted as a pathway for the emplacement of evolved, Cu-Ni-PGE rich, sulphide melts derived from embayment structures at the basal contact of the impact melt. These footwall ore deposits were partially remobilised by post-impact hydrothermal systems active in the footwall of the crater [1,2].

The genetic processes that formed Sudbury breccia are not yet fully understood, with three competing theories, citing in-situ frictional melting [3,4], cataclasis [5] or injection of allochthonous impact melt into the brecciated crater floor [6]. In addition, previous work has identified significant variations in the metal content of the breccia away from ore zones that warrant further investigation as potential vectors towards mineralised zones [7].

This study utilises a mixing model [8] to constrain the Sudbury breccia matrix at three localities, stepping outwards from the Creighton Embayment in the South Range of the SIC. We demonstrate that the breccia matrix can be constructed from local footwall lithologies with no requirement for a contribution from the impact melt sheet. Instead we support a dynamic, parautochthonous in-situ melt, which was transported over tens of metres via pressure driven injection into low pressure, extensional fractures zones that developed adjacent to zone of decompression melting during uplift in the transient crater [4]. Furthermore, our findings reveal that, away from ore bearing zones, the trace metal content within the breccia can be accounted for by assimilation of metal bearing mafic units in the footwall and is not necessarily linked with the expulsion of metals from footwall deposits.

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Specifying ore mineral types and determining the transformations in ore minerals using confocal Raman spectroscopy: Dumluca iron ore deposit, Sivas, Turkey

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In the vicinity of Dumluca Iron Ore Deposit, serpentinite unit of Gunes Ophiolite which emplaced tectonically over Munzur Limestones before Maastrichtian takes place. Serpentinite unit is cut by felsic and mafic intrusive rocks of Dumluca pluton (Upper Cretaceus-Paleocene) and overlaid by Yamadag volcanics (Pliocene). Actual position of the deposit shows that the contact between ore and wall-rock units is tectonically controlled. Dumluca Ore Deposit is formed by the intrusion of Dumluca pluton into serpentinites of Gunes ophiolite and contains 8 million tonnes of high-grade (57% Fe) magnetite ore.

Confocal Raman Spectroscopy studies performed on ore samples shows that “Dumluca iron ore deposit” is mainly composed of magnetite (668.81 cm-1), hematite (1309.33 cm^{-1}, 406.43 cm^{-1}, 606.32 cm^{-1}), goethite (411.76 cm^{-1}, 535.12 cm^{-1}) and pyrite (378.89 cm^{-1}, 342.7 cm^{-1}, 983.2 cm^{-1}) as ore minerals. Beside ore minerals, characteristic skarn zone mineral paragenesis diopside (682.24 cm^{-1}, 1033.68 cm^{-1}), actinolite (671.12 cm^{-1}, 1062.3 cm^{-1}), biotite-phlogopite (678.16 cm^{-1}, 572.33 cm^{-1}) and quartz (487.41 cm^{-1}) has been identified. Within ore minerals, transformation of magnetite to hematite and hematite to goethite has been figured both in Raman studies and polished section investigations. Also transformation of diopside to actinolite/biotite (±phlogopite) has been identified. Moreover, serpentine mineral type has been identified as chrysotile (387.53 cm^{-1}, 690.46 cm^{-1}) and effect of carbonitization has been figured in Raman studies.

Propylitic Alteration and Metal Mobility in Porphyry Systems: A Case Study of the Northparkes Cu-Au Deposits, NSW, Australia

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Propylitic alteration is typically the most ubiquitous and laterally extensive alteration facies in porphyry ore systems; with exploration increasingly focused on searching under cover, it may be the only visible sign of hydrothermal activity. Consequently, knowledge of propylitic assemblages and how they form is crucial to effective exploration. Despite this, propylitic alteration is relatively poorly understood, with deposit models generally assuming an isochemical process driven principally by heated meteoric water. We present a detailed study of the Northparkes porphyry cluster to test this paradigm and establish whether systematic changes in whole rock and alteration mineral chemistry are developed that could assist with exploration targeting.

Northparkes, located in central NSW, consists of several small alkalic Cu-Au porphyry bodies, host to both high grade and sub-economic mineralisation. These multiphase quartz monzonite intrusions are particularly narrow (~200 to 300 m diameter) but highly elongate (>1.4 km vertically), emplaced within and above a larger monzonite pluton. Field observations show each porphyry is surrounded by a small scale alteration halo, with progression from inner potassic alteration, characterised by K-feldspar + biotite, through a magnetite + biotite halo, passing outwards to a widespread propylitic epidote + chlorite zone.
The flux of metals (e.g., Cu, Au, Zn, Mn, Pb, V, Co) and ore-related elements (e.g., As, S, K, Ca, Sr) passing through the principal alteration zones was quantified using bulk rock geochemistry and chemical mass transfer analysis. The mineralogical residence of these elements was also mapped throughout the propylitic zone, with an extensive epidote and chlorite LA-ICP-MS mineral chemistry dataset. Results show propylitic alteration is not isochemical; rather elements lost from the potassic zone are typically gained in the propylitic zone (e.g., Ca, Fe and Co), and extensive outwards dispersion of other elements is observed. This is reflected either as a decreasing outward concentration (e.g., Cu, Si, Ti and S), or in a halo of higher values (e.g., Zn and Mn). Similar trends exist, but often with a greater magnitude of variation, in the chemistry of epidote and chlorite from the innermost to outermost propylitic zone.

Such distribution patterns for metals and ore-related elements, in particular their residence within propylitic alteration minerals, indicates a close link in space and time between intense propylitic alteration and ore formation. This is further supported by the $\delta^{18}O$ and δD composition of epidote, chlorite and quartz separates from the E48 deposit. These indicate propylitic alteration was driven by a magmatic fluid during equilibration with the country rock at progressively lower water:rock ratios while cooling through 350-200°C.

We contend that propylitic alteration is generated principally by lateral and upward infiltration of magmatic fluids into the host rock sequence. For exploration, it is clear examining propylitic mineral chemistry and recording details such as mineral assemblages, alteration intensity and texture is critical to improving success.

