UNIVERSITY OF LEICESTER

Mineral Deposits Studies Group

44th Annual Winter Meeting

4-6 January 2023, Leicester

ABSTRACT VOLUME

Edited by:

Erin Thompson, Kate R Canham and Daryl E Blanks

ZEISS BHP Addison Mining Services MSA Mining Consultants UK Society for Geology Applied to Mineral Deposits Oxford Instruments Geodex Consultants Ltd Evident Olympus Optiva Resources srk consulting Peak Nickel Ltd. Halliburton micromine AMG RioTinto

ABSTRACTS

Abstracts of all talks and posters are arranged in alphabetical order of first author, or, by presenting author if they are not listed as first author.

To cite this volume:

Abdulkadir AM, Basu S, Downes H, Verchovsky AB, Beard AD, Jourdan AL, McFall K, Jones AP. 2023. Magmatic evolution and Rare Earth Element enrichment of the Loch Borralan carbonatite complex, Scotland. *In*: Thompson E, Canham KR, Blanks DE (Eds.) Abstract Volume, Mineral Deposits Studies Group, 44th Annual Winter Meeting, University of Leicester, 3.

Note

These abstracts will also be fully published with a citable doi (unless otherwise requested by the authors) in a volume of Applied Earth Science (Transactions of Institutions of Mining and Metallurgy B) later in 2023.

Magmatic evolution and Rare Earth Element enrichment of the Loch Borralan carbonatite complex, Scotland

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The Loch Borralan complex is located in the Assynt district in the N.W. Scottish Highlands. It is the only silica-undersaturated alkaline complex that exhibits some of the most 'exotic' and diverse rock-types of all the Caledonian alkaline intrusions in the British Isles [1]. We present results from an integrated mineralogical, geochemical and isotopic study to constraint the different magmatic components in these rocks. Based on this study, Loch Borralan carbonatite is genetically linked to glimmerite and carbonated glimmerite, either by fractional crystallisation of carbonated silicate parent or liquid immiscibility. For the first time, we report rare earth-rich minerals from Loch Borralan carbonatites, including bastnaesite, synchysite, ancylite, monazite, zirconolite, titanite, baddeleyite and REE-rich ilmenite. Stable isotope studies ($\delta^{18}O$ and $\delta^{13}C$) confirm that Loch Borralan carbonatite is mantle-derived with average value of -4.5 ‰ for $\delta^{13}C$ and +9.5 ‰ for $\delta^{18}O$. Stepwise vacuum-crushing data for nitrogen and argon isotope composition and element ratios indicate multiple generations of magmatic fluids, released at different crushing steps [e.g., 2, 3]. In this study $^{40}Ar/^{36}Ar$ ratios in calcite range from atmospheric to ~ 5000, and $\delta^{15}N$ values range from 0 to +9.4 ‰ indicating a significant contribution of crustal fluids either from the host Archean rocks or as a result of subduction. The carbonatite is characterised by an additional late stage fluid that introduced atmospheric argon and crustal nitrogen identified from their distinct N and Ar isotopic signatures. The measured argon and nitrogen isotopic ratios and elemental abundances clearly suggest mixing between mantle and crustal components, which may suggest the introduction of REE in late-stage magmatic processes.

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Scale Invariance in Ore deposits; a method to quantify nugget effect

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The short-range variability (nugget) component of ore deposits is a poorly understood but vital component of a mineral resource. At the current time, the variograms produced to describe grade relationships throughout the deposit simply ascribe a proportion of grade variation to an unquantifiable nugget component.

The author proposes that a definition of short-range grade variability can be provided by analysis of the scale-invariance inherent in all ore-bodies. By using a mathematical method that incorporates measurement ratios to define a fractal dimension for the ore deposit, this leads to a tightly constrained quantification of the short-range grade variability / nugget component.

The author has developed a method for showing a minimum sampling density based on sample-block distance in block models, which can then be used to experimentally determine the fractal dimension that underpins the distribution of mineralisation in the deposit, and its relationship to sampling density.
Once the shape of a curve relating sampling density to grade has been modelled, a minimum sampling density can be defined on a deposit-type, and on a commodity-by-commodity basis.

There are multiple applications for this method, including:

- Basis for classification of multi-element mineral deposits
- Quantification of parameters for restricted area kriging, and other methods for estimating nuggety deposits.
- Basis for Monte-Carlo simulation of grade distribution
- Applications in quantifying dilution

The author hopes that with further development, this can become an industry-wide rapid method for assessing estimation confidence.

Investigating precious and critical metal deportment in porphyry-epithermal transition of the Muratdere porphyry Cu-Mo-Au deposit, Turkey

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Porphyry Cu deposits (PCDs) are known to concentrate the highest copper reserves in the world, as well as sourcing precious (Au, Ag) and critical (Se, Te) metal by-products. Expanding source diversification of commodities is essential to fully implement the net-zero carbon transition, and to sustain their increasing global demand. Understanding the source and mechanisms of transports and deposition of precious and critical metals in PCDs is fundamental to guide energy-efficient processing methods, and to shed light on deportment and remobilisation of metals in these systems.

Samples sourced from the Muratdere Cu-Mo-Au deposit (Turkey) were examined through detailed petrography and microscopy, with a particular focus on precious (Au, Ag) and critical (Te, Se) metals. Analysis of assay data showed the late stage polymetallic veinset (V5, [1]) to have the highest Au, Ag and Se concentrations, with less Au present in earlier hypogene porphyry veinsets. V5 veins consist primarily of quartz-barite-sphalerite-galena-pyrite-chalcopyrite, and LA-ICP-MS analysis has shown Au and Te to be below detection in V5 pyrite, sphalerite and galena, with up to 400 ppm Ag and Se present in galena [2]. Preliminary SEM-EDS analysis of V5 vein samples confirmed the presence of Au-Ag alloy (electrum), as ~2 µm droplets hosted in arsenious pyrite. An isolated Cu-Au alloy disseminated in quartz phenocrysts was also found in association with bornite. Minor Ag-, Sb- and As- bearing tennantite–tetrahedrite (fahlore) minerals were also observed, often associated with galena.

These findings suggest an ore mineralogy analogous to a late hypogene hydrothermal deposit such as low temperature Ag-Pb-Zn deposits, rather than traditional porphyry stock. This might indicate that V5 veins are preserving the transitional stage between porphyry and intermediate sulfidation epithermal deposits, while overprinting the primary ore, and that late stage low-temperature fluids remobilised Au, Ag and Se from the hypogene porphyry-stage veins.

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Adapting our traditional geoscience workflows and skillsets to cope with a data tsunami

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The size of geoscientific datasets used in exploration and orebody modelling are growing at a rapid rate. However, commonly, the industry has still been interpreting them using manual, somewhat subjective and outdated processes.

Rio Tinto Exploration (RTX) experienced its first tsunami of data through the discovery and delineation of the Winu Cu-Au deposit. This was in part because the vast majority of RTX samples now have >200 channels of information (geochemistry, spectral, petrophysical, geological meta-data). The desire to process this data in compressed timeframes, with increased value realisation, and with a workforce of varied backgrounds and experience, forced changes in data handling and interpretation practises.

Some examples of step changes in interpretation methods are automated lithogeochemical prediction and supervised labelling of core imagery to consistently identify textures of interest. These products mean that Rio Tinto has an objective deposit-scale geological and sulphide-vein classification model, which has had an impact on the resource modelling process and our understanding of the orebody. Close collaboration with service providers has been critical in achieving these objectives.

Looking towards a future where mineral exploration and mining must become more efficient and effective in order to deliver sustainable resources at the lowest possible cost to the environment and our communities, the authors would like to pose two key questions. How can Rio Tinto partner with the broader geoscience and data science community across industry, academia and government to:

1. *Develop solutions for extracting deeper, objective, real-time insights from our geoscience data?*

2. *Ensure future graduates entering the industry are equipped with the necessary skillsets required to harness the energy of the tsunami?*

Stratigraphic constraints on the Per Geijer iron ore bodies

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Human civilisation has been built upon iron, especially since the industrial revolution. Today, 98% of iron ore mined is used for making steel. However, there is a need to use new low-carbon technologies such as Direct Reduced Iron (DRI) steel-making processes, which uses green hydrogen as a reducing agent instead of metallurgical coal and other fossil fuels. This means that carbon emissions from steel production will drastically decrease. A requirement of DRI is high-quality iron ore (>67% Fe) with minor impurities. Worldwide, only 4% of the global iron supply is suitable for this purpose and therefore, there is an increased demand to secure future DRI-quality Fe-ore supplies.

This study focuses on the Per Geijer iron ore deposits, situated northeast of the DRI-grade iron ore deposit of Kiirunavaara. The genesis of Kiruna-type magnetite bodies continues to be debated and consequently, this complicates exploration of such resources. The Per Geijer deposits sit stratigraphically higher than the Kiirunavaara deposit and are hosted within a volcanic-sedimentary pile of the Matojärvi Formation. This study aims to identify the stratigraphic constraints of the Fe-mineralisation within the upper volcanic-sedimentary pile to determine the lateral continuity across field outcrops and drill core.

Using a combination of field outcrops and core logging, initial observations from stratigraphic correlations across the Per Geijer area indicate a barren andesitic unit/s surrounded by mineralised sediments. It varies in thickness and occurrences within the pile but can be potentially used as a marker horizon. This needs further investigation using mineral relationships in thin sections and scanning electron microscopy, alongside assays by lithium borate fusion, to determine the elemental fingerprint of this unit/s and whether it is geochemically distinct across the pile. By understanding the key stratigraphic units within the Matojärvi Formation, it can help decipher the timing and relationship of the side-rocks to Fe-mineralisation and focus future exploration efforts.

Remobilisation of chalcophile elements in the mid-crust

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Gold (Au), copper (Cu), and tellurium (Te) mineralisation is closely associated with syn- and post-subduction, alkali to calc-alkali magmatism [1]. This Au-Cu-Te enrichment is thought to be controlled by a combination of processes that occur through the lithosphere, including metasomatic enrichment of the mantle source, partial melting in the mantle source, melt fractionation, sulfide saturation, sulfide dissolution and hydrothermal enrichment/fractionation [2,3]. These processes can lead to the formation of a mineral deposit, and critically can also explain why a system may fail.

Mid-crustal magma chambers are a key stage in the sulfide journey from mantle to deposit in syn- and post-subduction settings. Sulfide inclusions in cognate xenoliths from The Gate (Colorado, USA) provide a window into the processes of sulfide saturation and dissolution at a mid-crustal level. Cognate xenoliths (0.5 – 3 mm diameter) in the Lake Fork andesite (Early Tertiary) from the central San Juan Volcanic Field, Colorado, are comprised of clinopyroxene, magnetite, and minor feldspar and orthopyroxene. Within the clinopyroxene and magnetite are sulfide inclusions (~ 0.03 mm) of pyrrhotite, chalcopyrite, pyrite, and minor pentlandite.

Primitive mantle normalised chalcophile element profiles from laser ablation analysis of these inclusions are typical of mid-crustal sulfide signatures [3], with a positive slope from Ni to Pd, and a downward inflection in Au-Cu-Te. These chalcophile elements, which have lower $D_{sul/sil}$ values than PGE, are posited to have redissolved and remobilised back into the silicate melt from the immiscible sulfide melt. This may have occurred during ascent and depressurisation of the magma [4], or a replenishment of melt into the mid-crustal magma chamber over the long-lived San Juan batholith [5]. The silicate melt becomes enriched in Au-Cu-Te, and are therefore primed for fluid exsolution at shallow, porphyry-epithermal levels. Sulfides in mid-crustal magma chambers are key indicators of sulfide saturation and dissolution in syn- and post-subduction magmatism, and can be used to determine the likelihood that a magmatic system can lead to a mineral deposit.

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Mobilising 'immobile' elements: implications for critical metal transport in saline systems in the Congolese Copperbelt

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Kyanite, the high-pressure Al2SiO5 polymorph, is traditionally considered a high-pressure, high-temperature mineral. Common kyanite-forming reactions such as pyrophyllite or chlorite dehydration take place at ~ 400°C and >600°C respectively[1,2]. In this study, kyanite is observed within low temperature (sub greenschist facies) carbonates and carbonaceous siliciclastic lithologies hosted in post-evaporitic breccia. Kyanite occurs within hydrothermal kyanite-quartz-magnesite-chalcopyrite-monazite veins, within fractures associated with quartz + pyrite and as porphyroblasts in host rock lithologies. The occurrence of kyanite in low pressure-temperature rocks indicates unusual conditions of kyanite growth. Cathode luminescence, laser ablation mass spectrometry, raman spectroscopy and U-Pb monazite dating are used in this study to unravel the complex vein paragenesis and characterise the multiple textural generations of kyanite.

The Central African Copperbelt (CACB) is the world's primary source of copper and cobalt, producing about 70% of the metal which is critical for the production of batteries needed to help decarbonise our societies[3]. Highly saline fluids are associated with extensive mineralisation and alteration in the CACB[4]. Intimate association of kyanite-bearing veins and Cu-sulphide mineralisation indicates that the unusual thermodynamic conditions facilitated the mobility of traditionally immobile elements such as Al, Ti and Ge, as well as mobilising technology metals such as Cu. Co and Ni.

Understanding the paragenesis of kyanite in relation to Cu, Ni and U mineralisation at Menda, as well as the unusual thermodynamic conditions required for low-temperature kyanite growth and Al-mobilisation, has implications for the exploration for technology metals in the CACB, as well as metal mobility in highly saline systems. Additionally, the interpretation of the vein kyanite-copper-bearing assemblages in the higher grade metamorphic Domes region of the Zambian Copperbelt is called into question.

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Predicting tech-metal abundances in ore deposits: can mineralogically associated predictors be used to estimate abundances of technologically essential but rarely reported resources

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Modern industry and digital technologies are utilising a greater diversity of elements than at any other point in human history. Over 60 elements are considered critical to ongoing operation of our technological and economic infrastructure. The technology metals are a group of elements possessing unique chemical characteristics that make them key enablers for many established and emergent technologies including those supporting a low carbon energy transition. Production of many technology metals occurs as a by-product of the refining of major industrial and precious metals. This makes their supply dependant on the demand for other metal commodities. The supply dependency of these essential elements on external production chains and economic pressures, combined with the broadly uneven geographical distribution of mineral deposits, has resulted in many technology elements being included in the criticality lists of major industrialised nations. Securing long-term supplies of these metals has become a focus of national resource strategies and two viable strategies have been proposed; 1) identifying and developing new resources rich in technology metals or, 2) optimising by-product recovery and material efficiency in existing mines.

Accurate resource models for the technology elements will be essential in securing long-term supplies. However, these are currently unavailable, with existing models being back-calculated from production estimates. Current resource reporting practices focus on high value major and precious metal commodities, whereas resource estimates for technology metals are rarely reported in to the public domain. Here we utilise open-source ore composition data from a range of deposit types and examine the effectiveness of machine learning tools as a method for predicting the technology metal concentrations in existing ore deposits. Preliminary results indicate tech-metal geochemical suites can discriminate between different ore forming processes and that technology metal abundances in ore samples can be estimated based on mineralogically associated predictors.

Alteration products of seafloor massive sulphides: A source of base and critical metals?

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Metal resources in deep-sea mineral deposits could make a major contribution to future global raw material supply. Requirements to reduce carbon emissions may result in deep sea mining within the next decade as these deposits have little to no overburden and cause significantly less deforestation.

While the metal budget of deep-sea sulphides has been extensively studied, the fate of metals during seafloor weathering remains poorly constrained. It is uncertain if metals contained in sulphide minerals, such as Cu, Au, and Co, are lost from the primary minerals during seafloor weathering or are potentially stored in alteration products such as Fe-oxyhydroxides, forming supergene gossans.

42 samples of Fe-oxyhydroxides and massive sulphide were collected at Semyenov hydrothermal field, an extinct, ultramafic hosted, Seafloor Massive Sulphide (SMS) system at the Mid-Atlantic Ridge. The Fe-oxyhydroxides occur as various morphologies including: chimney, layered, massive, brecciated, ocherous and ochre.

Some Fe-oxyhydroxides exhibit supergene enrichment in metals compared to massive sulphides collected. Brecciated Fe-oxyhydroxides and ochre contain a median grade of 1.3 wt.% Cu and layered morphologies exhibit a median grade of 0.015 wt.% Co compared to massive sulphide samples at 1 wt.% Cu and 0.0029 wt.% Co. Relatively pristine massive sulphides collected, however, can be enriched in Au (13.4 ppm) and Cu (8 wt.%) compared to Fe-oxyhydroxides signifying metal loss during alteration. The variation in metal enrichment and morphology in Fe-oxyhydroxides are related to their unique formational processes at these systems.

Despite seafloor weathering resulting in metal loss from the sulphides, some of these metals can be trapped in Fe-oxyhydroxides and potentially generate supergene enrichment such as Co, thus, retaining the metal tenor of these extinct hydrothermal systems. Seafloor exploration at SMS deposits largely ignore Fe-oxyhydroxides, however, this research demonstrates the potential of Fe-oxyhydroxides for possible future exploitation and should be considered when estimating the metal budget of these systems.

