ORAL PRESENTATIONS

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SESSION ONE: INNOVATION IN UNDERSTANDING CRITICAL MINERAL SYSTEMS AND DEPOSIT GEOLOGY

Predicting porphyry copper prospectivity with plate reconstruction models and machine learning

***Edward Clennett*[1], *Moloud Rahimzadeh Bajgiran*[2], *Jonny Wu*[3], *Herve Rezeau*[4]**

1University College London, UK
2Princeton University, USA
3University of Arizona, USA
4Massachussets Institute of Technology

Porphyry copper systems are known to be strongly controlled by plate tectonics and related petrological processes. Therefore, plate reconstructions are increasingly being used to help find new copper deposits, often integrated with geochemical data in machine learning frameworks. However, the tectonic history of the North America Cordillera is debated, with competing models for the number and polarity of subduction zones, timing and location of exotic terrane accretion, and nature of strike-slip motion. In addition, identifying the unprospective rocks used to train AI models poses an additional challenge. In this study, we train machine learning models on three different plate reconstruction models, assessing the correlation between porphyry copper deposits and different tectonic factors to build a predictive model. We also investigate the effects of implementing a significantly larger labelled training database of unprospective rocks, compiled using magmatic fertility indicators. We find that the distance to a ridge-trench intersection and the convergence rate are the strongest controls of copper deposit formation, although the ranking of parameter importance changes depending on the tectonic history implemented. We then use our machine learning models to predict the probability of forming a porphyry copper system at any given time and location along the North American Cordillera. Our results show that all models predict high prospectivity in southern British Columbia between 80-60 Ma and in Arizona and Mexico throughout the Laramide period. However, there is high variability in the mineral predictions in Alaska and Yukon, and we therefore suggest that detailed investigation of the tectonic history of this region should be a priority. Our framework represents a way of assessing uncertainty in large-scale, AI-informed mineral predictions and provides a method for more robustly identifying prospective regions for porphyry copper exploration.

Prospectivity on a Plate: Tectonic Reconstructions for Critical Mineral Targeting

Jamie Price*[1]*, *Bruce Eglington*[2]

1SRK Consulting
2University of Saskatchewan, Canada

Critical mineral deposits form in geological settings that change over time. As continents move and oceans open and close, mineralised belts can be fragmented or displaced by later tectonic events. However, most regional exploration studies do not explicitly incorporate palaeo-location, instead focusing on present-day configurations rather than the arrangements that existed when mineralisation formed. This can hide relationships and make it harder to recognise areas that were favourably positioned during mineral-system development. This work develops a repeatable workflow using plate reconstructions to support critical mineral exploration, using the Neoproterozoic Arabian-Nubian Shield of northeast Africa and Arabia as a case study.

By closing the Red Sea and restoring the pre-rift connection between Nubia and Arabia, now-displaced terranes, suture zones, magmatic belts and mineralised belts can be correlated across the reconstructed shield. Geological, geophysical, geochemical, and mineral-occurrence data can be moved back into their reconstructed positions. Recently released public datasets from the Arabian Shield, including high-resolution aeromagnetic data and multi-element stream-sediment geochemistry, can guide critical mineral exploration in less explored parts of the Nubian Shield.

Plate reconstructions can be used to examine where portions of crust were located during key stages in the development of the Arabian-Nubian Shield. Any mapped feature can be relocated through time using plate reconstructions. These areas can then be assessed against the geological conditions associated with a selected critical mineral or deposit type. For example, the approach can identify crust that occupied favourable arc, back-arc, suture, collisional or post-collisional settings. It can also consider how later deformation and erosion affected the preservation and present-day exposure of prospective rocks.

This work highlights the value of plate reconstructions as a predictive tool in early-stage critical mineral exploration by reconnecting displaced terranes, identifying new search spaces, and helping to reduce the cost, land disturbance and environmental footprint of exploration programmes.

Evolving tectonic style governs metal mineralisation in mountain belts

***Alex Copley*[1]**

1University of Cambridge, UK

Mountain belts host many in-demand metallic ores, with a wide range of uses, but the tectonic controls on their distributions have been only partially explored. This presentation addresses this issue by applying a recently-developed understanding of the structure, dynamics, and evolution of mountain belts to the question of metal mineralisation. The results show that presence and distribution of Tin, Tungsten, and related ores is governed by the location and magnitude of low-angle thrusting (` thin-skinned shortening') on range-fronts, with regions of high-angle reverse faulting (` thick-skinned shortening') unable to result in mineralisation. Copper porphyry distributions depend upon crust that is thick enough for the required evolution of mantle melts, but thin enough that the mountain belt has not reached it's dynamically-limited elevation, and begun to form a slowly-eroding and internally-draining plateau. Therefore, the dynamic evolution of mountain belt deformation, thickness, and range-front shortening style, and their interaction with surface erosion, govern large-scale patterns of mineralisation. These results have been applied to a range of locations (e.g., the Andes, Iran, western North America, Europe, and New Guinea), and provide a means of global range-scale assessments of mineralisation potential in past and present mountain belts.