A classification of styles of orogenic (shear zone) gold mineralization, with examples from Scandinavia

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Excluding those interpreted as deformed epithermals, many Scandinavian gold deposits are orogenic, or shear zone related. The implication is that gold was scavenged, carried and deposited by metamorphic fluids. This talk focuses not on the origin or transport mechanism of gold, which is controversial, but instead emphasizes the controls on gold distribution at the deposit scale. It is based on over 25 years of detailed mapping, logging, 3D modelling and targeted sampling at numerous orogenic gold deposits and mines in Scandinavia and elsewhere in the world (Canada, Peru, Malaysia).

Mapping is now a sadly under-used tool in the armoury of exploration geologists. This talk aims to redress that balance. It illustrates the power of detailed mapping, particularly when combined with careful sampling. Understanding the detailed distribution of gold is vital if mineral resources are to be modelled correctly. And there are several examples of mines which have failed, some soon after start up, because of faulty resource models and mine plans based on poor, or non-existent, geological models.

With one or two exceptions, described in the talk, most orogenic (shear zone) gold in Scandinavia does not occur within classic shear zones. Some structures described as major ‘shear zones’ are instead important lithostratigraphic contacts between competent and ductile rocks, strongly modified by regional deformation.

The principal style of orogenic gold mineralization in Scandinavia is lithology controlled, related to competence. Rigid rocks, such as felsic intrusions, in otherwise ultrabasic-dominated sequences were particularly fertile for mineralization. Alteration halos, such as sericite, around these competent bodies imply they were the focus of fluid activity. Gold principally occurs in veins, which tend to evolve from early carbonate-, to later, quartz-dominated types. In detail, gold frequently occurs in microfractures, cutting brittle minerals; clearly it arrived as a last gasp.

The importance of contact-related mineralization is emphasized. Some of the largest gold deposits, such as Björkdal in Sweden, are clearly orogenic in style, but gold is strongly controlled by a profound lithology change. The competent granodiorite at Björkdal occurs immediately beneath a very ductile marble. Vein swarms in the granodiorite, immediately beneath the contact, carry gold. The veins clearly developed during regional deformation; it is highly unlikely to be an intrusion-related gold deposit; it falls squarely into the orogenic category. Other examples will be given in the talk.

Assessment of Automated Mineralogy in Characterising Zn-Pb nonsulphide ore

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Automated Mineralogy using SEM-EDS analysis has been routinely applied to ore characterisation, notably using the QEMSCAN. The main application of this technique has been to quantitatively characterise the mineralogy as applied to mineral processing and other applications of geometallurgy.

This preliminary study explores the capabilities of the next generation of Automated Mineralogical analyses using Mineralogic Mining (ZEISS) technology. Mineralogic utilizes modern quantitative EDS technology to allow minerals to be classified based on the wt% element abundance (stoichiometry) which is sensitive to subtle elemental variations.

In this study, samples from the Jabali Zn-Pb-Ag Mine and 3 from the Reef Ridge prospect were analysed using Mineralogic Mining. Samples were taken from different oxidation zones representative of the deposits comprising complex and varied Zn-Pb nonsulphides that require thorough characterisation before economic assessment can be made. The main nonsulphide Zn mineral at Jabali is smithsonite, which replaces both dolomite and sphalerite. Previous studies revealed zoned smithsonite, variably enriched in CaO, MgO and FeO and the occurrence of up to 20% Zn-dolomite, considered the main reason for Zn loss during processing. The Reef Ridge nonsulphide ore concentrations also consists of smithsonite commonly associated with Fe-(hydr)oxides (mainly goethite), with remnant sphalerite, and minor pyrite/marcasite.

Mineralogic Mining, as well as the previously used QEMSCAN, was able to build high-resolution maps and to clearly identify and quantify the major phases such as smithsonite and goethite (up to ~70wt.% and ~30 wt.% respectively in the highly oxidized samples), dolomite and sphalerite (up to ~45 wt.% and ~50wt.% respectively in the un-weathered samples). It was also possible to identify the “impure” metal bearing minerals, i.e. Zn-dolomite (from 14 to 26 wt.% Zn on average), Fe-dolomite (from ~4 to ~6wt% Fe on average), Mg-smithsonite (10 wt.% Mg on average), Fe-smithsonite (~28 wt% Fe on average). The technique was clearly able to distinguish between two very similar mineral phases (i.e. ankerite and Fe-dolomite).

The software was also able to automatically calculate the distribution % of Zn in the different mineral phases: from Jabali, results show that the Zn occurs mostly in smithsonite and Zn-dolomite, while at Reef Ridge Zn is largely in smithsonite and goethite. This information is critical for geometallurgical modelling, feasibility studies and process planning, allowing for quantification of the metal deportment between minerals, predicting metal losses during the treatment.

This study outlines the effectiveness of the new generation of automated mineralogy (Mineralogic) in ore characterisation at the exploration stage as an early aid to the evaluation of possible processing problems.

Geochemical and petrological study of the gabbro and granodiorite rock series hosting the Vasilkovskoe gold deposit (North Kazakhstan)

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The Vasilkovskoye deposit is located in North Kazakhstan in the Kokshetau Massive, a large block of Precambrian metamorphic rocks with anatexis and Paleozoic magmatism comprising gabbro and granodiorite series. The deposit is a typical example of a large intrusion-related gold system of the stockwork type. Faults and fracture zones of NW, NE and latitudinal directions are identified as feeder structures. The Vasilkovskoye deposit is situated at the contact of gabbrodiorite and diorite with hornblende-biotite granodiorite and plagiogranite. The deposit is characterized by concentric metasomatic, mineralogical, and geochemical zoning. The mineralogical zoning is expressed by distinct paragenetic assemblages and characteristic minerals. Gold grade is irregular and varies from 1.5 to 3.6 g/t (cut-off 0.8 g/t). Native gold is fine grained (up to 0.12 mm) and associated with pyrite-arsenopyrite-quartz and bismuthinite-pyrite-arsenopyrite-quartz assemblages. Results of our geological, geochemical and mineralogical study allow us to reconstruct the intrusive sequence and to distinguish the sequence of the different intrusive phases and mineral associations within the Vasilkovskoye gold deposit.