Reassessment of the source controls on the fertility of Ni sulfide mineral systems

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The mantle is known to be the principal source of metals for Ni, Cu, and the platinum group elements (PGE) in magmatic sulphide deposits, hosted within sulfide, metal alloys, oxides and olivine. The simplistic model of priming mantle-derived melts in these metals from these minerals requires high degrees of partial melting (>14 %) via a significant heat driver (e.g. a mantle plume) of a sulfide- and/or olivine-rich peridotite source. However, such thermal anomalies are isolated in space and time, and thus these conditions required to form Ni-Cu-(PGE) deposits were limited.

The existing model for mantle melting applied to the formation of mafic-ultramafic magmas that host Ni-sulfide deposits have thus far focussed on 'dry' peridotite melting in closed systems [1]. Although this model is useful to demonstrate the release of Ni, Cu and PGE from sulfides/olivine at varying degrees of mantle melting, it is overly simplistic in terms of the assumed mantle composition. Nonetheless, it has been the basis for most genetic models of magmatic sulfide deposits.

In metasomatically enriched mantle domains, the mineralogical assemblage of the mantle is much more diverse and may comprise Fe-Ti oxides, carbonates and hydrous minerals, such as amphiboles and micas, in addition to olivine, pyroxene and garnet or spinel. Critically, the presence of hydrous and volatile-bearing minerals causes mantle source rocks to melt at lower temperatures than dry peridotites. Some of these minerals have high partition coefficients for Ni, similar to that for olivine [3, 4], and may also concentrate other first-row transition elements [4]. This offers an alternative way to fertilise partial melts other than the conventionally considered olivine and sulfide. Crucially, the implication here is that lower degrees of partial melting of a metasomatised source can produce melts that are fertile in Ni +/- other metals and that Ni sulfide deposits may be found in a more diverse range of geotectonic settings than previously recognised.

Here we show new data of the Ni deportment in silicates in a range of variably metasomatised mantle rocks to illustrate that some mantle assemblages contain significant sources of Ni in silicates that can melt at lower temperatures than olivine. We place this into context with recent experimental work on melting of hydrous pyroxenites [2] and put forward an alternative model for Ni sulfide ore genesis.

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From micro to nano - a TEM and APT study on Te incorporation into pyrite

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Tellurium (Te) is an important commodity for renewable energies and high-tech applications. While most Te is currently recovered as a by-product of base metal smelters, rising demand drives the search for additional Te sources. Mineral deposits with a high potential for Te recovery are mostly related to epithermal systems in alkaline igneous rocks, where Te concentrations in pyrite may reach 1.6 wt. % [1]. As such, pyrite may represent an underestimated resource for Te. However, future Te recovery from pyrite requires a full mineralogical and chemical characterization to the nano-scale. While lattice incorporation of Te in correlation to As has previously been proposed [2], electron microprobe WDS mapping of pyrite from the Vatukoula epithermal Au-Te deposit (Fiji) revealed that As and Te can also be decoupled on the micro-scale. Subsequent (S)TEM work on a low-As and high-Te zone revealed nano-scale oscillatory As zoning following the growth zoning. Tellurium, in contrast, also forms discrete telluride particles in micro- to nano-cracks, giving evidence for an intragrain mobilization as melts. Atom probe tomography (APT) of the Te-rich zone revealed dislocations, in which Te is significantly enriched (up to 0.5 at. %) together with As, Cu, Sb, Ag, Pb. In addition, areas lacking telluride inclusions or dislocations yield Te concentrations >0.15 wt. % based on (S)TEM, STEM-EDXS and APT, indicating Te solid solution. This implies that the solubility limit of Te in pyrite may significantly surpass what was previously reported [2], which may be an important implication for the recovery of Te from pyrite.

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Vanadium Deposits in the African Continent: a Review

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Metals and minerals are integral to all renewable energy technologies. Some of them are relatively easy to recycle, making them eminently suitable for a circular economy. Vanadium is not an exception to this concept and its use has risen substantially in recent years, as have the number of innovation-driven industries that depend on vanadium for their operations and products.

Vanadium can be obtained from primary and secondary sources. The latter mostly consist of metallurgical wastes (from steel industry), tailings and slags from ancient and modern mining areas and plants. Primary vanadium sources are of variable importance, with V-hosting titanomagnetites in the forefront. Africa is a continent enriched in all types of mineral deposits, including vanadium, as a result of its geological legacy [1]. In fact, a large spectrum of vanadium mineralizations with different economic value has been recorded in the African continent, reflecting its geological and climatic evolution.

In Africa, not only the resources from Namibia (Otavi Mountainland) and South Africa (Bushveld) are historically well-known and exploited, but also minor occurrences in other countries are rather significant, where vanadium minerals are extracted with old artisanal methods. Of particular interest are the vanadium mineralizations associated with graphite bodies in the Mozambique Metamorphic Belt and vanadium linked with uranium in the deposits/occurrences in the Upper Paleozoic-Mesozoic Karoo continental sediments. Typical examples occur in Botswana, South Africa, and Zimbabwe. Significant uranium-vanadium concentrations occur in relatively recent (Tertiary-Quaternary) calcrete formations in former fluviatile beds throughout the African continent. Variable vanadium amounts have been recorded in iron ore deposits, phosphorites, and laterites.

To ensure sufficient vanadium supply worldwide, even the smaller concentrations should be currently regarded as a potential resource. A brief review of the most important vanadium occurrences in several African countries will be made in this talk, organized as follows:

(1) Southern Africa (Botswana, Namibia, South Africa, Zambia, Zimbabwe)
(2) Eastern Africa (Burundi, Kenya, Madagascar, Mozambique, Tanzania)
(3) Western Africa (Angola, Burkina Faso, Cameroon, DCR Congo)
(4) Northern Africa (Algeria, Egypt, Libya, Mauritania, Morocco, Niger, Tunisia).

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Deep Electrical Resistivity Tomography as a mineral exploration tool: the Calamita distal Fe-skarn, Elba Island (Italy)

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The Calamita distal Fe-skarn deposit, Elba Island, Italy, consists of massive magnetite-hematite ore bodies hosted in marbles and micaschists of Tuscan Units [1]. Skarn and ore formation at Calamita matches with the waning stage of the Miocene magmatism on Elba. To date, no genetic or spatial link between the deposit and a potential causative intrusion has been established and little is known about its structure at depth.

In this project, a full-3D Deep Electrical Resistivity Tomography (DERT) survey has been carried out to investigate the Calamita deposit, using the Fullwaver technology as a mineral exploration tool. This innovative method contrasts with traditional resistivity methods by its accessibility and easy set-up and allows a 3D arrangement of autonomous and cable-less receivers [2]. We performed 148 current injections on 48 receivers over an area of 2km² and inverted resistivity and chargeability measurements. Geophysical data were combined with a high-resolution 3D Digital Elevation Model acquired by standard and thermal drone imagery.

The 3D resistivity model is reliable up to a depth of 600 meters and correlates with the surface geology. The inverted chargeability model fits with the distribution of the outcropping ore bodies and suggests the presence of hidden mineralization in the flanks of the system. The inverted data reveal a conductive sub-vertical pipe-like structure connecting the two main skarn bodies at depth interpreted as a paleo-hydrothermal channel way for the skarn- and ore-forming fluids, merging at depth, and tentatively interpreted as pointing towards the cupola of potential magmatic intrusion.

This study contributes to the understanding of the deep structure of distal skarn deposits and will define the potential of DERT to investigate mineral deposits for fundamental research and exploration purposes.

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webNORM: A New Open Source Web Application for Calculating Normative Mineralogy

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The concept of calculating normative mineralogy for igneous rocks from bulk geochemical assays [1] has undergone several revisions and modifications to improve accuracy [2][3][4], simplify the procedure [5] or to extend the concept to other rock types [6][7][8]. The algorithmic nature of normative calculations is well suited to being implemented in code, and as such there have been several developments in a range of different programming languages [9].

These tools have provided a convenient way to calculate normative mineralogy, however they have several different shortfalls, such as performance issues on larger datasets, being closed source with unmaintained code bases, or requiring users to be familiar with working with code. To improve on these issues, a normative mineralogy algorithm including two iron oxidation ratio adjustment methods [4] has been reproduced in Python and made available as both an accessible a web application (available at *https://webnorm.streamlit.app*) with a graphical user interface, herein named webNORM, or through a coding environment using the Python package pyrolite [10]. The outputs from webNORM are shown to be very consistent with the outputs from a previous software implementation of the same algorithm [9], with the additional benefits of being accessible and fully open source.

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The secrets of Spodumene revealed – observations on this enigmatic mineral and applications for ore deposit formation & traceability in the battery mineral ecosystem

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Spodumene ($LiAlSi_2O_6$) is a member of the pyroxene group of lithium aluminium inosilicate minerals and is found in commercial quantities within cross-cutting pegmatite dyke swarms in the Kaustinen area of western Finland. It is proving to be a useful mineral in the current energy transition era because it can be easily converted (through heat treatment) from its natural monoclinic state (α-spodumene), into an industrially-useable tetragonal form (β-spodumene), thus making it amenable to subsequent chemical treatment, whereby the valuable lithium can be efficiently extracted and made into battery-grade lithium hydroxide monohydrate ($(LiOH{\cdot}H_2O$).

This presentation describes new mineralogical, petrological and geochemical observations made on Keliber's spodumene ore deposits from the Kaustinen area, using an innovative multi-dimensional, multi-modal (multi-analytical) and multi-scalar approach. We document the characteristics of Finnish spodumene in terms of: colour (optical); 3D texture (X-CT); crystallography (QXRD); 2D micro-chemical variation (SEM-EDS, QEMSCAN, EPMA, & μ-XRF); and laser-based isotopic & geochemical composition (LA-MC-ICPMS).

The results suggest that, even though Finnish pegmatite bodies clearly have complex paragenetic histories, their distinctive petrological characteristics allow for some degree of regional provenance to be established. This in turn shows promise for the traceability of spodumene from *in-situ* ores, to processed mineral concentrates, and even the possibility of linking various man-made products back to their original mineral deposits, at least within a Nordic context.

This study forms part of the BATTRACE Project (Sustainable Processing and Traceability of Battery Minerals, Metals and Materials), funded by Business Finland, as well as a GTK-funded project on "Mineral systems and material characterisation methods".

Supergene enrichment of the Kitumba IOCG deposit, Zambia

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Iron oxide copper-gold (IOCG) deposits host Cu and Au, as well as numerous other potential by-products such as Ag, Co and U [1]. Supergene alteration of a deposit can enrich grades of Cu, Au and trace metals, as is often observed in oxidised zones of porphyry and sediment-hosted deposits [2]. Whilst supergene processes have been well studied in these deposits, development of supergene mineralisation is much less common in IOCG deposits and as such only limited research on supergene processes in IOCGs has been undertaken.

The Kitumba IOCG deposit in Zambia is an example of a supergene enriched IOCG deposit. Zones of supergene enrichment are recorded down to depths of several hundred meters, Cu reaches up to 30% in supergene zones and several successive stages of supergene alteration are recorded. Stage 1 hypogene chalcopyrite-pyrite is replaced by Stage 2a chalcocite-minor covellite, Stage 2b cuprite-native Cu, Stage 2c malachite and finally Stage 2d brochantite. Hypogene chalcopyrite-pyrite was replaced by chalcocite under acidic conditions (pH 5.5-6), followed by the precipitation of cuprite and native Cu under more neutral (pH 6) and further oxidising conditions. Malachite then precipitated under increasingly oxidised conditions (pH 6.5-8) and localised zones of acidity (pH 5.9-7) allowed brochantite to precipitate. In addition to Cu, Kitumba hosts a distinct supergene Au zone (up to 2 ppm) within Fe-oxide breccia located within the upper parts of the deposit, this appears to be hosted by an isolated pocket of folded and heavily Fe-altered Katangan metasedimentary rocks. Cobalt is notably depleted in the supergene zone, whilst Ag is enriched.

These findings have begun to establish the behaviour of Cu, Au and trace metals within supergene zones of IOCG deposits, and as such may have implications for other IOCG deposits which have experienced supergene alteration.

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A rapid change in magma plumbing taps porphyry copper deposit-forming magmas

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Porphyry-type deposits are a vital source of green technology metals such as copper and molybdenum. They typically form in subduction-related settings from large, long-lived magmatic systems e.g.[1][2]. The most widely accepted model for their formation requires that mantle-derived magmas undergo an increase in volatiles and ore-forming constituents in mid- to lower crustal reservoirs over millions of years e.g.[3][4] however, this is mostly based on observations from shallow, sporadically exposed parts of porphyry systems[5]. To examine this paradigm, we have evaluated the timeframe and geochemical signatures of magmatism in a ~8 km palaeodepth cross-section through plutonic and volcanic rocks of the classic Yerington magmatic system, Nevada[6]. We show that the magmas in the upper parts of the system (<8 km) underwent a major and rapid change in chemistry over a period of <200 kyrs that is coincident with the initiation of ore formation. We attribute this change to a shift from extraction of quartz monzodiorite and quartz monzonite magmas evolving in mid-crustal reservoirs, and that had relatively poor ore-forming potential, to extraction of volatile-rich granitic magmas from greater (~30 km) depths. As the granites crystallised, late stage melts were intruded through the carapace as aplite dykes which contain traceable expressions of the porphyry deposit-forming fluids[7][8]. The rapid nature of the shift in ore-forming potential narrows the temporal-geochemical footprint of magmas associated with porphyry mineralisation and provides new constraints for exploration models.

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Textural indicators of mineralisation potential in porphyry systems – A framework from the archetypal Yerington district, Nevada

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Porphyry-type deposits are spatially and temporally associated with the relatively shallow and texturally complex parts of magmatic systems [1][2]. Whilst certain textures offer snapshots into the physical processes which result in fluid exsolution and hydrothermal mineralisation [3][4][5], their documentation and interpretation remains disjointed. To address this, we describe a suite of magmatic and magmatic-hydrothermal textures from the classic Yerington Cu(-Mo-Au) porphyry district, Nevada, where Cenozoic extension and tilting has exposed a unique, ~8 km palaeodepth, cross-section through the magmatic system [6][7]. Within the granite cupolas that underlie the Ann Mason and Yerington porphyry deposits, these textures include pegmatitic pods and massive silica bodies. Emplaced through the cupolas, and genetically associated with ore formation, are aplite dykes that host mineralised unidirectional solidification textures (USTs), pegmatitic segregations, miarolitic cavities and early A-type quartz veins. Based on field relations, including associations with hypogene mineralisation, petrography and Ti-in-quartz crystallisation temperatures (method of [8]), we highlight how these textures may record the timing and location of the magmatic-hydrothermal transition and ore-formation [9][10]. By doing so we provide a textural framework for exploration geologists to assess the likely 3D spatial and temporal architecture of porphyry mineralisation at the district-prospect scale before employing more invasive and expensive techniques.

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Identifying source of Sb, As and Pb anomalies at Ribeiro da Serra, Portugal, using factor analysis and features spatially associated

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Ribeiro da Serra Mine, an abandoned mining complex from the late 19th century exploited antimony and gold, belongs of a regional structure of Valongo Anticline, with several Au-As, Sb-Au, Sn-W and Pb-Zn-Ag deposits and a long history of exploitation since at least the Roman era. Today the antimony, for instance, is considered a critical raw material for the European Union.

A soil geochemical survey was undertaken in the zone to understand the mineralisation distribution, identify possible new mineralized structures and verify soil contamination distribution. The soil analysis method used was the inductively coupled plasma mass spectrometry (ICP-MS).
Since the area had previous exploitations, there was a necessity to understand if high concentrations of target elements are due anthropogenic contamination or natural occurrences.
A factor analysis verified the relation between selected elements, Sb, As, Ti, Pb, Zn, Mn, and certain features - wastepiles, adits, veins, and streams – and to identify the source of anomalies of Sb, As and Pb. The near distance between the sampling points and the features wastepiles, adits, veins and streams were used in the analysis.

The factor analysis explains 97.79% of the variance for the selected data through three factors. Combined with the interpretation of the outputs, associating the geology and topography the method helped in the understanding the source of the elements and its distribution. Although is clear that the wastepiles have influence in some high Sb and As values, acting as source of contamination, some high values are associated with known mineralized veins and maybe undiscovered veins.

Development of a metallogenic framework for auriferous mineralization in the Loch Tay area, Scotland

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Historical mining to the South of Loch Tay has exploited Cu (Tomnadashan) and Pb-Ag (Choire Buidhe) [1]. Exploration in the 1980s identified in-situ gold mineralization at Calliachar Burn [2] and Tombuie [3]. Recent work identified gold at Lead Trial near Ardtalnaig [4] and discovered a new auriferous vein in upper Glen Almond. All auriferous veins within the Pitlochry Fm. exhibit NNW-SSE orientations, but the known in-situ mineralization cannot explain the wide distribution of alluvial gold [5]. Here we present a summary of ongoing research largely focussed on the licence areas of Green Glen Minerals that has clarified regional metallogeny through identification of three distinct gold mineralization events:

1. Orogenic gold in the north of the study area. Auriferous veins at Calliachar Burn and Glen Almond exhibited very similar paragenesis including multiple quartz stages identified by cathodoluminescence. [6,7] Close similarities in compositional signatures of in situ gold with those of alluvial samples from local drainage has indicated that there are further undiscovered sources of this gold type[7].
2. Gold from magmatic hydrothermal systems at Lead Trial and Tomnadashan. Vein textures at Lead Trial are distinct from those observed elsewhere, and the S isotope analyses of vein material suggests a genetic link with the mineralization at Tomnadashan, but not other veins. The gold exhibits a Bi-Mo component, strongly suggestive of a magmatic hydrothermal system.
3. Auriferous porphyry- epithermal mineralization in the environs of the Comrie pluton and other Devonian igneous rocks, as indicated by distinctive gold alloy and inclusion signatures of alluvial gold.