Magmatic Ni-Cu-Co-PGE deposits from craton to orogenic belt: new search space for battery metal discovery

***David Holwell*[1], *Daryl Blanks*[2], *Marco Fiorentini*[3]**

1University of Leicester, UK
2BHP
3University of Western Australia, Australia

Conventional models for the magmatic Ni-Cu-Co-PGE sulfide mineral system emphasise the requirement for a large heat driver to sufficiently melt enough mantle peridotitic olivine to liberate Ni into the resultant melts; hence much exploration is focussed within Large Igneous Provinces (LIPs) which have undergone high temperature melting, e.g. via mantle plumes. However, it is becoming apparent that melting of hydrous, metasomatized mantle can also produce metal-rich melts, but at lower melting temperatures and as such, opens up a broader range of non-LIP related settings for Ni-Cu sulfide potential. Based on this understanding, we have identified evidence of diverse mantle source compositions and melting dynamics in the variable chalcophile metal signatures of magmatic Ni-Cu-PGE deposits. Through Earth history, the metal signature of magmatic sulfide systems evolves, with mostly high temperature melting events producing Ni- and PGE-dominant deposits >1.8 Ga, associated with large igneous provinces (LIPs). Conversely, from 1.8 Ga onwards, low temperature melting of hydrous mantle becomes more common, forming dominantly Ni- and Cu-dominant rich deposits that are characteristically poor in PGE, and generally have no spatial or temporal link with LIPs. We interpret these secular changes to be a function of: (1) a cooling mantle from the Archaean to the present; (2) varying compositions of mantle as a product of a spectrum of mantle metasomatism processes; (3) the mineralogical deportment of chalcophile metals in mantle rocks; and (4) the variety of thermal triggers to melt such assemblages. We provide a predictive capacity to assess the relative metal fertility of mafic-ultramafic systems through time, opening up new search space for exploration and potential discovery.

A 4D Petrogenetic Model for the Uis Pegmatite Field

***Joseph Benson*[1]**, *Nicholas J. Gardiner*[1], *Joshua M. Garber*[1], *Nicholas M.W. Roberts*[2], *Harvey Pickard*[2], *Richard M. Palin*[3], *Laurence J. Robb*[3]

1University of St Andrews, UK
2British Geological Survey, UK
3University of Oxford, UK

As major sources of the world's lithium, tin, and tantalum, Lithium-Caesium-Tantalum (LCT) type pegmatites are vital exploration targets. Yet, their ore forming processes remain heavily debated, with the specific roles of source composition, melting conditions, and magmatic fractionation in controlling whether a system becomes economically mineralised still unresolved.

To evaluate these competing models of LCT-type pegmatite formation, we present a study of the Uis Pegmatite Swarm in the Damara Orogen, Namibia. This region provides an exceptional setting to disentangle the drivers of mineralisation because it encompasses the Uis Li-Sn-Ta mine, well-exposed mineralised and unmineralised pegmatite suites, and three distinct regional granite suites (Salem, Grey, and leucogranite). By integrating fieldwork, petrography, and mineral-based microanalysis, including geochronology, we develop a 4D petrogenetic framework for the Uis Pegmatite field.

Multi-mineral U-Pb geochronology has been necessary to untangle the age relations, and we use zircon, cassiterite, titanite, monazite, xenotime and apatite to provide a robust magmatic age framework for the region. The Uis pegmatites were emplaced in two phases at c.500 and c.490 Ma, consistent with their late-tectonic intrusion into tension gash structures. Crucially, the majority of the surrounding granites predate the pegmatites by up to 50 Ma, ruling them out as parental magmas. While, Hf isotopes in zircon reveal these granites are derived from distinct sources. Reset apatite U-Pb ages of c. 490 Ma within these older granites record a widespread thermal event linked to pegmatite emplacement.

Mineral trace element analysis yields a record of progressive metal enrichment and demonstrates that the pegmatites and nearby leucogranites underwent separate paths of magmatic evolution. Our findings indicate that the Uis Pegmatites likely originated independently as small volume melts of a distinct protolith late in the orogenic cycle during a late, regional thermal event.