Major and trace elements were analysed for 27 least altered igneous rock samples. Based on geological observations, samples were grouped in seven distinct rock types, here listed in sequence of formation: gabbro, gabbrodiorite, diorite, quartz diorite, plagiogranites, that form a combined group (called collectively here “gabbro series”) and granodiorite, granite (called here “granodiorite series”). All sample series plot within the volcanic arc granite + syn-collision granite setting on the tectonic discrimination diagram. Overall, granodiorite and gabbro series show similar enrichment and depletion patterns. The chondrite normalized spider diagram of the Vasilkovskoye rock suite exhibits pronounced negative K, Nb, P and Ti anomalies, but lesser Sr anomaly. Negative Nb anomalies are also characteristic of the continental crust and may be an indicator of crustal involvement in magma processes. Notable is the significant enrichment in U, Ta and La that is more profound in the granodiorite series compared to the gabbro series. There are also some notable differences between the two series. For example, granodiorite series rocks are enriched in Rb, Th, Ce and Zr, whereas gabbro series rocks show depletion in these elements.

Granodiorite series rocks with highest REE abundances show a distinct pattern with enrichment in light REE relative to heavy REE and strongest developed negative Eu anomaly, compared to gabbro series rocks that display much flatter REE patterns and a positive Eu anomaly. Positive Eu anomalies suggest plagioclase accumulation. The REE pattern of one plagiogranite sample differs from other rock suites reflecting strong potassic alteration. Different patterns for behaviour of REEs with negative vs. positive Eu anomalies respectively, as well as contrasting behaviour of other elements as discussed above, indicates either derivation of the granodiorite and gabbro series from different sources or variable melting mechanisms.

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Petrogenesis of rare-metal pegmatites in high-grade metamorphic terranes: a case study from the Lewisian Gneiss Complex of Northwest Scotland

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Many rare metals used in a range of in high-technology and clean energy applications are derived from granitic pegmatites, but debate continues about the origin of these rocks. It is clear that some pegmatites represent the most highly fractionated products of a parental granite body, whilst others have clearly formed by anatexis of local crust. However, the relative importance of these two processes in the formation of rare-metal pegmatites is not always evident.

The Lewisian Gneiss Complex of northwest Scotland represents an area of largely Archaean tonalite-trondhjemite-granodiorite (TTG) gneisses that was highly reworked during accretional and collisional events in the Palaeoproterozoic (the Laxfordian Orogeny). Associated crustal thickening led to melting and the formation of abundant granitic and pegmatite sheets in many parts of the Lewisian Gneiss Complex. The majority are biotite-magnetite granitic pegmatites while a few are rare-metal pegmatites. The latter are mainly intruded into a belt of Palaeoproterozoic metasedimentary and meta-igneous rocks known as the Harris Granulite Belt (HGB).

The rare-metal pegmatites are distinct in their mineralogy, containing garnet and muscovite, with local tourmaline and a range of accessory minerals including columbite, aeschynite-(Y) and beryl. In contrast, the biotite-magnetite pegmatites have biotite and magnetite as their main mafic components. Rare-metal pegmatites also have different bulk-rock and mineral chemistry, including a more peraluminous character and enrichments in Rb, Li, Cs, Be, Nb and Ta. However, the age of these pegmatites (c. 1690–1710 Ma) is within the range of the age of nearby biotite-magnetite pegmatites, indicating the possibility of similar genetic origins.

The peraluminous nature of the rare-metal pegmatites strongly suggests a metasedimentary source. This is consistent with their occurrence being restricted to those areas of the Lewisian Gneiss Complex where such a source is present. The available evidence thus suggests that all the Laxfordian pegmatites are formed by a process of crustal anatexis, with the formation of rare-metal pegmatites being largely controlled by source composition.

Diffusion and partition coefficients of minor and trace elements in magnetite at 1150°C as a function of oxygen fugacity: Implications for understanding the petrogenesis of porphyry ore-forming magmas

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There is increasing interest in the use of magnetite as a petrogenetic indicator to interpret ore forming processes. Trace element concentrations in magnetite vary considerably between different deposit types [1] and can be used as a tool for fingerprinting mineralisation styles and for interpreting primary conditions of crystallisation. However, it is possible that modification of the original magnetite chemistry may occur, particularly in igneous systems, during subsequent disequilibrium (diffusion) processes. Thus, in order to utilise magnetite as a petrogenetic tool, it is important to understand the transport properties of elements within the mineral so that the likelihood and timescales necessary for the trace element chemistry to be influenced by disequilibrium element partitioning can be assessed.

Lattice diffusion coefficients and partition coefficients have been determined for Sc, Ti, V, Mn, Co, Ni, Zn, Ge, Zr, Nb, Mo, Hf, Ta and some REE (Lu, Yb, Tm, Er, Ho, Dy, Tb, Gd) in single crystals of natural magnetite as a function of oxygen fugacity ($\mathrm{FMQ} + 1 \leq fO_2 \leq \mathrm{FMQ} + 3$) at 1150°C and 1 bar, by equilibration with a synthetic silicate melt reservoir. Twelve-hour experiments generated diffusion profiles between 25 to > 200 µm in length, which could be analysed using scanning laser ablation inductively coupled plasma mass spectrometry. Diffusion coefficients, the element concentration at the magnetite-melt interface, and the initial element concentration in magnetite, can be calculated by fitting data from individual element diffusion profiles to the conventional diffusion equation. Additionally, equilibrium magnetite/melt partition coefficients can be extracted using the interface and liquid element concentrations. Diffusion coefficients and magnetite/melt partition coefficients calculated from the data are consistent with those previously reported in the literature [2,3]. Furthermore, we present transport properties for a number of elements in magnetite which until now, have remained unexplored.

Magmatic-hydrothermal ore deposits involve an interplay of hydrothermal and magmatic processes which span a wide range of time periods. In magnetite, diffusion coefficients for different elements can vary by more than 3 orders magnitude. As a result, slower diffusing elements will provide a more robust indicator of the magmatic environment, whereas faster diffusing elements will be more susceptible to modification of the original magnetite chemistry, for example via interaction with a hydrothermal fluid.