Ongoing work includes geochronology, stable isotope studies and development of a regional structural framework.

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Porphyry Cu-Au deposits in thin and thick arcs: distinct magmatic processes and metal endowments

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Most porphyry Cu-Au deposits form in a syn-subduction arc emplaced upon thick (~30-60 km) continental crust and are associated with low- to medium-K calc-alkaline magmas [1]. However, in recent years, it has been recognized that world-class porphyry Cu-Au deposits also form in thin-intermediate (<~20-25 km thick) island arcs, particularly in post-subduction settings, in association with both calc-alkaline magmas and variably alkaline magmas. Examples of these porphyry Cu-Au deposits are those formed recently in the SW-Pacific (e.g., Batu Hijau, Onto, and Elang, Indonesia; Tampakan, Philippines; Grasberg and OK Tedi, Papua New Guinea), and elsewhere in Mesozoic and Paleozoic times (e.g., Oyu Tolgoi, Mongolia; Cadia, Australia; Atlas, Philippines). Deposits in thin-intermediate arcs are characterized by a gold enrichment over copper (Au tons/Cu Mt ~80: *Au-rich porphyry Cu-Au type*) when compared to the syn-subduction (Andean) type formed on thick continental crust (Au tons/Cu Mt ~4: *Cu-rich porphyry Cu-Au type*) [2]–[4]. Additionally, deposits in thin-intermediate arcs also have the largest gold endowments of all porphyry Cu-Au deposits (from >500 to ~2600 tonnes Au: Batu Hijau, Onto, Cadia, Oyu Tolgoi, Grasberg), yet contain Cu endowments that allow their classification as giant (>3.16 Mt Cu) to supergiant (>10 Mt Cu) porphyry-Cu deposits.

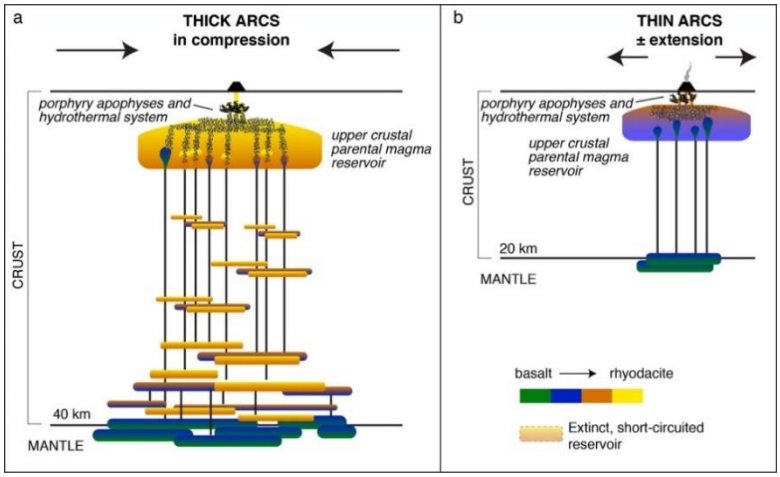

Figure 1: Transcrustal magmatic system in thick (a) and thin (b) arcs.

Using mass balance petrological modeling, I argue that porphyry Cu-Au deposits in thick and thin arcs form by two distinct magmatic evolution precursors. In thick arcs porphyry Cu-Au deposits are tied to the deep crust build-up of large volumes of magmas, volatiles and metals. These large volumes of magmas are H_2O-undersaturated and need to rise to shallow level to exsolve fluids and metals. In contrast, porphyry Cu-Au deposits in thin arcs form by little differentiated mantle-derived magmas that rise directly to shallow crustal levels where they exsolve fluids and metals. These two distinct magmatic pathways of porphyry Cu-Au generation are ultimately controlled by the different arc thicknesses in the two environments, even though the processes of metal precipitation in the actual deposits of the shallow crust are similar.

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PRISMA hyperspectral remote sensing and reflectance spectroscopy for Mineral Exploration: an overview through different ore deposit-type

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Hyperspectral remote sensing has been a well-established tool in mineral exploration since its advent [1], as it provides targeting information for follow-up sampling and surveys, potentially reducing exploration costs. Both hydrothermal and supergene alteration minerals have diagnostic spectral absorptions in the Visible Near (VNIR) to the Short-Wave Infrared (SWIR) wavelength regions (400 to 2500 nm) [2], useful for extracting information about their relative abundances and compositional variations in outcropping rocks.

At the Earth Sciences Department of the University of Naples Federico II, an ongoing research project aims to evaluate the capability of the 30m/pixel Italian Space Agency's PRISMA hyperspectral satellite for mineral exploration, by inspecting its performances in mineral mapping.

In this frame, spectral mapping of diverse alteration patterns was performed through a multi-scale approach, from field-based and laboratory-level spectroscopy to spaceborne hyperspectral imaging then validated via mineralogical and geochemical analyses. The test sites include genetically different ore deposit types: (1) the Mississippi Valley Type Jabali Zn-Pb(-Ag) deposit in Yemen, (2) the Iron Oxide Copper Gold Marimaca ore in the Coastal Cordillera of Chile, (3) the five-element Co-Ni Bou Azzer district area in Morocco and (4) the Punta Corna Project in Italy. Spectral mineral maps were produced by applying VNIR and SWIR feature-based band ratios to PRISMA. The distribution of target minerals such as Fe-(oxyhydr-)oxides (hematite and goethite in gossans), di- and tri-octahedral phyllosilicates (white micas, kaolinite, chlorite), hydroxyl-bearing sulphates (alunite), epidote and carbonates (dolomite), was highlighted, as well as their compositional variations over the investigated areas.

The results obtained so far demonstrate that PRISMA is effective in mapping alteration assemblages vectoring to the mineralized bodies and defining new exploration prospects potentially unknown or unreported.

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Application of PRISMA satellite hyperspectral imagery for mapping hydrothermal alteration zones in the Río Blanco-Los Bronces Porphyry Cu district, Central Andes (Chile)

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The Río Blanco-Los Bronces Porphyry Cu cluster is the largest known copper concentration in the world and is located approximately 50 km northeast of the city of Santiago, in the late Miocene to early Pliocene Porphyry Cu belt. Most of the Cu porphyry endowment is related to the evolution of the granodiorite-dominated San Francisco batholith, which intruded the Abanico and Farellones Formations [1]. The ores are intimately associated with hydrothermal alteration zones, characterized by typical schematic patterns [2]. The aim of this study is to use the PRecursore IperSpettrale della Missione Applicativa (PRISMA) satellite hyperspectral sensor for mapping the alteration zones associated with magmatic-related porphyry Cu deposits in the Río Blanco-Los Bronces area.

PRISMA, funded by the Italian Space Agency, comprises 234 spectral bands in the Visible Near (VNIR - 400 to 1300 nm) and Short-Wave InfraRed (SWIR - 1300 to 2500) regions of the electromagnetic spectrum with spectral and spatial resolution of ~13 nm and ~30 m, respectively [3]. This spectral range contains diagnostic spectral features of several hydrothermal alteration minerals: Al-sheet silicates (i.e., white micas), kaolin group, chlorite, and epidote, which are characterized by absorption features at around 2200 nm, 2185-2215 nm, 2250 nm, and 1550 nm, respectively [4]. Applying feature extraction band ratios and indices to the PRISMA spectral images of the area of interest, it was possible to identify several features of hydrothermal alteration minerals and to produce mineral distribution maps of the district. The PRISMA performances were assessed by using PRISMA-derived reflectance spectra, which were compared to United States Geological Survey (USGS) spectral library.

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Geochronology of the Ruwai Fe-Zn-Pb-Ag skarn deposit, Indonesia: evidence of Cretaceous mineralization in the Central Borneo metallogenic belt

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The Ruwai skarn deposit is the largest polymetallic skarn deposit in Borneo and is located in the Schwaner Mountains. Yet its age is unknown, and its genesis has not been studied in detail. This study provides U-Pb garnet and titanite ages and trace elements compositional data, as well as Re-Os ages of sulfides and magnetite in combination with U-Pb zircon ages from associated intrusions to constrain the mineralization age and its relationship to regional tectonic events.

The marble from the Jurassic Ketapang Complex, which was intruded by Cretaceous Sukadana Granitoids, is where the ore deposits and skarns are found. Titanite and garnet from the retrograde stage gave U-Pb dates of approximately 97.0-94.2 Ma and 96.0-95.0 Ma, respectively. These dates agree with Re-Os ages found in magnetite (99.3 3.6 Ma) and sulphides (96.0 2.3 Ma). The Early Cretaceous magmatism at Ruwai (ca. 145.7 and 106.7-105.7 Ma; andesite-dacite), Late Cretaceous (ca. 99.7-97.1 Ma; diorite-granodiorite), and Late Miocene phases are all discernible from the U-Pb zircon ages (ca. 10.94-9.51 Ma; diorite-dolerite). According to our geochemical and multiple isotopic data (C-O-S), the Ruwai skarn deposit was generated by oxidised hydrothermal fluids with temperatures of around 162 to 673 °C, and the ore-forming fluids and metals were mostly of magmatic

This work demonstrates that the Late Cretaceous formation of the Ruwai skarn deposit was linked to the subduction of the Paleo-Pacific plate beneath Sundaland following the accretion of the SW Borneo block. Within the Central Borneo metallogenic belt, the Ruwai skarn deposit is the first evidence of Cretaceous mineralization.

Geochemical tools of magma fertility related to porphyry copper deposits: case studies of Chachimbiro Volcanic Complex and Cerro Tolondro, Ecuador

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Porphyry indicator zircons (PIZs) are currently largely applied in the exploration for porphyry copper deposits (PCDs), due to the fact that zircons provide information related to the parental magmas, and their ability to retain the primary chemical and isotopic composition from the time of crystallization [1].

The geochemical signature of zircons has been determined as an indicator of the oxidation state of a magma, its water content, the degree of fractionation, and, consequently, for potential fertility of magmas. However, recent work by Chiaradia and Caricchi [2] has shown that the use of fertility tracers of zircons is not so straightforward and that also barren volcanic centers that are associated with large eruptions may have the same zircon geochemistry as those from mineralized porphyry rocks.

Rock samples of two volcanic complexes from the Western Cordillera of northern Ecuador were collected. These correspond to the barren Chachimbiro Volcanic Complex (CVC) and the potentially mineralized Cerro Tolondro prospect. A combination of whole rock and mineral geochemistry, specifically zircon trace elements and apatite volatiles, is carried out in order to compare the results from the barren CVC and the mineralized Cerro Tolondro prospect with those from PCDs found in the literature.

The geochemical signature evolution of the barren CVC is characterized by an increase of Sr/Y values of bulk rocks through time, similar to that of magmatic systems associated with supergiant porphyry Cu deposit.

Further mineral geochemistry and isotope dating will provide complementary data to constrain fertility indicators for both barren (CVC) and potentially mineralized (Cerro Tolondro) magmatic systems, and may provide important information for a more complete understanding of zircon fertility tracers in PCDs.

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Evaluating the purity of the NIST Standard Reference Material 182 (petalite) when compared with the petalite from the Barroso-Alvão field, Portugal

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The Standard Reference Material (SRM) from NIST (National Institute of Standards and Technology) are known to be certified materials with well-characterized composition and/or properties intended to be used when performing instrument calibrations, verifying the accuracy of specific measurements and to support the development of new measurement methods.

Some new calibrations for a portable equipment of Laser Induced Breakdown Spectroscopy (LIBS) were developed with the goal of analyzing the composition of the Li-minerals, spodumene and petalite, from the Barroso-Alvão aplite-pegmatite field (Portugal). During this process the SRM 182 (petalite) used as a QC (Quality Control) for the petalite samples showed other minerals in cathodoluminescence (CL).

In the Barroso-Alvão aplite-pegmatite field is very frequent to find Spodumene Quartz Intergrowth (SQI), a common texture resultant from the breakdown of petalite, which could result from decreasing the temperature (T) of the emplaced rock. Petalite becomes unstable and recrystallizes to spodumene + quartz, a more stable form. Since petalite ($LiAlSi_4O_{10}$) has more Si than spodumene ($LiAlSi_2O_6$), the excess of Si forms quartz that is intergrown with spodumene. The chemical composition of spodumene + quartz after petalite should be similar to the chemical composition of petalite and thus, chemical results from the mixture of spodumene + quartz after petalite should have similar results to the analysis of a petalite [1].

However, although for some other quantitative equipment what is important is the certified chemical composition, LIBS is an equipment extremely sensitive to changes of the crystal structure. Therefore, when the matrix changes the spectra also changes, altering the peaks area disproportionately to the element concentration. For that reason, CL was being used to evaluate the purity of the petalite samples and check if any spodumene + quartz was mixed with them.

Petalite is a Li-aluminosilicate that emits a weak blue light (luminescence) when bombarded with cathode-rays in vacuum; while spodumene, although having a similar composition, has a strong luminescence (usually orange). The different optical characteristics allow to distinguish pure petalite samples from samples of petalite with spodumene and quartz even if the materials are milled into fine powders [2, 3].

X-ray diffraction (XRD) was also used to analyze the NIST SRM 182 standard. Our results indicate the presence of a large amount of petalite but also indicated that quartz, spodumene and traces of phyllosilicates are also present.

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Controls on the high grade gold-cobalt mineralisation at Rajapalot, Northern Finland

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Rajapalot is a Au-Co deposit in Northern Finland, 35 km WSW of Rovaniemi. It is owned by Mawson Gold who discovered the deposit in 2012 and it has potential to be one of the largest producers of the two commodities in Europe [1].

As with many other hydrothermal gold deposits in the Northern Karelian Province greenstone belts, Rajapalot has an 'atypical metal association', in this instance with cobalt. The cobalt was likely deposited in an earlier stratiform sediment-hosted phase, and later remobilised and deposited in the Au-bearing phase [1]. Gold mineralisation occurs in silicate and sulphide fractures and the cobalt is hosted in cobaltite, linnaeite and cobalt pentlandite and is associated with albitization and a later sulphidation event [2]. The correlation between Au and Co grades is very weak implying that they are deposited under different conditions and by different fluids [3].

This study aims to define the paragenesis of the late Au-Co mineralisation through a detailed mineralogical and textural study using the Cathodoluminescence facility of the SEM; whilst also identifying any dateable minerals and whether they are inherited or not. The evolution of the hydrothermal system(s) will be studied using the trace element distribution and concentrations in sulphide minerals, determined using electron microscopy, electron microprobe and laser ablation ICP-MS. This could be applicable to other deposits with 'atypical metal associations' in the Northern Karelian Province, as well as other hydrothermal cobalt deposits globally.

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Porphyry-epithermal deposits of the Chatkal-Kurama region, Uzbekistan

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The Kurama region (Uzbekistan Middle Tienshan) forms the easternmost part of the Valerianov-Beltau-Kurama volcano-plutonic arc. Late Carboniferous to Early Permian bimodal andesite to rhyolite volcanism and granitoid plutonism are widespread [1]. Super-subduction magmatism controls the formation of the giant Kalmakyr-Dalnee Cu-Au porphyry (~315Ma U-Pb zircon, ~314Ma Re-Os molybdenite [2]). For the nearby low-sulfidation (LS) epithermal Kyzylmalmasay Au-Ag-Se field [3] we established a coeval formation age (~314Ma U-Pb zircon, ~313Ma Re-Os molybdenite), in contrast to its historically assumed link with Silurian magmatism [2]. Common understanding has been so far that the switch from compression (subduction-related porphyry copper deposits) to post-collisional extension (intrusion-related, mesothermal-epithermal, orogenic gold deposits) takes 10-20 My [1]. The intrusion-related gold (IRG) mineralization discovered at Kyzylalmasay and at some drill targets in the wider ore field exposes an important geodynamic, petrological and metallogenic link to the gold-bearing of the Kalmakyr porphyry copper deposit (PCD), hence challenging established views. The spatial and temporal coexistence of distinct IRG and PCD hints on variable magma types and strong redox control - with consequences for mineral exploration strategies.

For comparison, as representative of epithermal deposits, the high-sulfidation (HS) type Kochbulak field was included in this study [3]. At Kochbulak (~299Ma U-Pb zircon; 296Ma Re-Os pyrite), ore bodies are steeply dipping veins, interfacial vein-metasomatic bodies, explosive breccia pipes with gold content up to 2 kg/t. At Kyzylalmasay, ore bodies are represented by veins, interformational lodes hosted in altered andesites, syenite-diorites, granites (S2-D1; C2). The ore-controlling zone extends over 10 km. Geochemical and nanomineralogical methods have been used to study the high sulfidation ores of the Kochbulak deposit (Au-Ag-Te, gold-telluride-polymetallic) and the low sulfidation ores of Kyzylalmasay (Au-Ag-Se, electrum-selenide-sulfosalt).

Acknowledgements
This publication has been produced within the framework of the Grant "*Resourcing low-carbon technologies for green economy of Uzbekistan*" (REP-24112021/70), funded under the MUNIS Project, supported by the World Bank and the Government of the Republic of Uzbekistan. The statements do not necessarily reflect the official position of the World Bank and the Government of the Republic of Uzbekistan. The research is also sponsored by the Department for Business, Energy & Industrial Strategy (BEIS) Tactical Fund project grant "*Energy-technology metals in Uzbekistan aiding the UK supply chain*".

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Fe-Co-Ni mineralization in the Punta Corna hydrothermal vein system (Western Alps, Italy): preliminary results

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The Punta Corna Mining District is located in the Lanzo Valleys, North-West of Turin (Italy). It consists of Fe-Co-Ni mineralization which is part of a wider polymetallic hydrothermal vein system occurring throughout the Western Alps.
The ore was exploited for Fe and Co, mainly used for pigment production, until the 20th century. The global concern about the "*green transition*" and Critical Raw Materials (CRMs) supply, such as Co, has raised a renewed interest in old mining sites where the CRMs' economic potential was not fully investigated. Since 2018 the Junior Exploration Company *AltaMin ltd.* owns the exploration license of the Punta Corna area for assessing the economic viability of the ore.
Mineralization occurring at Punta Corna can be considered as a five-element vein type deposit, analogous to Bou Azzer [1]. The mineralization consists of a complex vein system interpreted as the product of late Alpine (post metamorphic) hydrothermal events [2]. It is hosted in metaophiolites of the Internal Piedmont Zone (IPZ), representing a portion of the Alpine Tethys oceanic lithosphere and its sedimentary cover of Jurassic age [3] and [4].
In this work, we present the results of a detailed geological survey of Punta Corna area and geochemical, petrographic, and mineralogical investigations on several samples from selected veins. Field work was conducted in collaboration with *AltaMin Ltd.* It focused on geological mapping and a detailed geological-structural study aimed at understanding the brittle deformation stages related to the mineralizing event. Petrographic, mineralogical and chemical characterization of samples collected from different hydrothermal veins were performed by optical microscopy, XRD, multi-elementary bulk chemical analyses, micro-textural and microchemical analyses via SEM-EDS and WDS techniques at the University of Turin and Milan.
The mineralized veins are almost exclusively hosted in metabasic rocks, locally preserving primary basaltic structures, and are associated with a sub-vertical E-W trending faults system.
Iron, cobalt, and nickel mostly occur as (di- and tri-) arsenides (i.e., skutterudite and safflorite series), and relative alteration products (erythrite, annabergite); Ag occurs predominantly as Ag sulfides or contained in tetrahedrites, while Cu and Fe (with lesser quantities of Zn) also occur as sulfides.
The geochemical composition of the veins is spatially variable within the mining district: the western sector is rich in Fe arising from the abundant presence of Fe minerals (i.e., siderite, ankerite), whereas Co and Ni are absent; the central sector shows enrichment in Ni-minerals (i.e., rammelsbergite and Ni-skutterudite), whereas, in the eastern sector, Co and Ni occur at comparable high grades. Gangue minerals are ubiquitous and include calcite, dolomite, siderite, ankerite, quartz, and baryte. Chlorite and white mica are common hydrothermal alteration products.
Further investigations will be addressed towards various aspects, including detailed ore characterization during the upcoming drilling campaign, identification of possible sources for metals (especially Co) and dating of the Co-rich vein swarm within the framework of the late-alpine hydrothermal activity along the western Alpine sector.

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The Marela Ultramafic Project: Developing a potentially world-class polymetallic nickel-cobalt-scandium and titanium-vanadium project in Guinea, West Africa.

Charles Douglas-Hamilton, Technical Director, Optiva Resources Limited.

The Marela Project is located on the north-western border of the Archaean craton & contains a large elliptical shaped ultramafic intrusion (7km x 0.9km) composed of an inner dunite core surrounded by rims of wehrlites and pyroxenites. The intrusive body has similarities with other Ural-Alaskan type ultramafic intrusions around the world. Supergene formations are observed across the whole of the intrusive complex resulting in significant grade enrichment of titanium, vanadium and scandium and nickel, cobalt and scandium in the laterites overlying the pyroxenites and dunites, respectively. 3D modelling from drilling, magnetics & gravity data indicate the intrusion has a vertical thickness to about a kilometre in depth.

The southern pyroxenite unit on the Marela Project is particularly well mineralised in titanium (ilmenite) and vanadium (magnetite) with strong enrichment in the laterite profile. The BRGM estimated, on behalf of Mitsubishi Corporation, that the hard rock pyroxenites (over a strike length of 1000m x 150m width x 250m depth) contained approximately 141 million tonnes at approximately 10% TiO_2 and 0.1% V_2O_5. Evaluating vanadium titanomagnetite deposits has its challenges particularly with separating clean ilmentite from magnetite concentrates from the host rock. Often there are multiple processes across different countries to produce final saleable products with established markets and clear specifications for pricing. Understanding the markets and processing is essential before designing exploration programs.

Laterites overlying the dunites on the Marela Project are enriched in nickel, cobalt and scandium. A recent JORC-compliant Mineral Resource Estimate reported 29 million tonnes at 0.79% Ni and 0.08% Co in the Inferred category. The Marela Project has the potential to become a viable standalone nickel-cobalt-scandium project. Evaluating dunites for nickel, cobalt and scandium, however, has its challenges. Developing an understanding of the mineralogy and how easily the nickel and cobalt and scandium can be leached is critically important. Some nickel laterite deposits need to first be assessed for their favourable mineralogy and acid-leachable nickel before mineral resources can be defined. Nickel grade, level of acid consumption and degree of leachability / extraction / recovery (largely a function of mineralogy and approach to leaching) are critical factors determining economic viability.

Commitments from different governments to decarbonise energy systems and reach net zero targets will cause a massive demand shift for minerals essential for the energy transition. This is expected to lead to higher commodity prices over a sustained time period, particularly in battery metals and rare earth metals. Projections made by the International Energy Agency show a quadrupling of mineral requirements for clean energy technologies by 2040.

The Government of Guinea is committed to diversifying its commodity exports to lower its reliance on bauxite and to encourage beneficiation of ore in Guinea. The Marela Project has the potential to produce titanium, vanadium, nickel, cobalt and scandium. None of these are produced or exported from Guinea and their production would involve in-country beneficiation.

Optiva Resources is also an active member of the UK Critical Minerals Association.

The role of metasomatism in the Ilímaussaq Complex REE deposit, South Greenland

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The Ilímaussaq Complex in South Greenland is a layered peralkaline intrusion containing 4.3 billion tons of rare earth element (REE) resource [1]. Eudialyte, the primary ore mineral, is a complex Na-Ca-zirconosilicate that occurs within a series of agpaitic nepheline syenites (kakortokite). The kakortokites exhibit layering of repeated units (c. 8 m thick) with differing eudialyte contents. The formation mechanisms of the layering are debated, broadly representing closed or open system magmatic evolution [2]. However, this is complicated by widespread metasomatic alteration and hydrothermal overprint which redistributed some of the REE and high field strength elements among the secondary mineral phases. Metasomatism as a layer forming process has not been studied in detail at Ilímaussaq. Hence, we question whether the layering formed through primary magmatic or secondary metasomatic/recrystallisation processes.

This study presents the mineralogical and textural observations of magmatic and post-magmatic processes within the complex and examines the geochemical effects of metasomatic alteration on the mineralogy. Our results confirm that the dominant hydrothermal assemblage contains: 1) analcimised sodalite and nepheline; 2) albitised K-feldspar; 3) aegirine replacing arfvedsonite and aenigmatite; and 4) altered eudialyte to phases such as catapleiite and gittinsite. Alteration within eudialyte ranges from partial modification along grain boundaries to complete pseudomorphic replacement. Trace element mapping of eudialyte by LA-ICP-MS demonstrates complex oscillatory and sector growth zoning for minor elements (Ta, Hf, Ce) inferred to reflect magmatic crystallisation processes. Modification by metasomatism through fluid/melt-rock interaction is potentially indicated by the ‘patchy’ diffusive nature of Rb, K, and Pb. Late-stage alteration is observed along fractures and grain boundaries by Ba and Sr. Future work will address whether these processes are the mechanisms responsible for the layering, ultimately providing a deeper understanding of this important ore deposit.

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The applicability of G-BASE stream sediment geochemistry as a combined geological mapping, and prospective exploration tool for As-Co-Cu-Ni mineralisation across Cumbria, UK.

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Stream sediment geochemistry is an incredibly useful tool to analyse the geochemistry of local geology within the source catchment area. This has significant applicability within the field of mineral exploration where understanding regional lithological geochemistry is needed, facilitating the identification of critical metal deposits. Successful identification of these deposits is essential to help tackle the deficit of these metals supply chains, especially for cobalt. This is in order to meet future carbon-neutral technological demand as part of global initiatives towards a more environmentally sustainable society.

We make use of the UK Geochemical Baseline Survey of the Environment (G-BASE) dataset to demonstrate that stream sediment geochemical data has the potential to be used as a useful tool for isolating potential Energy Critical Elements (ECEs) in host rocks across the UK Lake District. We reduced the dimensionality of the G-BASE stream sediment data, creating geochemical maps that identify a combination of volcanic, sedimentary, and plutonic lithologies lining up geological boundaries from established 50k scale geological maps of the area. This was conducted through a combined statistical and mapping approach within QGIS and ioGAS making use of empirical data statistics, principal component analysis (PCA) and K-means clustering tools.

Furthermore, we identified average ore metal concentrations (Ag, As, Bi, Co, Cu, Mo, Ni, Sn, Zn) for the Skiddaw Group and the Borrowdale Volcanic Group, two established host groups for As-Co-Cu-Ni mineralisation. Average concentrations of Co in the Skiddaw have been modelled to be 63.26 ppm, and in the Borrowdale volcanics to be 26.86 ppm. These values, combined with As, Cu, and Ni modelled concentrations, and other available exploration-related data (structural maps, underlying batholith topography, mining history etc.) have allowed us to identify 10 prospective areas of interest for possible As-Co-Cu-Ni mineralisation across these two lithological groups.

Fieldwork was then undertaken to investigate several of these identified areas. Ore metal-bearing minerals were identified both disseminated in local host rocks, and in hydrothermal veins. Characterisation of these minerals is still in progress; however, so far we demonstrate this workflow has strong applicability within critical metal exploration in other, more prospective regions across the globe.

Do apatite inclusions record the same chemical signature as their host?

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Arc magmas may experience processes such as volatile fluxing, volatile saturation, magma mixing and changes in redox state during their evolution. These processes may trigger eruptions, or drive ore formation [1]. Apatite offers a unique insight into these processes due to its ability to incorporate volatile elements, including Cl, F, S and H_2O [2]. Cl and S play key roles in the transport and precipitation of metals in porphyry copper systems.

SEM-EDS point analysis of apatite inclusions in amphiboles from Pinatubo dacites revealed distinct core-rim patterns in both apatite inclusions and amphibole hosts. Apatite from the cores of amphibole hosts record the highest sulphur (0.15-0.32 wt.%), whilst apatite from rims record lower sulphur (from 0 to 0.07 wt.%). XF/XCl in apatite shows a gradual increase from core to rim (from 1.43 to 2.10), driven by increases in XF (from 0.28 to 0.36) and small decreases in XCl (from 0.19 to 0.16). Chemical mapping of amphibole hosts revealed a higher aluminium content in the core than the rim. These chemical changes are interpreted to result from magma mixing with a more fractionated melt, where, following crystallisation of the high-Al amphibole core, fractionation of plagioclase takes up aluminium, resulting in subsequent low-Al amphibole overgrowth. As chlorine is more compatible in fluids under silicic conditions [3], it becomes depleted in the melt, thereby driving an increase in the apatite XF/XCl ratio. The sudden decrease in sulphur is likely due to increased degassing in the newly mixed magma or efficient removal by fluids.

Future work on this study will focus on detailed analysis of amphibole hosts. The host will be analysed adjacent to previously analysed apatite inclusions, through both SEM-EDS point analysis and laser ablation, with potential for SEM-WDS analysis for high-precision Cl data. The findings have broad applications for understanding the volatile evolution of magmas and porphyry copper deposits.

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A Question of Source: Assessing the Origin and Geodynamic Setting of Proterozoic Granites and Associated Sn-W-Ta Mineralization in Central African

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Rwanda lies in the NE section of the Kibaran Belt, within one of Central Africa's most prospective metallogenic provinces[1]. Rwanda has been intruded by two generations of granitic intrusions, with the younger generation having a temporal and spatial link to Sn- and W-bearing quartz veins and Sn-W-Ta(-Nb) (3T) pegmatites. Collectively these represent a significant source of the critical metals required for the transition into a "net zero" society. There has been recent geochronological and geochemical analyses to characterise the different granitic generations, yet there remains no consensus on a geodynamic model for their emplacement[2]. This study focuses on samples taken from both generations, and utilises zircon U-Pb and Hf isotope analyses to better constrain the nature of their source, with implications for Rwanda's tectonic history and the origin of its 3T mineralization.

Petrographically and geochemically, both granitic generations have the characteristics of crustal melt S-type granites. Our U-Pb data confirms the time of the first generation to the 1375 Ma Kibaran event[3] and the younger "tin granites" to between 967-995 Ma. The zircon age profiles of the tin granite suggest that material has gone through a sedimentary cycle, unlike the barren older granites. Zircon Hf isotopic data from all generations are nonragiogenic (εHf -17.1 to -1.2) suggesting crustal reworking of older crustal material, which is also reflected in their peraluminous compositions. All data lies on a Hf evolutionary trend that is broadly consistent with derivation from the Archean Tanzanian Craton, and also shows that both granitic generations share a common source. The Tanzanian Craton would appear, therefore, to underlie Rwanda[4] which is likely to have evolved in a collisional tectonic setting[5].

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Mineral Criticality – why critical minerals are different and why they are not

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Metals, minerals and materials and their sustainable supply are important for society. They are key for achieving the goals set out in COP21 and for several of the United Nations Sustainable Development Goals. Some of the important metals to underpin the energy transition are viewed as *critical*.

Criticality of minerals is generally assessed in terms of two dimensions, the likelihood of supply disruption, often termed *supply risk*, and the economic vulnerability to potential supply disruption, the *importance*. Critical minerals (CRMs) are high on the agenda globally and several initiatives are underway to understand and mitigate criticality, on an international level (e.g., UNECE's resource classification framework (UNFC), and EU assessments and funding initiatives) and on the national level and the level of certain sectors. UK is committed to developing a CR strategy and establishing long term understanding of implications and possible mitigations of criticality. The British Geological Survey recently conducted the first UK criticality assessment, in which 26 minerals were assessed for their potential criticality to the UK economy in terms of their global *supply risk* and the UK *economic vulnerability* to such a disruption [1]. Three indicators were used to estimate supply risk: production concentration, companion metal fraction and recycling rate. Economic vulnerability was calculated from six indicators: production evolution, price volatility, substitutability, global trade concentration, UK import reliance and UK gross value added contribution. Eighteen of the 26 minerals have a 'high' potential criticality rating and constitute the UK Critical Minerals List 2021.

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Climate Change and Tailings Dams; Do Traditional Dams Have a Future?

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Tailings dams (TDs) allow for storage of mine processing waste during the mine life cycle and post-closure. Rising metal demands for green technologies combined with decreasing ore grades increase the pressure for additional, larger TDs. Construction of larger TDs, however, results in a higher risk of structural failure. Climate change is exacerbating this risk of structural failure due to increasing temperatures, rainfall, and the frequency of extreme events [1]. Research into alternative disposal methods is therefore imperative to avoid devastating impacts.

Climate change poses risks to TDs, including through high rainfall (overtopping and waste seepage), permafrost thaw (damage to structural stability) and frequent earthquakes (structural collapse). These events lead to leakage, often as acid mine drainage, that pollutes and acidifies surface and groundwater. Leakage of mine waste poses a major risk for river-dwelling organisms and human health downstream. This is evident in TD disasters such as that at Brumadinho. The risks associated with TDs can be somewhat reduced through proper management, however further consideration of receptors and alternative methods are required.

The risk of leakage and collapse associated with conventional TDs has motivated mining companies to seek innovative disposal methods. Paste tailings are the most accepted alternative, involving thickening tailings to improve waste stability. Submarine disposal is a less common option that reduces acid generating potential, however can severely impact marine populations. Reprocessing of mine waste is becoming more popular, reducing the volume of waste stored in TDs, therefore decreasing the risk of collapse. Reprocessing may also provide a solution to the supply and demand gap created by the transition to green technologies. As mining companies strive towards sustainability, additional research into waste disposal alternatives and reprocessing is crucial. It therefore poses the question; do traditional tailings dams have a future in the mining industry?