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Re-Os age of molybdenites from the Sungun porphyry Cu-Mo deposit, NW Iran, and its temporal relationship with similar occurrences in the Lesser Caucasus and Central Iran

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Neo-Tethyan subduction in Iran is characterized by the Urumieh-Dokhtar magmatic arc (UDMA), which extends from northwest to southeast of Iran over nearly 2000 km and formed by north-eastward subduction of the Neo-Tethyan oceanic crust during the Alpine orogeny (late Mesozoic-early Cenozoic; e.g. [1]). This magmatic belt also coincides with the porphyry copper metallogenic belt of Iran, comprised of several metallogenic zones like Arasbaran and Kerman, which host most of the major and small porphyry copper deposits (PCD) and prospects such as Sungun (NW Iran) and Sarcheshmeh (the largest PCD; central Iran). Sungun PCD is the second largest deposit in Iran with ore reserves of about 850 Mt at 0.62 wt% Cu and 0.01 wt% Mo and probable reserves over 1Gt. The early Miocene ore-hosting porphyry stock with a monzonite-quartz monzonite composition intruded upper Cretaceous carbonates and Eocene volcano-sedimentary rocks. Re-Os dating of molybdenites from this PCD has given ages ranging between 22.9±0.2 to 21.7±0.2 Ma, corresponding to the early Miocene (Aquitanian). On the other hand, the zircon U-Pb dating of the host porphyry stock has given ages of about 22.5±0.4 to 20.1±0.4 Ma [2], which shows that molybdenite mineralization occurred at the early stages of emplacement and crystallization of the host stock, and that both the magmatism and mineralization in Sungun are post-collisional events.

Comparing the ages obtained for molybdenites and the porphyry stock in Sungun with the similar occurrences in adjacent Lesser Caucasus indicates that this PCD is younger than all the dated PCD's and prospects in the Lesser Caucasus (Meghri-Ordubad pluton; MOP), though it coincides with the third metallogenic epoch in the Lesser Caucasus (Eocene to Miocene; [3]). Similarly, it is younger than all dated mineralizations in NW Iran, including Qaradagh batholith (considered as the southward extension of MOP; 31.22±0.28 to 25.19±0.19 Ma) and the neighbouring Haft Cheshmeh PCD (28.18±0.42 to 27.05±0.37 Ma). In this regard, mineralization in Sungun occurred during the second porphyry mineralization event in NW Iran (20-22 Ma). All these data testify to the episodic occurrences of plutonism and mineralization across the Meghri-Ordubad-Qaradagh complex. Meanwhile, mineralization in Sungun is older than all the porphyry Cu-Mo mineralization across the central and SE parts of UDMA (except for Bondar Hanza PCD in Kerman zone with the age of 28.71±0.46 to 28.06±0.47 Ma). Therefore, it indicates that collision between the Arabian and Iranian plates was dischronous, being earlier in NW Iran and later in SE Iran, which can be resulted from the oblique convergence of the plates.

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Host rock effects on epithermal Au-Te mineralisation

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Alkaline magmatic rocks host some of the world's largest epithermal gold deposits, including Cripple Creek (CO, USA), Porgera (PNG), and Ladolam (New Britain, PNG). As well as the high gold tonnage in these systems, alkaline-hosted epithermal deposits have a number of other notable features, including abundant telluride minerals, quartz-poor alteration assemblages, and a paucity of advanced argillic (acid sulfate) alteration. In spite of evidence for direct magmatic-hydrothermal contributions to these systems, there are very few "high sulfidation" type epithermal deposits recorded. Alkaline-hosted epithermal are often considered a distinct sub-class of the low sulfidation epithermal class [1].

Geochemical models using CHILLER [2] were prepared to determine the effect of host rock composition on fluids hosted in alkaline rocks under epithermal conditions (300°C, pressure at vapour saturation). An initial acidic volcanic condensate was progressively reacted with increments of various rock types, including an average andesite composition, and alkaline compositions reported from various ore deposits. The method used follows that of Reed [3].

Results show that alkaline magmas are no more effective at neutralising initially acidic fluids than sub-alkaline equivalents, kinetic effects notwithstanding. However, models show that at low water: rock conditions (e.g. rock-buffered equilibrium) that fluids hosted in silica-undersaturated alkaline rock-hosted systems lose hydrothermal quartz. When quartz dissolves out of the alteration assemblage, important pH buffering reactions break down, and fluids rise to pH values of 7 – 8.2. In contrast, sub-alkaline systems produce abundant hydrothermal quartz and pH is capped at a maximum of 5.5 – 6, with near-neutral chloride fluids.

At high fluid pH (>7) Au and Te are significantly more soluble. Tellurium solubility is at a nadir at pH 5.5 – 6; thus the models demonstrate that host rock silica saturation and alkalinity can explain the paucity of Te and tellurides in most low sulfidation epithermal deposits, but their relative abundance in alkaline-hosted deposits. The host rock effects also boost the capability of the fluid to transport gold, and provide an explanation for the unusual enhancement of mineralisation in alkaline rocks.

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The relationship between emplacement and mineralisation in the Land's End Granite, Cornwall

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The Land's End Granite in Cornwall is associated with three major episodes of mineralisation. These comprise an initial episode of ENE-WSW striking tourmaline ± quartz veins, a second episode of tourmaline veins striking at 280° and a final episode of tourmaline-quartz-cassiterite veins striking at 340° [1]. However, the structural relationship of the Land's End Granite to this mineralisation is poorly understood. This study uses data on mineral veins, igneous foliations, bedding/cleavage planes, granite sheets and fold axes in the area to investigate the structural controls on mineralisation. Preliminary results suggest that mineralisation occurred due to both tectonic controls and emplacement of the granite. The findings are consistent with former work on the Cligga Granite in Cornwall [2], indicating that magmatic controls may have more importance for Cornubian mineralisation than has previously been recognised. Planned further work includes an Anisotropy of Magnetic Susceptibility (AMS) study, which aims to determine micro-scale fabrics and thus provide further insight into the processes of mineralisation.

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The Geological Survey of Ireland: Your source for minerals and geological information on Ireland

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The **GEOLOGICAL SURVEY OF IRELAND (GSI)**, founded in 1845, is the National Earth Science Agency. It is responsible for providing geological advice and information, and for the acquisition of data for this purpose. GSI produces a range of products including maps, reports and databases and acts as a knowledge centre and project partner in all aspects of Irish geology.