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Tracing metal fluxing through the lithosphere from magmatic sulfide, through porphyry to epithermal and even orogenic

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Alkaline magmatic systems are host to some of the largest porphyry and epithermal base and precious metal mineral deposits on earth (e.g. Bingham, Cripple Creek). These systems are the product of low degree melting of what is generally thought to be a metasomatised mantle source, in post subduction/collisional environments. Whilst the upper crustal porphyries and epithermals are well known, if still poorly understood, the alkaline magmatic mineral system includes a range of magmatic sulfide mineralisation in the lower to mid crust. In this talk, we explore the journey of Ni-Cu-PGE-Te-Au magmatic sulfides from their mantle source, into the crust, aided in some cases by a volatile thrust, and their link with the upper crustal porphyry and epithermal deposits. We show that the magmatic sulfides and porphyry-epithermal systems are linked by a trans-lithospheric alkaline mineral system, that may also include some orogenic-type gold deposits. Furthermore it will be demonstrated that tellurium can be used as an excellent tracer of a range of magmatic and hydrothermal processes along that journey.

New Applications of portable XRF in Mineral Exploration

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Users of portable X-Ray Fluorescence (pXRF) analysers continue to demonstrate incredible innovation in the application of this now ubiquitous exploration tool. Whilst manufacturers attempt to implement the latest technology into the hardware and software of portable XRF's, it is the users of the technology who drive genuine innovation by finding new ways to use the instruments and implement these ideas into exploration programs. This talk will present real world case study examples of the application of portable XRF in ways not generally considered “typical”. The talk will summarise the most recent generic developments of this technologies application in mineral exploration. It will touch on innovation and developments in vegetation analysis, inclusion of pXRF on various automation systems and robots including (but not limited to) core scanners as well as developments in 3rd party software and workflows to control pXRF QA/QC and data management. The talk will also present information on new developments to be able to measure gold to 20 parts per billion (ppb) with pXRF as well as the latest developments in addressing low level cobalt in the presence of problematic associated Fe and Ni peaks and discuss the use of portable XRF for Lithium. New techniques for pXRF calibration will be discussed from innovative work on drill core to provide quantitative data on chemo-stratigraphy in order to make near real time drilling optimisation decisions. The talk will aim to collate the latest innovations in pXRF applications over the last 4 years and show case studies in most instances.

PROMT: Philippines Remediation of Mine Tailings

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More metals are needed for low carbon technologies to minimise the effects of climate change. The Philippines is the fifth most mineral-rich country in the world and will benefit from this increased demand, but sustainable mining technologies are needed to prevent negative impacts on the environment and surrounding communities. It is estimated that in the Philippines about 33 million tonnes of tailings are produced annually. Tailings storage facilities at both operational and closed mines pose environmental hazards; failure could cause contaminated materials to be released affecting people and ecosystems. The risk of failure is increased in the Philippines, due to the rugged topography, high rainfall, and frequent earthquakes. On the other hand, tailings are significant resources of unrecovered metals, especially older facilities that were produced using less efficient mineral processing circuits. The fact that the material is already finely ground makes reprocessing of tailings appealing but challenges here include the danger of damaging the structural integrity of the tailings by re-excavation, handling costs, and the potential for release of contaminants.

The PROMT project involves over 40 UK and Philippine researchers working together with mining companies in the Philippines to develop new sustainable technologies to manage metal mine tailings, to recover metals, and to make soils to support plant growth and allow the land to be reused. We are applying our research to both nickel laterite and copper-gold mines which make up 99% of the value of metallic minerals mined in the Philippines. PROMT brings together three science areas that are vital for innovation:

1. We aim to show how tailings storage facilities can be monitored in real time to allow reactive management to environmental changes; to achieve this we will use emerging technology in geophysical tomography and remote sensing to monitor and understand tailings behaviour in 4D.
2. We are investigating novel environmentally-benign solvents as a new method to dissolve metals *in situ* from tailings in tandem with electrokinetics to infiltrate solvents into low-permeability material; this will allow more metals to be recovered with economic value and also benefit tailings management by decontaminating hazardous components.
3. We are studying how plants and microbes colonise mine wastes, how this is affected by the use of solvents, and identify the best ways to promote biological growth. This will not only rehabilitate the land and allow it to be reused for agriculture or wildlife, it also minimises environmental hazards by improving the stability of the tailings and decreasing their toxicity.

Whilst these approaches have been applied separately in other settings, this is the first time that they have been used in combination to address the pressing issue of tailings remediation.

Uranium mineralisation in the Damara Orogen, Namibia

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Namibia was the world's second largest producer of uranium from mines in 2021 [1]. Most of this uranium occurs within leucogranite dykes and sills which intruded during the latter stages of the Damara Orogeny at c. 520 Ma. This presentation re-examines the geologic and tectonic setting of these mineralised leucogranites on the basis of extensive new geological mapping, combined with field structural analysis and a review of the geochemical, geochronological and metamorphic data available for the wider Damara Orogen.

Conventional understanding of the regional geology is based on stratigraphic mapping which considers that the younger Damara Metasedimentary Supergroup was deposited unconformably onto an older c. 1 or 2 Ga pre-Damara Abbabis Metamorphic Complex. Here, I dispute this interpretation, and present extensive new field evidence which shows universally that the underlying granitic rocks of the Abbabis Complex *intrude into* and *cross-cut* the overlying Damara Metasedimentary Supergroup at all locations visited. I propose that the Abbabis Complex is in fact a c. 550-500 Ma syn-orogenic migmatite complex which formed from partial melting of the Damara Metasedimentary Supergroup during the Damara Orogeny. Migmatites of the Abbabis Complex are therefore likely to be genetically related to the uranium-enriched leucogranites which intrude into the overlying Khan Formation of the Damara Supergroup. In contrast to previous studies which assume that differences in the sources of partial melting act as the key control on the uranium content of leucogranite dykes, I postulate that the processes responsible for uranium enrichment may instead have occurred over long time periods (potentially millions of years) in migmatitic rocks of the Abbabis Complex. These migmatites may have existed as a formerly partially molten 'magma mush' from which melt and fluids were continually added and extracted over long periods of time.

This new geological mapping of well-exposed rock outcrops along the Swakop River acts as a key analogue for the interpretation of geophysical aeromagnetic data covering poorly exposed Exploration Prospecting Licences to the south of the south of the Swakop River.

[1] https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

Experimental constraints on As partitioning at the pyrite-fluid interface

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Pyrite is among the most abundant sulphide minerals in the Earth's crust and an important sink for As and valuable elements like Au and Te [1, 2]. Hence, arsenian pyrite is of potential economic interest, but also an environmental hazard, if As is released into the aquatic environment. Knowing the mechanisms and limits of As incorporation into pyrite is therefore vital to better understand the formation of high-grade ores in various deposit-types. It is suggested that As either substitutes for S or Fe in the bulk crystal or forms localized high-As domains within the pyrite lattice. Partition coefficients (D_{As}) between pyrite and the precipitating fluid range from 300 to 1600 [3]. However, these results are exclusively based on As-rich fluid compositions (1 – 200 ppm), whereas the partitioning behaviour in low-As fluids (<1 ppm) has not been studied to date. We synthesized pyrite under Carlin-style, hydrothermal conditions (200°C, pH=5) by replacing siderite in H_2S-rich fluids with initial As concentrations ranging from 1 ppb to 10 ppm. Fluid analysis and high-resolution LA-ICP-MS mapping of the pyrite indicate an extreme increase in D_{As} (~15000) in As-poor fluids (1 ppb), leading to unexpectedly high As contents in associated pyrite. This observation suggests a highly efficient mechanism of As fixation into pyrite from As-poor fluids at moderate temperature conditions.

References:

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Lithium and Potash Mineral Systems Prospectivity Analysis in an Andean Setting

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A well-rationalised and robust Prospectivity Model is arguably one of the most important stages in regional mineral exploration to ensure there is reasonable evidence at an appropriate scale to indicate mineral potential within a study area. Supporting this, the application of Mineral System Analysis (MSA) in Mineral Prospectivity Modelling (MPM) allows for the characterisation of a logical framework to define geological phenomena, from the source of fertile regions, through pathway features, to depositional environments and subsequent preservation settings. Traditionally the method defines mappable criteria that can be analysed in modern GIS software to spatially represent real-world features (e.g. published maps and literature, satellite imagery and elevation models, inventories and databases) that may have controlled the occurrence and preservation of mineralisation. This process also highlights gaps in the current knowledge base and/or the data available, defining opportunities for further development and research.

CGG is currently applying MSA-guided Prospectivity Modelling to lithium and potash in the Andean Margin of western Argentina. This combines geospatial layers that proxy large-scale geological systems with key exploration vectors. The result is an expert knowledge-led, weighted prospectivity assessment to produce a ranked prospectivity heat map across the study area. In addition to using geological data, CGG has integrated environmental, infrastructural, and social data layers to define a holistic risk map that transcends a typical mineral prospectivity model, enabling informed exploration decisions based on multiple and non-conventional data layers. This approach has promoted further research and development, including workflow advancement and investigations into data handling efficiency through automation. An aim now is to use this work as a base to further research and support MSc projects to enhance understanding of the lithium mineral system.

The role of crustal anatexis in porphyry copper formation during flat-slab subduction: Insights from the Laramide Belt, Southwest USA

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The prevailing paradigm for the formation of porphyry copper deposits (PCDs) along convergent plate boundaries involves deep-crustal differentiation of volatile-rich juvenile magmas derived from the mantle wedge. However, many PCDs with the highest grade (hypogene) mineralisation formed during a period of shallow angle subduction when the mantle wedge would have been significantly thinned if not absent, leaving it unclear from where the metal-bearing fluids were derived. We seek to resolve this conundrum by investigating the deep crustal processes that occurred during the formation of the Laramide PCD province (80–50 Ma) in Arizona, which formed during a period of shallow angle subduction of the Farallon Plate beneath North America. We show that pressure – temperature conditions of amphibolite-granulite facies migmatites from the Harcuvar and Harquahala mountains in central Arizona exceeded ca. 0.75 GPa and 750–780°C between ca. 73–64 Ma constrained by U–Th–Pb dating of monazite, that define an extremely elevated geotherm of ca. 27.5°C/km. Crucially, this Laramide thermal climax overlaps with (1) the zenith of granitic magmatism and PCD genesis (73–56 Ma), and (2) the timing of dehydration reactions occurring in the subducted Farallon Plate (80–60 Ma) directly beneath Arizona. To explain these contemporaneous processes, we propose that volatiles derived from subducting slab locally passed straight into the overlying lithosphere, facilitating water saturated anatexis of Proterozoic crustal sources without the requirement of a juvenile mantle component. This is consistent with Sr–Nd–Pb isotopes and Hf-in Zircon isotopes from Laramide granitoids, which exhibit highly non-radiogenic signatures and Nd and Hf model ages spanning ca. 1.7–1.1 Ga, suggesting water saturated crustal anatexis was fundamental to the formation of the Laramide PCD province in Arizona.

Improving Access & Interoperability to British Geological Survey World Mineral Statistics Data

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Accurate and timely statistical data on mineral production is important for understanding how raw materials flow through our society and what the environmental or social effects of extraction may be. This statistical data underpins a vast amount of minerals related industrial policy and strategy, as well as scientific studies. Concerns about the supply of certain 'critical' raw materials highlight how understanding this data is more important than ever.

The British Geological Survey (BGS) is one of only three organisations that collects, analyses and publishes mineral production data by country for more than 70 commodities. The BGS dataset contains continuous annual data from 1913, with digital data available from 1970 [1].

At BGS we recognise the value of open data [2] and that the value can only be fully realised when that data is Findable, Accessible, Interoperable and Reusable (FAIR). To maximise the value of BGS data we use international standards and best practices to make our data discoverable and useable for stakeholders. These include working in line with spatial data on the web best practices [3] and BGS Strategy. These practices reduce time to science and increase the reproducibility of science.

BGS has recently made some of our data collections, including the World Mineral Statistics Data available using the recently released OGCAPI suite of standards [4] to make these collections more FAIR. This presentation shows users how they can access data using this new delivery mechanism.

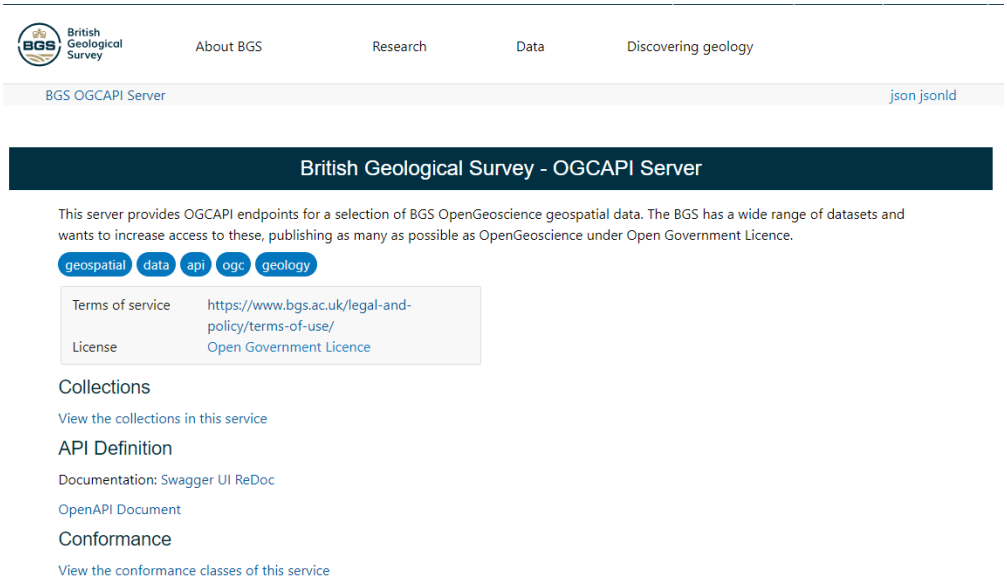

Figure 1. BGS OGCAPI Server to Access Data

References:

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Controls on the Magnitude of Ce Anomalies in Zircon and Implications for Porphyry Deposit Magma Genesis

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Increases in the magnitude of positive Ce anomalies in zircons from igneous rocks are often interpreted to be controlled by progressive melt oxidation and have been used to provide evidence for the elevated redox state of magmas associated with porphyry Cu deposits [1,2]. In this presentation, we test this idea by comparing trace element compositions of zircons from the Resolution porphyry Cu-Mo deposit, Arizona, with numerical models of melt Ce systematics and zircon-melt trace element partitioning. We show that although Ce anomalies in Resolution zircons (estimated by the chondrite-normalised ratio of Ce and Nd) may increase by over an order of magnitude throughout the period of zircon crystallisation, oxybarometric estimates in fact indicate a constant melt redox during this time. We employ a Monte Carlo approach to model the evolution of the Ce anomaly in zircon as a function of temperature, fO2, and melt composition, and compare our model against literature zircon data from chemically well-constrained volcanic rocks. We find that large increases in the magnitude of the Ce anomaly can be reproduced by cooling at fixed oxidation state and that this effect is magnified by increasing the melt Ce/Nd ratio, which can be driven by the co-crystallisation of amphibole, apatite and especially titanite. Increases in melt oxidation state are not sufficient to explain high positive Ce anomalies in zircons from some hydrous, oxidised volcanic and hypabyssal rocks, which additionally require a combination of titanite co-crystallisation and low crystallisation temperature. We therefore caution against the interpretation of zircon Ce anomalies solely in the context of melt fO_2 variation.

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From Moose Pasture & Elephant Country to Mine Site: Nickel Mining for the Modern World

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Mineral exploration and mine discovery & development is a long, complex process dependent on many variables – technical, economic, political and social. Political factors have recently changed and now cause substantially increased demand for "battery metals" to electrify vehicle fleets etc..

Mines are long-life industrial developments taking many years, and lots of money, to explore and commission. A single mine complex can create thousands of direct (and tens of thousands of indirect-) jobs and can have a long-term influence on a country's development and prosperity. Fluctuation in commodity prices and other socio-economic issues may hinder mine development or put mines out of business. Technological advances and increased demand for certain metals generally speeds things up, and may make sub-economic projects viable.

As rampant NIMBYISM has taken hold in the West over the last 4 decades, Western (over)consumers are now less aware of their impact, especially on other countries. The "disposable smartphone generation" is less attached to the land, and appears content to just consume "stuff" from overseas with not much thought to the consequences. Now, in a post-Covid world, the UN Sustainable Development Goals appear more questionable and unachievable. The vast majority of the UK's metals are now sourced overseas: most metals for EV's and so-called "green energy" are sourced from countries with lax environmental controls and produced using distinctly non-green power sources.

The talk will look at geological case histories addressing the positives of nickel mine development in Botswana, highlighting the changes that occurred over decades to turn uneconomic prospects into world-class mines, and then back again. Parallels will be drawn with the potential of NE Scotland to supply responsibly-sourced and low environmental impact battery metals for the future economy.

Battery Mineral Potential of NE Scotland

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The nickel-copper potential of NE Scotland was investigated by Exploration Ventures Ltd (a joint venture between Rio Tinto and Consolidated Goldfields) in the later 1960s and early 1970s. This work resulted in the discovery of two Ni-Cu resources; Arthrath and Littlemill. The former was also extensively prospected over during the early 2000s, indicating that the low-grade resource appears to be uneconomic.

In contrast, the higher-grade and still open resource at Littlemill had no further exploration conducted over it until recently. The historical resource was known to be also associated with significant widespread graphite mineralisation. Recent extensive prospecting has confirmed the presence of significant LCT (Lithium Caesium Tantalum) pegmatite-associated mineralisation close to the known graphite and battery metal occurrences.

These prospects are currently under evaluation by further geochemical sampling and a planned drilling programme.

Critical Metals and Circular Economy: a SW England Perspective

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Recent global events have further highlighted risks related to global supply chains. On this backdrop, ambitions to achieve the Sustainable Development Goals and Net Zero are placing increasing demand on Critical Raw Material supply chains – as these related ambitions are metals intensive. Multiple UK and European strategies on Critical Raw Materials reference the need for a Circular Economy [1,2], with primary resource extraction supported by recycling, unconventional secondary anthropogenic resources, materials tracking, and regulation development around recycled materials content. Circular Economy is, in its simplest terms, the opposite of a take-make-waste 'linear' economy; with principles emphasising waste reduction, circulation of materials and products in the economy at their highest value, and regeneration of natural capital.

The UK is experiencing a renaissance in exploration and development of technology critical minerals deposits; with Cornwall and Devon SW England having an initial lead in the number of such projects. Recent resource and reserve estimates total approximately 330 kt Li, 375 kt WO_3, and 175 kt Sn for active hard-rock projects in the region. Hard-rock mineralisation styles are diverse, including granite-hosted lithian micas [3], sheeted and lode-style vein systems [4], as well as lithium-bearing brines [5]. In addition to primary metalliferous resources, there is a broader spectrum of resources present in SW England, including secondary resources related to anthropogenic activity including, but not restricted to: historic mine wastes such as waste rock, tailings, and effluents (*e.g.*, adit drainage), renewable energy sources such as wind, solar and geothermal, plus in-use stocks for recycling at end of life. This diverse resource landscape is set within a backdrop of an environmental and social legacy from historic mining activity (*e.g.,* contaminated land, existing infrastructure, employment opportunities, *etc*.); as well as ambitions to develop the region as a natural powerhouse of renewable and green technologies, with ongoing geothermal and floating offshore wind projects.

Here, we present an updated resource inventory for SW England and discuss how circular economy principles can encourage synergies between projects, help project economics and help ensure sustainable development.

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Lu-Hf Isotope Systematics and Trace Element Constraints on Gardar Rift Magmatism: Did Archaean crustal recycling contribute towards metal endowment?

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Magmatism in the Mesoproterozoic Gardar Province of Southern Greenland is associated with two distinct rifting episodes: 'Early Gardar' between 1300-1270 Ma and 'Late Gardar' between 1180-1140 Ma [1]. Activity during this time gave rise to a spectrum of alkaline magmas, with the more evolved representatives manifested in the form of central intrusive complexes. Several of the complexes have attained significant concentrations of critical metals such as Zr–Y–Nb–Ta–REE–Zn at Ilimaussaq and Nb-Ta-REE at Motzfeldt [2,3]. Understanding the sources of these deposits is of importance in the development of accurate geomodels of alkaline igneous systems. This study uses the Hafnium isotope composition of zircons in tandem with whole-rock incompatible trace element data from the medium to highly evolved peralkaline central intrusive complexes to better understand the source of Gardar parental magmas.

The dataset of this study encompasses samples from 14 central complexes spanning the entire geographical and temporal extent of the Gardar. Incompatible trace element ratios highlight differences in source characteristics between Early and Late Gardar intrusions. Hf isotope analyses reveal that Gardar magmas have εHf_t values too low to be congruous with derivation from the depleted mantle during the Gardar period. Specifically, most Early Gardar zircons are found to have appreciably more negative εHf_t values (between -9 and +4) compared to those in Late Gardar (between -3 and +1). The exception is Grønnedal-Ika, which lies the closest to the εHf_t composition of the depleted mantle. The data appear to be inconsistent with a scenario in which the εHf_t of Gardar magmas is lowered by crustal contamination, since the lowest εHf_t values found in Kûngnât, which intrudes Ketilidian (c.1800Ma) basement, lie very close to the Ketilidian zircon evolution line and would likely require far more assimilation than is found to occur in the Gardar. Instead, the range in Gardar Hf isotopic ratios is consistent with the generation of Gardar magmas in the sub-continental lithospheric mantle which contained a source(s) of unradiogenic Hf. Several possibilities for the development of this source, linked to Archaean crustal recycling, are explored in this study using Gardar Lutetium-Hafnium systematics.

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Forgotten Treasure – applications of Niggli Numbers in mineral exploration.

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Niggli Numbers are values obtained from the major element analysis of a rock (plus a few important trace elements if these are available). Paul Niggli introduced the method in 1933 based on the concept of equivalent molecular numbers of component rock oxides (defined as the ratio of weight percentage of an oxide component to its molecular weight). These were combined and converted into 4 primary Niggli Number values (*al, alk, c* and *fm*), 3 secondary values (*si, ti* and *p*) and two ratios (*mg* and *k*) [1]. Meaningful Niggli Numbers can be calculated for any rock type or mineral without needing to take account of additional factors such the oxidation state of iron or the volatile content. Niggli Numbers were originally designed for broad rock classification, provenance determination and deriving likely petrogenetic association in high-grade metamorphic rocks of ambiguous origin [2]. Despite its usefulness, simplicity and popularity in the 1950's and 1960's, the Niggli methodology was overtaken by a range of other major and trace element classification schemes and has largely been forgotten to the point that it is mentioned only in passing (if at all) in modern petrology textbooks.

Niggli Numbers were never designed with exploration in mind [1] but they track mineralogy more closely than major element plots alone and the vectors that emerge on Niggli plots can be applied to potentially important mineralization processes such as magma contamination and/or alteration. Furthermore they arose at a time when analyses were slow and cumbersome there were limited volumes of whole rock data available to interpret. The availability of large datasets of major element data for petrology and exploration on platforms such as GEOROC, there is an opportunity to re-evaluate Niggli Numbers and find out what potential their ease and simplicity offer to the 21st century exploration geochemist. Figure 1 shows an example where the classic Niggli (*al-alk*) versus *c* plot originally designed to distinguish igneous and sedimentary rocks can be applied to exploration. Figure 1A illustrates where different alteration minerals fall in *al-alk* versus *c* space. Figure 1B illustrates an example where chloritization of basalts and andesites is evident at the Hongtoushan VMS deposit [3]. Further examples will also be outlined.

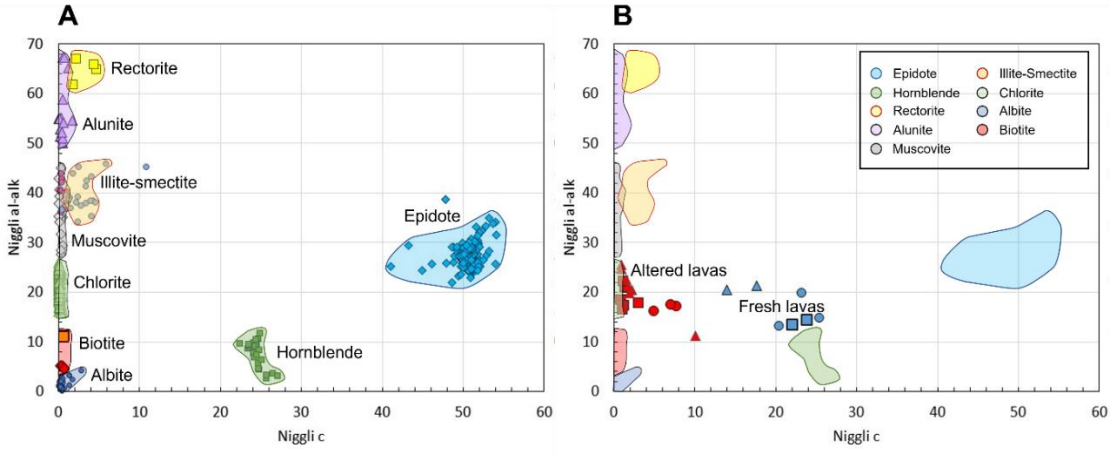

Figure 1: Niggli (al-alk) versus c showing (A) fields for various alteration minerals, and (B) fresh and chloritized mafic lavas compared to the alteration mineral fields [3].

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Does tectonic setting control the precious and critical metal endowment of porphyry Cu deposits?

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Porphyry Cu deposits commonly contain critical and precious metal by-products, including the chalcophile and siderophile elements Au, Pd, Pt, Ag, Te, Se and Bi. These elements partition into residual sulfides during the partial melting of mantle wedge peridotite during subduction, potentially depleting the source magma for subduction-related porphyry deposits. The chalcophile-rich residual sulfides in subduction-modified subcontinental lithosphere are thought to be the source of metals in post-subduction porphyry deposits, and as such these deposits may be more enriched in chalcophile and siderophile elements than subduction-related porphyry deposits. However, many post-subduction deposits have low Au grades and some subduction-related porphyry deposits have high Au and PGE concentrations.

We test the role of tectonic setting in precious and critical metal endowment of porphyry Cu deposits by comparing whole rock assay, PGE and LA-ICP-MS sulfide trace element data from three case studies with a newly compiled global database. The Skouries Cu-Au-(PGE) porphyry deposit, Greece, and the Muratdere Cu-Au-Mo porphyry deposit, Turkey are both post-subduction; these are contrasted with the El Teniente Cu-Mo porphyry deposit, Chile, which is a classic subduction-related system. We show that post-subduction porphyry deposit sulfides are relatively enriched in Bi, Te and Se compared to sulfides from subduction-related deposits. However, although some critical and precious metals (Ag, Bi and Se) reside in primary sulfide ore minerals, others (Au, Te, Pd and Pt) are hosted in minor accessory minerals. Whole rock data from mineralized samples show that both subduction-related and post-subduction deposits can be precious and critical metal enriched, with metal endowment independent of tectonic setting. PGE-enriched porphyry Cu deposits are also enriched in Bi, Te and Au, and semi-metal melts are suggested to play an important role in PGE transport and concentration in porphyry Cu deposits.

Economic Mineral Exploration: Multiscale analysis using combined micro-XRF and SEM-EDS analytical techniques

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Geological processes and our understanding thereof occur from planetary scales down to the atomic level. Accordingly, the ability to investigate such phenomena is wide and varied, often encompassing a multi-disciplinary and multi-technical approach. One key area in geological sciences is the ability to transition from the field to the laboratory, and this is where analytical techniques such as micro-XRF can be extremely useful, not only in its own right, but as a powerful component in a productive and timeous workflow. Specifically, micro-XRF has many analytical features, such as a focused beam and trace level elemental capabilities, that yield fast results at a micrometer scale over large sample areas with minimal sample preparation. In addition, the ability to combine micro-XRF with a SEM enhances the workflow capabilities and enables the transition into the nanoscale analysis whilst maintaining the textural relationship. In this presentation several example will be shown of the analysis of large scale samples (i.e. up to 1 m in maximum dimension) through to micometer identification of minerals of interest, whilst maintaining the overall textural relationships and bulk mineralogy, which is so important in the overall understanding of economic deposits. Specifically, examples from Au-bearing, Co-bearing, and REE-bearing mineral phases will be presented.

Scientific insights from the development and delivery of the UK Critical Minerals Strategy

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The world relies on critical minerals, often extracted in remote parts of the world, and made available through complex and challenging supply chains. The reliance on critical minerals is by no means new, but in recent years their importance has taken on new salience, driven by new technology and smarter devices. Over time, critical minerals have become more embedded in our daily life and have become integral to countries' ambitions around climate change and the increase in green tech.

In July 2021, the Government released its new critical minerals strategy [1] centred on the principles of accelerate, collaborate, and enhance. It recognised that there was a need to accelerate the UK's domestic capabilities alongside collaborating with international partners, while at the same time enhancing international markets.

This short talk will look at the science that underpins our understanding, and the challenges for science to policy in critical minerals, their extraction, and the full value chain across the economy. It will set forth some of the thinking and science underneath the formulation of the critical minerals strategy, and ask, what next in order to deliver this?

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Longevity of fault-controlled fluid flow within Cu-Au-Mo porphyry (Yukon, Canada) revealed by U-Pb carbonate geochronology

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Carbonate veins are ubiquitous in many ore deposits and often are interpreted as a late stage or cross cutting fluid flow events in the ore deposit history. Faults accommodate rock displacement and the resulting zones of weakness act as conduits for hydrothermal fluid and magma, localising fluid flow and leading to the formation of ore deposits. Dating of both veins and brittle fault material has been notoriously difficult because of a lack of 'datable' material. Using innovative techniques, it is now possible to date carbonate with the U-Pb isotopic system.

Here we use the U-Pb carbonate dating method to date a variety of fault material and mineralised and unmineralised veins within a major fault-controlled Cu-Au-Mo porphyry system in the central Yukon, Canadian Cordillera. Over 50 samples have been dated, revealing a long history of faulting and fluid flow in the deposit spreading over 10s of millions of years between ~75 Ma and <20 Ma. We combine petrography, U-Pb carbonate geochronology, trace element geochemistry and clumped isotope analysis to interpret the full temperature-time evolution of the fluids within the deposit. Our results show the carbonate veins crystallised during the main ore-forming event at ~75 Ma. Subsequently,

there was a prolonged period of fault-controlled fluid pulsing that likely concentrated metallic minerals in the deposit. The findings show that carbonate veins are not always late features within ore deposits and are an underutilised resource for understanding the full temporal and fluid evolution of a system. Carbonate U-Pb geochronology is therefore potentially incredibly useful for telling the previously untold and long history of fluid flow in a variety of deposits.

Searching for Copper in the age of Transition: from play-based exploration to mineral system workflows - the holistic exploration mindset

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Those prospecting to expand mineral portfolios increasingly need to look deeper and beyond known occurrences. New ways of thinking about exploration and, ultimately, production must be adopted. Working with our mining partners, we are taking applicable geological subsurface screening methods from the hydrocarbon industry and applying them within a broader mineral system approach to exploration.

Global plate tectonic models can be used to map out the location and duration of volcanic arc magmatism related to subduction zones. This can be used as a proxy for hydrothermal mineralisation, but also identify zones of lithospheric and crustal endowment exploited by younger events. While changing mineral system to sedimentary hosted copper, requires a significantly larger integration and manipulation effort, of many differing geological datasets (from tectonics to gross depositional environments).

These methods can be used as a global first pass screening map for selected locations and time periods to get one in the right location, to then apply higher resolution datasets at a more localised scale to further refine the spatial selection process. Exploration scales bare similarities between hydrocarbons and minerals but is ultimately an exercise in the reduction of scale. At each level it is about getting yourself to that right area and narrowing focus, while never actually forgetting the wider geological context established.

An ongoing shift in exploration mindsets and a new era of collaboration is emerging. There are, however, differences in the scale at which some of the hydrocarbon and mineral exploration concepts can be implemented, as well as the terminology used, so these need to be considered to ensure the most effective transfer of expertise and knowledge between these sectors. This results in the ability to test more concepts, make better predictions and ultimately reduce the time to resource discovery through efficient subsurface decision making, which is key to meeting the metal capacity needs of the energy transition.

The use of phlogopite as an indicator of magmatic Cu-Ni mineralisation in the Curaçá Valley, Brazil

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The Curaçá Valley sulfide deposits are located in the northern part of the São Francisco craton, Brazil[1]. The dominant geology is granitic-gneissic terranes, with greenstone belts and supracrustal terranes, intruded by mafic-ultramafic bodies between 2042 and 2085 Ma[2,3]. The mafic bodies are mostly pyroxenites that host Cu, and sometimes Ni sulfide mineralisation. The deposits differ from 'typical' magmatic sulphides, as they have a very high Cu/Ni ratio (~40)[4] and contain an unusually high abundance of phlogopite (Mg-rich biotite).

Phlogopite is observed in two main forms in the drillcores studied: alternating bands of phlogopite-rich rock within gneiss (country rock) or as glimmerite (>80% phlogopite) bodies within or at the margins of mafic-ultramafic bodies. Textural relations of phlogopite with Cu sulphides, in which phlogopite is included within chalcopyrite, indicates that some of the phlogopite is magmatic in origin, and not a late-stage alteration phase.

A pilot study undertaken in 2021, investigated the Ni contents of phlogopite and biotite in the Curaçá Valley. The work indicates, especially within Cu-rich deposits such as Pilar, that phlogopite can have a high Ni content (up to 3500 ppm). Conversely, in deposits that contain some Ni, such as Vermelhos, phlogopite Ni contents are lower and the Ni is found within sulphides rather than in the silicate phase. Therefore, phlogopite has the potential to be an indicator mineral for Cu or Ni deposits and can aid in the understanding of the mineralogical deportment of Ni within the deposits.

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Evidence for hydrothermal solution of barite in the Central Wales Pb-Zn Mineral District: discussion of textural development and mechanical significance

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Blocks from the Bryn-y-rafr tip show quartz filled moulds (QFM) giving clear evidence for complete solution of a euhedral precursor prior to deposition of a quartz infill. Fine siliceous sediment [1] buried the QFM precursors, preserving their outlines and giving geopetal information. Later deposition of marcasite on the sediment suggests the QFM occur in Mason's [2] A2e barite bearing assemblage.