GSI is organised thematically with sections dedicated to the various disciplines of geology such as Land mapping, Groundwater, Minerals, Heritage and Marine Geology; and through dedicated Programmes such as INFOMAR (a joint programme with the Marine Institute which is mapping the Irish seabed) and Tellus (ground and airborne geoscience mapping programme collecting geochemical and geophysical data). These are supported by additional thematically organised sections such as Information management, Cartography, Technical services (including drilling) and administration.

Information that is probably of greatest interest to minerals researchers will have been generated within the Land mapping and Minerals Sections and within the Tellus Programme. Increasingly GSI delivers its data digitally via the GSI website (www.gsi.ie). Data may be accessed on the website via map viewers either through the general Public data viewer or via dedicated specialist viewers such as the Aggregate Potential Mapping viewer. These viewers have been designed specifically for newly or recently acquired data. Much of GSI's legacy data (paper records) has been scanned and is available on-line through the GOLDMINE (**G**SI **O**n-**L**ine **D**ocument, **M**aps and **I**nformatio**N** **E**xplorer) application. Images are stored in PDF format and include Mineral data (Exploration reports, Mineral locality reports and Mine record reports and maps); Geotechnical Reports; Historic Geological Maps (at scales of 6":1 mile and 1":1 mile); GSI Publications (Bulletins, Published and Unpublished reports); Groundwater well hydrographs; Marine maps; and Airborne geophysical maps. GOLDMINE has a text based search system and a new map based one to make searching easier. Specifically for non-confidential (six year old reports or reports on surrendered licences no matter how old) company exploration reports the Department's website (www.dcenr.gov.ie) contains a search facility which allows access to reports filed in the GSI and in the Exploration and Mining Division (the sector regulator). Most of the data can be downloaded direct from the websites and is FREE of charge.

GSI also participates in European Commission funded projects and provides data and information for these cooperative projects (for example Minerals4EU – http://minerals4eu.brgm-rec.fr/).

During the presentation several of these valuable datasets will be explained and demonstrated.

Real-time drill core orientation as an aid to effective and dynamic decision making: An example from the Ferensola Gold Project

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The geological understanding of a minerals project during the early stages of exploration is often limited, particularly in areas of poor outcrop. Traditionally the risks associated with planning a drill programme on such projects have been mitigated by extensive grid-style drill patterns. However, these strategies are inefficient, costly and may still miss mineralisation if the drilling pattern is poorly oriented.

With many companies facing smaller exploration budgets in the current market conditions, every metre of drilling is important. The key to maximising return on drilling programmes is good decision making, which in turn requires high quality data that is available in a timely manner. In the past decade, analytical tools such as portable XRF and IR spectrometers have enabled a range of geochemical and mineralogical data to be collected and analysed almost instantaneously. However, none of these tools provide direct information on the geometry of mineralisation which, from a drill planning perspective, is arguably more important than geochemical or mineralogical vectors for most deposit types.

Modern core orientation tools have been available for over a decade now and can provide vital information on the geometry of mineralisation. However, in the authors' experience, this data is usually available too late to be of use and in many cases has significant errors due to insufficient quality control protocols.

In November 2015, a 1500m drill programme was completed at Sula Iron and Gold's Ferensola Gold Project in Sierra Leone. Due to a thick regolith cover there is no outcrop and thus information on the geometry of mineralisation was very limited prior to the commencement of diamond drilling. Processing of the oriented drill core and structural logging was completed on-site as drilling progressed, so that structural data and preliminary logging were available prior to the completion of a drillhole. This data was then assessed using advanced 3D modelling software and planned drillholes were modified as needed.

Critical aspects of this process included:

- High quality core, which in turn required effective and timely communication with the drilling contractor so that issues could be addressed as they happened.
- Rigorous quality control procedures and a system for assessing the confidence associated with the orientation line at any particular depth.
- An understanding of both how the orientation tool works and how the drill rig works, so that the source of any error can be identified and rectified.
- An understanding of how various structures that can be observed in drill core are likely to relate to mineralisation in terms of both orientation and timing.

This approach led to the successful definition of a complex mineralised shear zone with significant strike length. These results demonstrate how modern core orientation tools, coupled with best practice quality control protocols and structural interpretation can provide a valuable tool for assisting dynamic decision making; reducing drilling costs and maximising exploration value.

Sulphide mineralogy, geochemistry and textures at the Flatreef deposit, northern limb, Bushveld Complex, South Africa

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The Ni-Cu-PGE mineralisation of the Platreef on the northern limb of the 2.06 Ga Bushveld Complex is currently mined *via* open pit methods at Anglo Platinum's Mogalakwena mine. This represents the World's largest PGE producing mine exploiting a tabular pyroxenite orebody, dipping at 15 - 60° [1].

Along strike and down-dip of this world-class mine is the Flatreef deposit, located on the farm Turfspruit 241KR and owned by Ivanplats, with a defined Indicated mineral resource of 214 Mt @ 4.1 g/t 3PGE + Au using a 2g/t cut-off grade [2]. The orebody is flat to gently dipping at depths of between 700 and 1,100 metres (below surface) with a strike length of 6 km. This geometry and relatively shallow depths permit extraction by low-cost, mechanised underground mining methods and as such represents a 'game changer' for the platinum mining industry on the northern limb.

This study deals with petrographic observations on the sulphide mineralogy and texture with quantitative data on their composition and PGE content collected by LA ICP-MS. Previous studies at Turfspruit [3, 4] were conducted on near-surface, highly contaminated Platreef and reveal a strong decoupling of PGE from the sulphide minerals. In contrast, the focus of this study is on the deeper section of Platreef known as the Flatreef, which preserves a cyclic magmatic-layered stratigraphy interpreted as analogous to the Upper Critical Zone (UCZ) [5]. As such, the Flatreef should retain an orthomagmatic style of mineralisation currently best understood by chalcophile PGE deposit models [6] and a strong spatial coupling ought to be expected between PGE and base metal sulphides.

Initial observations on the sulphides have shown that a typical magmatic sulphide assemblage of pyrrhotite, pentlandite and chalcopyrite dominates the Flatreef deposit. Sulphide minerals throughout the succession typically represent <5 modal % (over 30 cm intervals) although on smaller scales (centimetres) they may contribute up to 25 modal %. The majority are present as medium-fine grained fractionated blebs located interstitial to orthocumulate silicates. However massive, disseminated and monomineralic sulphides with several types of textures and different mineral proportions are present in some sections. Sulphide alteration varies within a single thin section from relatively fresh to pervasive replacement to secondary silicates by predominantly felsic fluids and to magnetite by serpentinising fluids (c.f. [7]).