QFM have outlines indicating a former euhedral crystal with barite morphology. Clear quartz crystals grow in from the euhedral outline of the QFM. Quartz is fine grained at the QFM margin but coarsening inwards, with some crystals showing euhedral terminations in a central vug. Good evidence for open space on the QFM site and complete removal of the precursor. Possible evidence for coupled solution-precipitation replacement [3] was only found in margin of one QFM.

Some blocks show extensive areas of quartz with euhedral terminations growing **towards** the vein wall, indicating a cavity adjacent to the wall. Recesses in this surface are traced into partly filled QFM and the wall cavity lining can be seen to be laterally continuous with the QFM fills. Wall cavities are considered to have formed in the same way as the QFM but with precursor crystals forming a continuous layer.

Growth of barite was followed by deposition of fine sediment over the crystals and its infiltration into spaces between barite crystals. Quartz growing during sediment accumulation [1] may also cover the barite. Barite was dissolved leaving open, locally interconnected moulds. QFM sites filled with quartz and the larger voids became lined with terminated quartz. Immediately after solution was complete vein material was porous, permeable, mechanically weakened and partly separated from the vein wall.

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Lithium in volcano-sedimentary systems: a focus on the Jadar (Serbia) deposit

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Volcano-sedimentary systems (VSS) are an emergent type of "hard-rock" Li ore type with the potential to produce Li through low CO_2-footprint extracting technologies. VSS appear to be developed in hydrologically closed basins filled with lake and epiclastic sediments where lithium becomes fixed in clays (e.g., Thacker Pass, US, [1,2]). The Jadar deposit (Serbia), is the largest Li ore in Europe (Indicated and Inferred Resources of 143.5 Mt @ 0.838% Li) but here the assemblage is uniquely characterized by jadarite ($LiNaSiB_3O_7(OH)$) as the main ore phase, and represents a particularly Li-fertile VSS. This study focuses on the mineralogical and geochemical Li and B residency and on the diagenetic evolution of the Jadar mineral system. The deposit is hosted in a Miocene lacustrine basin located at the southern margin of the Pannonian basin, spatially related to the Mt. Cer I- to S-type granitic massif [3]. Mineralisation is hosted by dolomicrite and siltstone interbedded with tuffs. Mineralogical and geochemical data coupled with stables isotope data from dolomite suggest that the Li-B mineralization formed in two diagenetic stages. The first evolutionary stage took place in a shallow lake environment marked by high evaporation and salinity, which favoured alkaline diagenetic processes. Under these conditions, breakdown of volcanic glass in presence of Li-B-Na brines led to the formation of Li-rich B-silicates. The epigenetic subsidence of the basin triggered the decay of the kerogene, releasing organic and carbonic acids and buffering the pH of the system. The resulting partial dissolution of Li-B-silicates prompted a localized geochemical and mineralogical decoupling of Li and B leading to the formation of late diagenetic Li-phosphates and borates.

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The Arasbaran Magmatic Belt in NW Iran and its tectonic and metallogenic evolution

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The Arasbaran belt in northwestern Iran is part of the Tethyan orogenic collage. The tectonic and metallogenic evolution of the Arasbaran Magmatic Belt (AMB) is confined by its regional position as it straddles the border between Armenia-Azerbaijan and Iran. The AMB was formed as a Cenozoic magmatic arc near the southern margin of the Lesser Caucasus and is the second-largest copper porphyry belt in Iran. The AMB is associated with Late Oligocene to Early Miocene magmatism and is a subdivision of the Tethyan Metallogenic Belt (TMB). Some of the world's major porphyry systems in the Eurasian continent, besides those hosted by the dominantly Paleozoic Altaids (syn. Central Asian Orogenic Belt), sandwiched between Tarim, Siberia, and East European cratons, are part of the Mesozoic-Cenozoic TMB, extending across central and southeast Europe to Turkey, Iran, Pakistan, and Southeast Asia. The TMB hosts many Cu–Mo–Au porphyry, base-metal skarn, and precious metal epithermal deposits. These include the world-class Sungun porphyry Cu-Mo deposit and the nearby Haftcheshmeh Cu-Mo-Au deposit and other large porphyry deposits including Kighal and Niaz, skarn-type deposits including Sungun, Mazraeh, Anjerd and Ghowdal, and epithermal deposits including Sharafabad, Sarikhanlou, Safikhanlou, and Doostbaiglou [1]. Contemporaneous porphyry deposits discovered in AMB of Armenia comprise Agarak, Kadjaran, and Dastakert. The available data suggest that all deposits in the Arasbaran belt are related to the temporal evolution of the Tethyan arc magmatism and closure of the Neo-Tethys Ocean and post-collision of the Central Iranian Block and the Eurasian plate. Tectonomagmatic zonation, petrological, and isotope features of crustal architecture as well as geophysical signatures and distribution of seismic activity reflect a complex pattern of microplate assemblage controlling magma fertility and mineral potential of the distinct crustal blocks.

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Insights into Rare Earth Element Mineralisation Associated with Alkaline Igneous Roof-Zone Deposits: Motzfeldt Igneous Centre, Gardar Province, Southern Greenland

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The Motzfeldt Igneous Centre forms part of the Igaliko Complex: one of the major complexes of the Mesoproterozoic Gardar Igneous Province of Southern Greenland. This syenitic intrusion hosts a Ta-Nb-Rare Earth Element (REE)-Zr alkaline-silicate roof zone deposit, containing several metals classed as "critical" to the UK economy by the UK government in 2022 [1][2]. Since it lies between Europe and North America, Greenland is an attractive prospect for exploration with the potential to meet a significant percentage of western critical raw material demand.

Previous work on alkaline-roof zones has focussed upon the Nb-Ta mineralisation, with the behaviour of REEs being neglected despite their significant enrichment in the ore body. This study addresses this by carrying out detailed mineralogical, geochemical, and microtextural analysis of REE-enriched syenite variants from Motzfeldt using BSE-SEM imaging, EPMA, WDS mapping, and RAMAN spectroscopy.

Several REE-phases were identified including REE-phosphates (xenotime and monazite) and REE-F-carbonates (bastnäsite, synchysite, and parasite). First order deportment calculations reveal that in the most pyrochlore rich seams being targeted for exploitation, ~66% of Nd is hosted as a minor-trace component in pyrochlore, with the remaining third hosted in pyrochlore alteration phases.

Textural analysis reveals many elements in pyrochlore (REEs, Th, Ca, Na, Nb, F) are liberated from crystals during hydrothermal alteration. This results in the formation of "crusts" of secondary minerals on pyrochlore, with compositions that reflect elements lost during the alteration of primary crystals. In some samples, these crusts are remobilised by a later hydrothermal event, enriching a late fluid in REEs, potentially linked to late-veins and conduits crossing the roof-zone. This forms a carbonatite-like material, comprising ~40% modal major REE minerals. Importantly all the fluorcarbonate minerals have established methods of resource extraction.

The hydrothermal reworking of the pyrochlore microsyenite has played a key role in the final distribution of the REEs at Motzfeldt, underscoring the importance of late-stage processes in developing ore deposits in alkaline igneous systems.

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Gold mineralisation and vein paragenetic relationships in the Loch Tay area of Central Scotland

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Sulphide-bearing quartz veins associated with gold mineralisation [1,2,3] have been identified at targeted locations in the Loch Tay area of Central Scotland. However, both the genetic relationships between gold occurrence types and the mineralization style(s) relating to widespread alluvial gold remain unresolved. This study has two main objectives which facilitate predicting the nature of (as yet) undiscovered auriferous mineralization, that is also the source(s) of alluvial gold: i) to establish the paragenesis of gold-bearing veins in the Tay and Almond catchments, including compositional variations of gold between paragenetic stages; ii) to investigate any genetic variation between compositional signatures of gold from in situ, gossan and adjacent alluvial occurrences. Mineralogical analyses of sulphide-bearing vein samples have been executed using scanning electron microscopy and cathodoluminescence, to illuminate different quartz generations alongside. The characterization of populations of gold particles was achieved by combining alloy compositions and inclusion suites.

In situ mineralization at Calliachar Burn and River Almond records the temporal overlap of separate fluid pulses and at least two gold input events, late in the overall paragenesis and often associated with pyrite. Near Ardtalnaig, many vein quartz textures resemble those commonly associated with epithermal settings and the inclusion suite from the adjacent placer gold (including molybdenite and bismuth-bearing minerals) is consistent with derivation from a magmatic fluid.

In all cases, the range of gold alloy signatures exhibited by particle populations from alluvial localities is larger than that observed in local eluvial and in situ samples, suggesting subtle variation in mineralogy within geographically proximal and genetically related vein systems. Importantly, the suites of mineral inclusions recorded in the alluvial gold samples are almost entirely consistent with the mineralogy of adjacent veins. Consideration of the inclusion assemblages has allowed classification of the auriferous veins as either of orogenic or magmatic-hydrothermal origin.

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Lithium potential of Kazakhstan

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Lithium enrichments are well known from Palaeozoic and Mesozoic rare metal granites and pegmatites across Transeurasian orogenic belts. Kazakhstan is well-known for its endogenic rare-metal mineralisation in Early, Middle and Late Palaeozoic settings. Lithium, among other rare metals (Be, Cs, F, Hf, Mo, Nb, Rb, Sn, Ta, W, Zr), is found mainly genetically and spatially related to magmatic activities of accretionary, collisional and late- to post-collisional formations. Little research has been published to date on lithium enrichments in volcano-sedimentary basins and caldera setting, geothermal waters and oil brines.

World-class tin (Syrymbet), tungsten (Verkhny Kairakty), rare-earth elements (Verkhnee Espe) and molybdenum (Shalgiya) deposits have been discovered decades ago. All of them contain lithium mineralisation in either greisens and veins or weathering crust. But complex ore processing properties have in many cases affected and delayed or even prevented commercially sustainable mine development. Most attention is currently paid to rare-metal pegmatites in the Kalba-Narym belt in East Kazakhstan that have been mined in Soviet times and currently attract a renaissance in mineral exploration focused on lithium (spodumene) and by-products (Nb, Ta, Cs, Rb, Sn) [1,2,3].

The unique Alakha and Kalguta spodumene-bearing granite intrusions are located in the south-eastern most part of the Greater Altai of Kazakhstan across the Russia-Kazakhstan state border. The metallogenic zone prospective for Lithium extends into the Kazakhstan territory and is manifested in rare-metal (W, Mo) granites associated with poorly constrained greisen mineralisation.

The lithium potential of Kazakhstan is largely underexplored and requires a thorough assessment using modern criteria. Here we present the first results of a scoping study that aims to compile an inventory of Li-bearing mineral systems of Kazakhstan, to characterise for the identified objects the mineralogy, geochemistry and geological setting, to evaluate new features (anatomy) using a modern mineral system approach, to elaborate their geometallurgical constraints and present refined exploration models.

Acknowledgements
This is a contribution to NERC Highlight Topic NE/V007068/1 LiFT (Lithium for Future Technology). The research was also supported by the grant No. AP14870387 "Assessment of the lithium potential of Kazakhstan, criteria controlling deposit formation and guiding exploration" funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan.

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The surface chemistry of carbonatite soils: Implications for REE resources.

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The rare earth elements (REE), and in particular neodymium and dysprosium, are essential for renewable energy devices such as wind turbines and the development of electric motors for transport. At present the REE are sourced from either low concentration weathered granitoid (ion adsorption clay) deposits in southern China, or from high concentration carbonatite-related deposits [1], especially the World's dominant REE mine in hard-rock, altered carbonatite at Bayan Obo, China, but also including the Mt Weld weathered carbonatite, Australia. Weathered carbonatites (e.g. Tomtor, Russia; Mount Weld, Australia) are some of the world's highest grade REE deposits. As part of the NERC Global Partnerships Seedcorn fund project WREED, we have carried out preliminary investigations in weathering products on carbonatite hosted REE deposits. Three end member deposit styles can be identified – in situ residual deposits, where carbonate dissolution has generated primary REE mineral enrichment on palaeosurfaces or in karst; supergene enrichment from dissolution and reprecipitation of REE phosphates and fluorcarbonates forming hydrated phosphates or authigenic carbonate minerals; clay and oxide caps (either from in situ weathering or from soil transport from surrounding rocks) that may hold the REE adsorbed to mineral surfaces (c.f. the ion adsorption deposits). High grade weathered carbonatite deposits typically consist of supergene horizons, that may be phosphate-rich due to dissolution and re-precipitation of apatite and monazite during the weathering process (Mount Weld [2][3]), overlain by later sediments that may be REE enriched either by accumulation of residual minerals in lacustrine places (Tomtor [4]). The mineralogy of the ore zone is linked to, but distinct from, the unweathered carbonatite rock, and includes phosphates, crandallite-group minerals, carbonates and fluorcarbonates and oxides. We have carried out leaching studies, SEM examination and XPS characterisation of soil and weathered rock samples from a range of deposits. Residual and supergene processes can result in enrichments up to 100x times bedrock concentrations, with residual enrichments in particular hosted in monazite and bastnäsite for which processing streams exist. Supergene enrichment results in more complex mineralogy which may present processing challenges. Clay-rich soils have much lower REE concentrations. However, sequential leaching studies demonstrate that a significant proportion of REE are present at trace levels in the oxide fraction in residual and supergene deposits. In clay caps the easily leachable fraction of REE matches that of ion adsorption deposits and may represent a potentially easily extractable resource. Further work will investigate the processes involved in different weathering styles, and the potential for beneficial inter REE fractionation and separation from the actinides.

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Application of the PRISMA satellite hyperspectral data for mapping alteration facies in the Bou Azzer Co-Ni mineralized district, Morocco

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The Co-Ni arsenide ore deposits at Bou Azzer, Morocco, represent an uncommon type of Co mineralization, located in the central portion of Anti-Atlas chain. The ores, distributed along Hercynian reactivated major Paleoproterozoic Eburnian and Neoproterozoic Pan-African faults, are structurally controlled, and occur mainly within quartz-carbonate veins along the boundaries between the Neoproterozoic serpentinized mantle peridotites and quartz diorite-Precambrian volcanic rocks orebodies. Generally, the ores show evidence of zoned hydrothermal alteration patterns [1]. The aim of this study was to map mineralized facies and country rocks outcropping in the Bou Azzer district using the PRecursore IperSpettrale della Missione Applicativa (PRISMA) satellite hyperspectral sensor.

The Italian Space Agency's PRISMA satellite, comprises 234 spectral bands in the Visible Near (VNIR - 400 to 1300 nm) and Short-Wave InfraRed (SWIR - 1300 to 2500) wavelength regions, with spectral resolution of ~13 nm and Ground Sampling Distance (GSD) of ~30 m [2]. For this study, the SWIR wavelength region was considered since it contains diagnostic absorption features of several minerals either occurring in country rocks or associated with hydrothermal alteration zones occurring in the ore bodies proximity. The feature-based band was applied to the PRISMA data of the studied area, allowing to extract spectral information useful for identifying Al-bearing sheet silicates (i.e., white micas, smectite), chlorite, talc, serpentine, calcite and dolomite and to produce mineral distribution and composition maps of the district. The PRISMA performances were assessed by comparing PRISMA reflectance spectra, to United States Geological Survey (USGS) spectral library references. Finally, the Spectral Angle Mapper (SAM) method was performed, in order to understand the mutual distribution and relative abundance of the investigated minerals.

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PRISMA satellite hyperspectral remote sensing for mapping hydrothermal and supergene alteration zones: the Marimaca Copper district (Antofagasta Province)

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The Marimaca district is located in the Coastal Cordillera of northern Chile and consists of several Iron Oxide-Copper-Gold orebodies of Late Jurassic to Early Cretaceous age [1]. The host rocks are characterized by upward and outward zoned hydrothermal alteration patterns (sodic-calcic, potassic, sericitic). The primary mineralization underwent a supergene alteration, resulting in the formation of oxidized and iron-rich leaching caps [2]. In this study, we applied the feature-based band ratios method to the PRISMA hyperspectral imagery with the aim of mapping the relative abundances and composition of specific hydrothermal and supergene alteration minerals, that are optically active in the Visible Near (VNIR) to Short-Wave Infrared (SWIR) regions (400-2500 nm). The Italian Space Agency's PRISMA satellite is a pushbroom sensor that records 234 bands in VNIR-SWIR spectral range at a spatial resolution of 30 m [3]. PRISMA data were processed using a range of band ratio in the region around 900 nm and from 2100 nm to 2300 nm to extract the relative abundances of Fe-hydroxides and Hydroxyl-bearing minerals (white micas, chlorite, epidote, kaolin group and sulphates), and to evaluate their compositional variations through the shift of adsorption features position. The resulting PRISMA mineral maps allowed to recognize the hydrothermal alteration zones (potassic, propylitic, sericitic) and the areas covered by supergene leaching caps, as well as to define a new exploration prospect few kilometres east of the main Marimaca deposit area. The method proposed can be considered a useful cost-effective tool for mineral exploration and ore deposit characterization at district scale that can be applied to other deposits type worldwide.

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To Recrystallise or Not? The Petrogenesis of the Qeqertaasaq Phoscorite-Carbonatite Complex

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Carbonatites are igneous rocks composed of ≥50% carbonate [5] and can contain significant REE and Nb, metals used in the production of green technology. Despite their importance to the economy carbonatite deposits remain poorly understood [7]. From current understanding, carbonatites form in plutonic carbonatitic and alkaline-carbonatitic complexes within intracontinental extensional settings [5]. However, evidence of their petrogenesis is often lost to secondary processes, which have also been shown to change the stable isotope composition of carbonatites from the Gardar Province, southern Greenland [1] [2].