Ongoing LA ICP-MS measurements will test the expected orthomagmatic processes and suggested links with the UCZ.

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Blue Mining: What drives hydrothermal systems and how does it vary over time?

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Seafloor hydrothermal activity has been an active area of research over the last 35 years, since the discovery of the first active hydrothermal vent and the observation of massive sulphide (SMS) deposit formation on the seafloor. Since then, over 500 hydrothermal systems have been indicated worldwide, of which around 165 have been confirmed and are associated with SMS deposits [1]. These SMS deposits are thought to represent the modern analogue for ancient volcanogenic massive sulphide (VMS) and often show geological and mineralogical commonalities between the systems. However, relatively limited three-dimensional information on modern SMS deposits has been obtained to date due to their extreme environment, in comparison to the more easily accessible obducted ancient analogues.

The TAG mound, within the TAG hydrothermal field at 26° North, on the slow spreading mid-Atlantic ridge, is one of the most well studied active hydrothermal fields. Multiple research drilling cruises have been undertaken by the Ocean Drilling Programme (ODP), targeting the TAG hydrothermal field and TAG mound (Leg 158, 1994). Assessment of the active TAG mound estimated a mineral resource of 2.9×10^9 tonnes [2]. It is considered to be comparable geologically and economically to ancient 'Cyprus-type' VMS deposits.

This PhD project aims to combine information from currently known active hydrothermal systems, such as the TAG mound, with new data obtained from a research drilling cruise in 2016 targeting the 'recently' extinct SMS deposits on the Mid-Atlantic Ridge: namely the MIR and ALVIN zones. The extinct SMS include mounds the size of TAG but have been inactive for between 10ka and 100ka. The purpose of the study is to develop our understanding of the processes that modify SMS systems after hydrothermal circulation has ceased and cold oxygen-rich seawater starts to circulate through the subsurface. The research cruise will also enhance our understanding of the 'recently' extinct hydrothermal systems, and provide information for the potential future exploration and exploitation of this type of resource.

The project forms part of the European Commission funded "Blue Mining" programme, which aims to provide breakthrough solutions to enable sustainable and responsible deep sea mining.

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What can we learn from the trace element composition of silicate minerals in the Bushveld Complex?

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The Bushveld Complex is world's biggest layered mafic intrusion and the greatest known repository of platinum-group elements on Earth. In order to understand the evolution and emplacement of this colossal deposit, we analysed the abundance of 57 trace elements in plagioclase, pyroxene and olivine across the 3-km Bellevue Core that traverses the Upper Zone and Main Zone of the Northern Limb of the Bushveld Complex. These data permit the first comprehensive investigation of trace element distribution in the Bushveld Complex on a mineral-by-mineral basis.

Our data provide unexpected results. Firstly, the Cr content of pyroxene is the *only* proxy to record three cryptic magma injections, coincident with two pyroxenite horizons and the Upper Zone-Main Zone boundary. On the basis of Cr abundance, we infer the 'anomalous' troctolitic horizon at the base of the Bellevue Core was related to injection of relatively primitive magma, analogous to Lower or Critical Zone magmas in the Eastern and Western Limbs of the Bushveld Complex; this horizon defines the greatest inconsistency of magmatic stratigraphy between the Northern vs. Eastern and Western limbs of the Complex, and our data suggest it is very prospective for platinum-group element exploration.

However, the most significant finding of this study is that plagioclase, pyroxene and olivine have undergone extensive diffusive modification. The major and trace element geochemistry of these minerals record sub-solidus equilibration during the prolonged cooling of the Bushveld Complex, controlled by diffusion rates and local partitioning between adjacent minerals. By analogy, texturally mature cumulates in any layered intrusion are likely chemically re-equilibrated as well. This has important implications for which elements to trust in the exploration of magmatic ore deposits, as subsolidus equilibration obscures primary igneous processes.

A zircon perspective on magma dynamics leading to porphyry copper deposit formation

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Understanding the physical and chemical processes within the long-lived magmatic systems that underlie and feed porphyry copper deposits is essential to our conceptual models of how and when mineralisation occurs. The thermal evolution of the upper-crustal magma storage environment, prior to porphyry emplacement, is one critical aspect. It exerts key controls on: 1) magma mobility and ability to transport ore-forming components to shallower crustal levels; 2) the timing of volatile saturation; and 3) the style of magma interaction upon recharge of less evolved (S-rich) magmas.

Time-constrained thermal information is difficult to obtain owing to the dynamic nature and inherent vertical distances of the magmatic systems. However, due to the low-diffusivity of zircon and its protracted crystallisation within silicic magmatic systems, high-precision ID-TIMS U-Pb zircon geochronology in combination with Ti-in-zircon thermometry can be utilised to reconstruct temperature-time paths of magma within the deeper plutonic system preceding porphyry emplacement [1]. Linked with Rhyolite-MELTS [2] modelling, Tapster et al. (2015) [1] demonstrate that the parental magmas at the Koloula Porphyry Prospect were stored within a rheologically locked, volatile saturated state for extended ($\sim10^4$ yr) periods prior to porphyry formation. Porphyry emplacement and initiation of magmatic-hydrothermal systems occurred in response to brief ($\sim10^2$–10^3 yr) episodes of thermal rejuvenation of the magma, likely driven by volatile injection rather than by extensive magma mixing.

Here, further insights are drawn from a global compilation of Ti-in-zircon thermometry from silicic arc magmas – both with and without associated porphyry deposits. Temperatures from mineralised porphyry intrusions demonstrate comparable low-temperature characteristics. Given that a large volume of zircon crystallisation is likely to have occurred over 10^4–10^5 yrs prior to emplacement of their host porphyry; it indicates that porphyry copper deposit formation, in general, is unlikely to occur in response to the single path of emplacement, cooling and crystallisation of a large melt body. Rather, it suggests that melt extraction from a rheologically-locked, highly permeable, volatile-saturated deeper silicic pluton may be a requisite of porphyry mineralisation. In order to attain these conditions, it suggests that episodes of porphyry formation are favoured by periods of low magma flux within the 10^5-10^6 yr life-times of their host systems.

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All This is Yours:
The Natural History Museum's Ore Collection

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The Natural History Museum's Ore Collection has its roots in the Museum of Practical Geology which was founded in 1838 by Sir Henry de la Bêche. Since then, the collection has grown to over 16,000 specimens acquired from mineral deposits around the world. It consequently preserves a unique historical record of global mining activities.

This presentation introduces the Museum's Ore Collection to its main stakeholders, advocating its value as a reference and resource to the economic geology community and encouraging its enhancement through research, donations and outreach.

Controls on ore mineralisation at the Nkana Cu-Co deposit, Zambia

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The Nkana sediment-hosted copper−cobalt (Cu-Co) ore deposit is part of the Central African Copperbelt in D.R.Congo and Zambia. The Copperbelt is the largest and highest-grade sediment-hosted Cu-Co producing metalliferous province in the world. Ore mineralisation at Nkana is mainly hosted in the 15−20 m thick Copperbelt Orebody Member (COM), part of the Neoproterozoic Katanga Supergroup. These rocks were deformed during the Lufilian orogeny.

The ore occurs mainly as chalcopyrite and bornite that is disseminated, in diagenetic nodules and lenses and in various generations of veins. In this study we attempt to understand structural controls on ore mineralisation and investigate links between deformation structures, vein formation and fluid redistribution processes.

Significant lateral lithofacies changes are recognised in the COM, ranging from an argillaceous dolomite in the north, towards a carbonaceous mudrock in the south. A regional structural analysis of several open pits and underground mine sections shows that deformation at Nkana was mainly through NE-SW oriented parasitic folding on multiple scales with little evidence for large scale faulting. Folding in the COM and surrounding formations is tight to isoclinal, in non-cylindrical elongate periclinal geometries. These folds are often arranged en echelon and interfere laterally, leading to fold linkage structures and bifurcation of folds. A strong structural and rheological control is identified on Cu−Co mineralisation during folding.

Nine vein generations were identified in the carbonaceous mudrock lithofacies of the COM and a microstructural and vein fabric study was carried out to place these vein generations in the geological history. In particular, high densities of pre-folding bedding-parallel fibrous dolomite veins are present. These veins were subsequently folded as a single-layers or as dis-harmonic or poly-harmonic multilayers. During folding of these bedding-parallel veins, syn-folding dolomite and quartz veins formed together with significant Cu-Co ore mineralisation. The veins often formed in accommodation structures, indicating the creation of enhanced transient permeability during folding. Several later vein generations, syn- to late-kinematic with respect to compressional deformation, are also strongly mineralised. There was hence prolonged and intense veining in the carbonaceous mudrock lithofacies at Nkana during various stages of the Lufilian orogeny.

Neoproterozoic basement structures control New Guinea deep structure

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A regional synthesis and re-evaluation of the deep crustal structure in western New Guinea has identified Neoproterozoic normal faults and transfer structures in the crystalline basement of the Australian Plate. Cenozoic reactivation of these structures appears to control the location and orientation of brittle-ductile structures formed during the Central Range Orogeny.

The island of New Guinea is the emergent part of one of the most tectonically complex places on the Earth's surface. Three major plates and more than a half-dozen microplates interact in a continent-ocean collision zone that has been evolving since the Oligocene. Although the collision zone in western New Guinea strikes predominantly east-west, northeast-trending fault structures are also prominent. Of these, the Gauttier Offset can be inferred to pass from the Gauttier Mountains in the north of Papua Province of Indonesia 300 km south to the Mapenduma Anticline. Comparison with the orientations and scales of Neoproterozoic basement structures developed in the Arafura Sea, north of Australia, and the strike and location of basement lows in new reflection seismic maps of Neoproterozoic basement south of New Guinea, suggest that the Gauttier Offset may be a northeast-trending reactivated Neoproterozoic extensional fault. Neoproterozoic extensional faults in the Arafura Sea show domains of opposing extension-polarity bound by east-west transfer structures.

Similar structural relationships may be inferred in New Guinea associated with the Gauttier Offset and other parallel structures, although here, possible Neoproterozoic transfer structures are reactivated as more recent west-northwest-striking, strike-slip faults. The zone of intersection between west-northwest-striking faults and the Gauttier Offset coincides with the location of Pliocene magmatism and mineralisation; the fault intersection appears to provide a structural control for emplacement of magmatic rocks. Other northeast trending faults and lineaments are evident in Papua Province, east and west of the Gauttier Offset structure, and in Papua New Guinea.

Given the possible origin of these structures as reactivated Neoproterozoic basement faults, northeast-striking faults and alignments are likely to have a deep-seated control on east-west variation in Mesozoic and younger stratigraphic thickness, the location and depth of pre-Mesozoic basins, and magma pathways to shallow crustal levels. This has implications for mineral exploration and the development of petroleum source rocks and reservoirs. Recognition of Neoproterozoic basement control in Cenozoic structural evolution represents a first order re-evaluation of the deep structure of New Guinea.

Investigating erosion of the Dolgellau Gold Belt, mid Wales, through sediment collected from the Mawddach River and Mawddach Estuary

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The Mawddach Estuary in mid Wales has been considered as a candidate for an economic gold placer deposit [1]. Gold located within this estuary is thought to have been derived from quartz-gold veins situated within the catchment of the Mawddach River. This area is referred to as the Dolgellau Gold Belt (DBG). The current study investigates the composition of sediments collected from various locations along the Mawddach River and from the Mawddach Estuary. Composition has been determined through X-ray fluorescence (XRF) and optical microscopy. Preliminary results record no gold but allow the downstream abundance of material derived from the DGB to be modelled. Modelling suggests that there is a general downstream increase in sediment maturity and decrease in DGB-derived lithic fragments. However, dense igneous minerals have been recorded in the most distal parts of the Mawddach Estuary, suggesting that material from the DGB may concentrate in these areas. Further work aims to use the results of this study as a predictive tool for determining where gold placers associated with the DBG may locate, thus honing the search criteria for such deposits both here and within similar settings throughout the world.