The Qeqertaasaq phoscorite-carbonatite complex, southwest Greenland, formed due to the intrusion of magma into the West Greenland Archaean gneiss complex between 200-150 Ma [6]. Previous work suggests REE, Nb and other elements increase in concentration with evolution of the complex, with no explanation being provided [4]. Thus, providing ground to investigate whether secondary processes have caused the enrichment of these elements, or if they are involved in the original petrogenesis of the carbonatite complex.

Modelling of $\delta^{18}O$ and $\delta^{13}C$ compositions of the carbonatites provides a framework for the geological history of the Qeqertaasaq complex, including the alteration of lithologies by hydrothermal fluids causing REE enrichment, in addition to degassing of the magma body and formation of minor carbonatite veins. This is further supported by textures identified during SEM analysis. For further work, the isotopic values of alkaline-carbonatite complexes near to Qeqertaasaq could be analysed to determine a source for the fluids causing REE enrichment, providing possible tools for REE exploration in Europe.

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VECTOR: investigating social attitudes, environmental and technical challenges to mining in Europe

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VECTOR (Vectors to Accessible Critical Raw Material Resources in Sedimentary Basins) is a European research project investigating social attitudes, environmental and technical challenges to mining in Europe, and dedicated to sharing our new understanding.

The EU set out its goals for decarbonisation in the EU Green Deal, which include achieving Net Zero by 2050, and reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels).

Ensuring that the supply of renewable energy needed to achieve these goals is met will require a sharp increase in production, and a more responsible use, of critical raw materials. Whilst recycling can provide an increasing portion of these materials, recycling alone cannot meet the projected demand, which implies that further mining will be required if the EU is to meet its climate goals.

Sourcing raw materials from inside the EU, where suitable environmental, social, and political regulations could be implemented, may be instrumental in securing an ethical provision of metals. However, mineral projects face complex challenges in the EU.

These challenges include the:

- Technical - for example, we need a precise knowledge of the whereabouts of subsurface mineral deposits on the continent.
- Environmental - for example, we need to develop the least invasive forms of exploration to minimise impacts to the environment.
- Social - for example, there is a lack of social acceptance of mineral exploration across Europe.

The purpose of the VECTOR project is to explore these challenges. The consortium of 18 partners aims to understand the origin, connections, and complexities of the challenges, and consequently to develop solutions that may be used to address them. A major objective is to include all stakeholders, including the often overlooked and underappreciated general public, in a dialogue about the sourcing of critical raw materials within Europe. The project partners will investigate potential solutions that incorporate as many perspectives as possible, address environmental concerns, and solve technical challenges. This will result in pathways towards sustainable, responsible mineral exploration in Europe, which can serve as a reference for the rest of the world.

Hydrothermal Apatite: A Distal Proxy for Potassic Alteration in Porphyry-Cu Systems?

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Porphyry Copper Deposits (PCDs) require new exploration approaches capable of identifying concealed deposits. The chemistry of detrital apatite may be used effectively in regional exploration surveys to identify traces of PCDs in distal settings [1]. This is because magmatic apatite is abundant in PCD environments and its chemistry can permit a large variety of trace element substitutions (e.g. REE, Sr, Th, U, Mn, Fe, Mg, Si, Na) that re-equilibrate with hydrothermal fluids [2]. However, the extent to which apatites from different alteration zones around PCDs have unique chemical identities has been understudied. This precludes the separation of ore-bearing potassic alteration from un-mineralized alteration in detrital sediments.

Here, we investigate the variation of apatite chemistry in fresh and altered rocks from PCDs of the Baguio Mineral District, Philippines. Synthesising these results with a legacy database, we identify the global consistency of these chemical patterns whilst generating a model for characterising apatite from ore-bearing alteration assemblages.

Unaltered rocks contain Th and LREE-enriched (LREE > 3500 ppm) apatite with concentric zoning and well-formed crystal boundaries. By contrast, apatite from hydrothermally altered samples is relatively depleted in LREE, Th, XOH, Sr and enriched in XF and Si. The internal zonation is patchy and crystal boundaries are irregular. Specifically, apatite from samples with potassic alteration is greatly enriched in Mn (> 1500 ppm) and HREE (e.g. Yb > 10 ppm). These trends reflect the metasomatism of magmatic apatite under differing fluid temperatures and compositions [3]. This chemical variation is persistent on a global scale and linear discriminant analysis can identify porphyry related hydrothermal apatite with an accuracy of up to 88.5%. This statistical test can also delineate ore-bearing alteration assemblages 87% of the time.

Our results further the evidence of apatite re-equilibration in a wide range of alteration zones associated with PCDs [3]. Additionally, we demonstrate that apatite chemistry from the most economically prospective zones of potassic alteration is markedly distinct from that in the mostly barren propylitic terranes. This furthers the utility of detrital apatite not only for recognising PCD alteration, but also identifying the presence potassic alteration from afar.

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Tracing potential by-products Te, Bi and W through beneficiation at Björkdal Gold Mine, Sweden

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The transition away from hydrocarbons and race to net-zero requires a huge increase in metal and mineral consumption for low-carbon technologies. However, mining and minerals processing is energy-intensive and can be environmentally harmful, thus there is a need for novel solutions in extraction and processing. Te, W and Bi are designated 'high criticality' on the British Geological Survey's list of critical metals for the UK, for their applications in industry and green energy production such as for solar panels (Te), pharmaceuticals and alloys (Bi), and wear-resistance (W). However, production is dominated by a few countries and limited number of mines, and demand is expected to increase. More, and more sustainable, supply options are needed.

Due to gold's high unit value, it is economic to mine much lower grade ores than most other metals (such as copper or aluminium), resulting in gold having a notably higher relative carbon footprint [1]. However, gold deposits are often enriched in other rare metals, for example the Björkdal mine produces gold concentrates and tailings variably rich in Te, Bi and W-bearing minerals. Currently, there is little incentive and few options by which to process and extract these additional metals for Mandalay Resources, the mine operator [2]. Developing a way in which these metals could be recovered on site would be ideal for meeting some of the demand for these metals, without opening any new mines.

This work looks at tracing the flows of Te, Bi and W through the Björkdal processing plant, and mineralogically characterising feed, tailings and concentrates. Bulk geochemistry of ore, concentrates and tailings has been carried out externally by ALS Laboratories, and compared to automated SEM analysis. Target metals deport almost entirely into bismuth telluride minerals (Bi and Te) and scheelite (W), which are well-liberated in all concentrates and tailings. High grades of scheelite in some concentrates particularly are promising for recovery, potentially using gravity and/or leaching techniques. The next steps for this research will be to test the feasibility and impacts of inserting leaching stages with Deep Eutectic Solvents (DESs), and/or altering the processing procedure or reprocessing tailings, in order to maximise by-product recovery in an environmentally-friendly and low energy process.

Deep Eutectic Solvents (DESs), developed at the University of Leicester, are a promising advancement for both gold and by-product extraction. They are powerful organic solvents and crucially are liquid at room temperature. The components are cheap, readily available and environmentally-benign compounds, such as choline chloride and urea, and can be recycled and reused [3][4]. Previous work on DESs has demonstrated rapid leaching of Au, Ag, Sb, Te and other metals, including success with dissolution of tellurides and bismuth tellurides [2][5].

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A Geologist in the Circular Economy

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The UKRI Interdisciplinary Circular Economy Centre for Technology Metals (Met4Tech) has brought together a multidisciplinary team from across the whole value chain of the specialist metals such as rare earths, lithium, cobalt, tin and tungsten that enable so many of our green and digital technologies and are essential to achieving our NetZero ambitions.

I will discuss three points that we have learned about circular economy.
The first is about how exploration geology and mining fit into the circular economy. The term 'circular economy' (CE for short) is often used to describe the back loops in the materials cycles – recycling, re-use and repair, for example, but CE describes the whole economy. Concentrating on the back loops will never create a good and circular economy. The most effective actions to ensure circularity take place on the inbound steps of the materials cycle to ensure that products are designed ready for the back loops – and the first inbound steps are geology and mining.

The second is that CE is multi- and interdisciplinary – and about more than the 'techno' circular economy which is the most obvious, and interesting probably, to geologists. The exponential increase in demand for all raw materials needs to be mitigated by all kinds of interventions. Using less is a good place to start, using for longer and having effective regulation all need interdisciplinary collaborations. In Met4Tech we are trying to balance all these interventions to create a technology metals CE roadmap for the UK.

The third is about taking geological eyes to secondary resources. We do need to get much better at recycling and also re-using, repairing and remanufacturing. Geological concepts of the spatial distribution of ore deposits, concepts of ore grades, sizes and resource estimation and notions of reserves, resources and deposits are all applicable to anthropogenic resources.

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Sulphide isotope geochemistry of Au-Pb-Zn-Ag veins at Loch Tay, Scotland

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In recent years, the successful exploitation of Au at Cavanacaw and Cononish has encouraged further exploration in the Scottish Grampian Terrane. One area of current interest, due to the longstanding knowledge of auriferous mineralisation in the area, is Loch Tay [1]. Here, several polymetallic veins with a consistent strike of 120-140° sporadically outcrop throughout a 100km^2 swathe of Dalradian metasediments [1]. In some places, the mineralisation is spatially associated with Siluro-Devonian granitoids, e.g. the Tomnadashan Mine [2]. However, genetic information on the metallogeny of Loch Tay remains sparse. Our research seeks to elucidate whether the ore-forming fluids involved in each deposit were derived from a common source, or if they represent different mineralising episodes. In this presentation, we demonstrate the preliminary results from $\delta^{34}S$ signatures from galena, pyrite and chalcopyrite, to elucidate the "same or different" question.

Most of the veins throughout Loch Tay have $\delta^{34}S$ values between +5 and +10‰. However, the $\delta^{34}S$ signature from Ardtalnaig galena is +2.3 and +1.8‰. The results from this locality are similar to previous analyses that were conducted on sulphides from Tomnadashan (+0.5 and +2.0‰) [3]. The Ardtalnaig-Tomnadashan system may therefore represent a different system of mineralisation compared to the rest of the veins around Loch Tay. Lighter $\delta^{34}S$ values similar to the ones reported from here are typical of magmatic mineralisation processes [3].

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Investigating the enrichment of critical metals in granitic pegmatites from NE Scotland: melting process or protolith?

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The increasing global demand for electric vehicles has resulted in a marked increase in demand for Lithium (Li). Global supply of Li is controlled by a handful of countries, magnifying the risk of disruption to the global supply. Li, Tantalum (Ta) and Beryllium (Be) are often associated with Sn-W granites and lithium-caesium-tantalum (LCT) pegmatites, which are typically considered to form by anatexis of metasedimentary protoliths However, there is still uncertainty about the processes that act to concentrate these metals. This project aims to track these elements from the primary source to the mineralised granitic pegmatite.

Classically, LCT pegmatites were considered as the most evolved melts derived from parental granites that had a metasedimentary source. Recent studies have shown that some LCT pegmatites could be genetically unrelated to a fractionated granitic pluton and instead may be associated with direct melting of a metasedimentary source (e.g. [1],[2],[3]). These studies further emphasise the importance of protolith composition and crustal melting processes in critically evaluating whether an enriched pegmatite could result purely from anatexis.

We are investigating the potential concentration pathways of these critical elements, via combining *in situ* trace element analysis of individual mineral phases with modelling. By analysing contrasting samples, we aim to gain insights into the mobility and partition of critical metals during different stages of the melting process.

Detailed fieldwork at coastal sections at Portsoy and Fraserburgh NE Scotland was undertaken during summer 2021. These costal sections showcase excellent exposures of Dalradian migmatitic metasedimentary rocks closely associated with granitic pegmatites.

- We report a range of concentrations of Li and Ta from metasedimentary migmatites to granitic pegmatites with the highest values observed in the Portsoy pegmatite mica and tourmaline.
- Li mica from the Portsoy pegmatite has Li concentrations of up to ~5000ppm (parts per million). Elbaite tourmaline has up to 8000ppm of Li.
- Li concentrations in migmatites are lower than in the pegmatites, with biotite from metasedimentary units attaining Li values up to ~500ppm, while schorl tourmaline yields maximum Li concentrations of ~50ppm.
- In contrast to the Portsoy pegmatite, at Fraserburgh concentrations of Li and Ta in pegmatites are much lower and mostly dominated by biotite and magnetite.

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Key geological features and genesis of high-grade hypogene porphyry Cu deposits

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Porphyry Cu deposits host the majority of global Cu resources. High-grade hypogene porphyry Cu deposits (HGHP) are of particular interest to industry because of the reduced waste and energy consumption required in exploitation, leading to favorable economics and reduced environmental impact. We summarize the geology of significant HGHP porphyry deposits worldwide and identify key features that are frequently associated with high-grade mineralization. The sulfide assemblages constituting high-grade Cu mineralization are mainly of high-sulfidation state (bornite, digenite, covellite, chalcocite and enargite). A high density of quartz veins, breccia bodies, lode veins and cavities, representing significant open space creation phenomena, are the dominant host of high-grade Cu concentrations. There appear to be several favorable host rocks to high-grade hypogene ores, such as mafic rocks (potentially acting as effective pH buffers and reductants to promote sulfide deposition), carbonates (impermeable host rock to trap and concentrate hydrothermal fluids and effective pH buffers), and cemented sandstones/quartzite (impermeable trap and favorable host of high Cu/S ratio, high-sulfidation state sulfides). On the lithospheric scale, compressional or transpressional tectonic settings may be important for HGHP deposits to facilitate protracted deep magma evolution and long-lived magmatic-hydrothermal systems, as well as increasing the probability of superposition and telescoping of multiple events in the same location.

We find that a surprisingly large proportion (75%) of HGHP deposits have high-grade Cu mineralization associated with low-temperature (<400 ºC), acidic (sericitic to advanced argillic) hydrothermal alteration with late and shallow-crustal features. We suggest there are at least three reasons for this: 1) SO_2 disproportionation and rapid decreases in Cu solubility happen as fluids cool below ~400 ºC, corresponding to the chlorite-sericite alteration facies; 2) the most significant permeability creation often develops late – during rapid, syn-mineralization exhumation and magma doming stages – when the rock mass behaves in an increasingly brittle fashion and retrograde silica solubility occurs; 3) telescoping of the magmatic-hydrothermal system during such 'live' exhumation leads to overprinting of early sulfide assemblages by late-stage acidic and oxidized hydrothermal fluids that remobilize early Cu as well as adding additional Cu and thereby causing hypogene enrichment.

Genesis of the Subduction-Related Baotan Magmatic Ni-Cu Sulfide Deposit in the Western Jiangnan Orogenic Belt, South China

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The Baotan magmatic Ni-Cu sulfide deposit is situated in the western Jiangnan orogenic belt which marks the collisional suture between the Yangtze and Cathaysia blocks in South China. The intrusions were emplaced into early Neoproterozoic metamorphosed sedimentary rocks and consist of gabbroic and ultramafic portions. There are two types of sulfide mineralization associated with the intrusions: (1) disseminated sulfides that occur near the base of bodies of peridotite and clinopyroxenite; (2) massive sulfides in the metasandstone wall rocks. Zircon U-Pb isotope analyses reveal the consistent early Neoproterozoic age (835 Ma-840 Ma) for these ore-forming intrusions. Whole-rock samples are all characterized by moderate light rare earth element (REE) enrichments relative to heavy REEs and pronounced negative Nb-Ta anomalies, similar to those in arc-type ultramafic cumulates elsewhere in the world [1]. Furthermore, Cr-spinel in the ore-bearing rocks are remarkably similar to those in arc cumulates worldwide [2]. The studied rocks are characterized by negative whole-rock Nd-Hf isotope compositions ($\varepsilon_{Nd}(t)$= -2.3~-7.9 and $\varepsilon_{Hf}(t)$=-0.5~-4.3), suggesting involvement of both metasomatized mantle and continental crust materials in their genesis. These rocks also show enriched zircon Hf-O isotopic compositions ($\varepsilon_{Hf}(t)$=-0.4~-5.9 and $\delta^{18}O$=5.2~7.0). It is suggested that the ore-forming rocks were most probably derived by partial melting of metasomatized lithospheric mantle and the parental magma experienced extensive crustal contamination at a crustal level. The $\delta^{34}S$ and $\gamma_{Os}(t)$ of the sulfide ores are from 1.3‰ to 5.7 ‰ and from 32 to 147, respectively. These values indicate that extensive introduction of crustal sulfur played a key role in triggering sulfide segregation in the magma. Like some other subduction-related magmatic sulfide deposits [3, 4], the platinum group element (PGE) contents in the Baotan silicate rocks and ores are relatively low (44-598 ppb). PGE depletion in the Baotan parental magma is most likely due to previous sulfide segregation at depth or sulfide retention in the source mantle during partial melting. The above observations confirm that subduction-related mafic-ultramafic intrusions are capable of hosting economic Cu-Ni sulfide mineralization and should be considered as prospective targets for global Ni exploration.

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