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Chlorite chemistry as a new exploration tool in the propylitic halo of porphyry-epithermal systems: A case study of the Batu Hijau porphyry Cu-Au system, Indonesia

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Intrusion-centred mineral districts host many major ore deposits of diverse styles and metal associations, primarily porphyry and epithermal types. The characteristically zoned hydrothermal alteration and geochemical dispersion associated with these deposits have long been important tools for exploration. However, the mineral assemblages, textures and geochemical signatures that characterize each zone may also be present within barren hydrothermal systems, or produced by other processes such as regional metamorphism. Discriminating mineralized and barren systems, being able to locate strongly-mineralized hydrothermal centres, and recognizing the distal footprints of ore-grade mineralization continue to be great challenges to the minerals industry.

In the ‘green rock’ environment of propylitic alteration, alteration intensity decreases markedly outside the visible sulphide halos so that conventional geochemical and geophysical techniques struggle to detect proximity to mineralization. Recent work, part of a series of AMIRA projects led by the University of Tasmania, has developed new tools for exploration in this domain based on the trace element chemistry of propylitic minerals. Chlorite, in particular, has proven to be a key recorder of trace element dispersion and intensive parameters in the propylitic environment, providing a tool for vectoring towards the centre of mineralized systems and even for predicting absolute distances from ore[1].

Here, we summarise the main findings of this study, which was based on SEM-EDS and laser ablation ICP-MS analyses of chlorite chemistry from 80 samples from the propylitic halo of the world class Batu Hijau Cu-Au porphyry deposit in Indonesia. The current take-up of this methodology within the exploration industry and barriers to its wider applicability are considered.

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Actively forming Kuroko-type VMS mineralization at Iheya North, Okinawa Trough, Japan: new geochemical, petrographic and $\delta^{34}S$ isotope results

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In 2010, Integrated Ocean Drilling Program (IODP) Expedition 331 drilled five sites in the Iheya North hydrothermal field in the central Okinawa Trough back-arc basin, Japan. Hydrothermal alteration and sulfide mineralization is hosted in a geologically complex, mixed sequence of coarse pumiceous volcaniclastic and fine hemipelagic sediments, overlying a dacitic to rhyolitic volcanic substrate. At site C0016, located adjacent to the foot of the actively venting North Big Chimney (NBC) massive sulfide mound at a depth of 985 metres below sea level (mbsl), massive sphalerite-(pyrite-chalcopyrite±galena)-rich sulfides were recovered (to 30.2 % Zn, 12.3 % Pb, 2.68 % Cu, 33.1g/t Ag and 0.07 g/t Au) that strongly resemble the black ore of the Miocene-age Kuroko deposits of Japan. Sulfide mineralization shows clear evidence of formation through a combination of surface detrital and subsurface chemical processes, with at least some sphalerite precipitating into void space in the rock. Underlying volcanic rocks exhibit quartz-muscovite/illite and quartz-Mg-chlorite alteration, characterised by increasing MgO, Fe/Zn and Cu/Zn with depth.

Site C0013 (~1030 mbsl), ~100 m east of NBC, represents a likely location of recent high temperature discharge, preserved as surficial coarse grained sulfidic sediments (43.2 % Zn, 4.4 % Pb, 5.4 % Cu, 42 g/t Ag and 0.02 g/t Au) and containing high concentrations of As, Cd, Mo, Sb, and W. Near surface hydrothermal alteration is dominated by kaolinite and muscovite with locally abundant native sulfur, indicative of acidic hydrothermal fluids. Alteration grades to Mg-chlorite dominated assemblages at depths of >5 metres below sea floor (mbsf). At site C0014 (~1055 mbsl), ~150 m farther east, hydrothermal assemblages are characterized by illite/montmorillonite, with Mg-chlorite present at depths below ~30 mbsf.

Mineralization and alteration assemblages are consistent with the Iheya North system representing a modern analogue for Kuroko-type VMS mineralization. Fluid flow is focussed laterally along pumiceous volcaniclastic strata (compartmentalized between impermeable hemipelagic sediments), and vertically along faults. The abundance of Fe-poor sphalerite and Mg-rich chlorite (clinochlore/penninite) is consistent with the lower Fe budget of felsic-hosted hydrothermal systems worldwide. $\delta^{34}S$ values in pyrite are similar to NBC vent fluids, decreasing systematically away from the main hydrothermal mound in Mg-chlorite altered lithologies. No systematic variation in $\delta^{34}S$ was observed with depth, other than in the uppermost (i.e. least altered and coolest) levels at site C0014, where the influence of hydrothermal activity is considered to be minimal.

Using radioelement distributions to classify a composite granite batholith in the South West England Orefield

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The South West England Orefield is well-known for its polymetallic magmatic-hydrothermal mineralisation associated with the composite Cornubian granite batholith. The mineralisation contains elevated concentrations of a range of metals (e.g. W, Sb, Bi, As, Be, Cd, Ga, Ge, In, Li, Nb, Ta) used in high-technology and clean energy applications and for which security of supply concerns exist [1,2,3]. Exploration for these elements requires improved understanding of the spatial distribution of granite types and their relationship to the different mineralisation styles and parageneses. Previous granite classifications defined granite types based on mineralogical and/or textural observations from field sampling [e.g. 4]. However, these divisions over simplify mineralogical variation (e.g. micas), and the sample density is inadequate to reflect the heterogeneity of the batholith. Classifications based on whole-rock geochemistry, provide a more objective classification method [e.g. 5] and can guide mineral exploration, particularly in poorly exposed areas.

The Tellus South West Survey collected airborne radiometric data over the surface extent of the granites. This continuous sample set has allowed us to produce a 'geochemical' classification of the granites using potassium, thorium and uranium concentrations calculated from gamma-ray emissions. The gridded data were manipulated as ratios and relative abundances [6]. Principal Component Analysis was used to reduce noise from spurious pixels associated with high water content in peat. These spurious pixels were subsequently removed using a 'supervised' classification (Minimum-Distance). The data were standardised to zero mean and equal variance.

An 'unsupervised' classification (K-means) was used to automatically and objectively classify the remaining data in 9-dimensional space (based on the input variables). Six classes were found to be optimum for delineating geochemical variations within the granites. Here, we present this new classification of the granites using continuous data covering the whole batholith. We also consider how to incorporate ground-based geochemical and satellite multispectral (Landsat) data into the classification.

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