Magma recharge modulates major element evolution and REE mineralisation potential in alkaline-silicate rocks: a case study of Erongo, Namibia

***Caroline Soderman*[1]**, *Corinne Frigo*[1], *Owen Weller-Gibbs*[1], *Charles Beard*[2], *Teresa Ubide*[3]), *Silvio Mollo*[4]

1University of Cambridge, UK
2Utrecht University, the Netherlands
3University of Queensland, Australia
4INGV, Italy

Alkaline-silicate igneous complexes demonstrate substantial major element diversity in their evolved rocks, from nepheline syenites to granites, accompanied by varied REE mineralisation styles. Fractional crystallisation, pressure, crustal assimilation and magma recharge are known contributors to major element heterogeneity. However, their role in modulating trace element budgets and mineralisation potential in these systems is complex and remains poorly studied. Here, we investigate how mafic magma recharge and crystallisation may have suppressed mineralisation potential in the barren alkaline plugs of the Erongo Complex, Namibia.

Associated with the Etendeka-Parana large igneous province, Erongo is a volcanic-plutonic complex containing a late-stage suite of alkaline basanite-phonolite plugs representing a co-magmatic series formed at shallow depths with minimal crustal contamination. Unlike some contemporaneous Namibian alkaline complexes, these plugs lack late magmatic REE-mineralisation in the form of structurally complex zirconium silicates such as eudialyte. Crucially, the suite contains abundant concentrically-zoned clinopyroxenes—robust recorders of recharge. Recharge events are marked by Cr peaks correlating with decreases in Fe#, and REE and Zr concentrations. Associated sieve textures indicate partial resorption of clinopyroxene by hot, primitive magma between crystallisation intervals.

We use phase equilibria models, incorporating dynamic (composition and temperature-dependent) trace element partitioning, to successfully reproduce the major element and REE profiles observed in zoned clinopyroxenes. Our results demonstrate that frequent magma recharge dampens REE enrichment in residual melts (especially middle REE), partly by promoting clinopyroxene crystallisation. Middle REE, such as Sm, become compatible in clinopyroxene during fractionation, so are stripped from evolved melts. Zirconium behaves similarly to REE in this system, hindering late-stage Zr enrichment which could prevent the formation of REE mineralisation in Zr-silicates such as eudialyte. Consequently, we propose that magma recharge must be considered as a key control on REE and major element budgets of alkaline-silicate systems, with repeated mafic recharge limiting mineralisation potential.

Look Up, not Down! Rare Earth Mineral Deposits in the Roof Zones of Alkaline Igneous Intrusions

Adrian Finch*[1]*, *Krzysztof Sokół, Will Hutchison, Matthew Lewis, Curtis JW Rooks*[1]

1University of St Andrews, UK

The roof zones of alkaline igneous bodies are often the site of mineralisation, due to their chemical and thermal gradients. They are also volatile rich, such that many high field-strength elements (HFSE) become mobile. Several processes take place in roof-zones including hydrothermal alteration of country rocks in the roof ("fenitization"), assimilation of roof rocks and, in some cases, their anatexis. The magma in the roof may form an isolated lens with composition and properties distinct from that in the main body of the intrusion. To unpick the many processes in the roof zone, we examine fenitization around the nearby Illerfissalik (Greenland) intrusion. At Illerfissalik, a fluorine-rich fluid phase altered the country rocks, transporting HFSE into the envelope around the intrusion. Illerfissalik presents a system where the role of fenitization in the transport of HFSE is studied in isolation (Sokół et al. 2022). Armed with this information, we make sense of the more complex roof system at Motzfeldt where fractionation and assimilation of the quartzite accompany the fenitization.

Processes to products in supergene enrichment of carbonatite-hosted REE deposits.

***Martin Smith*[1], *B. Maciag*[1], *S. Broom-Fendley*[2], *Martin Li*[3], *Wei Chen*[4], *Frances Wall*[2], *Pankaj Kumar*[1], *Curtis Rooks*[1], *TuomAs Grasten*[5]**

1University of Brighton, UK
2Camborne School of Mines, University of Exeter, UK
3Imperial College London, UK
4China University of Geosciences, China
5Sokli Oy, Finland

Carbonatite-hosted rare earth element (REE) deposits provide most of the World's light REE, including Nd and Pr; they are key resources for decarbonisation and high technology industry. Lateritic weathering of carbonatite produces particularly rich REE grades, as at Mount Weld in Australia, and many weathered deposits are under exploration. It is therefore important to understand the supergene processes controlling enrichment and mineralogy of the REE. As part of the NERC funded SCREED project we have studied the geochemistry, mineralogy and microbiology of deep weathered carbonatites. Study sites include the palaeo-weathering profile at Sokli, Finland, and actively weathering carbonatite at Longonjo, Angola. Rare earth redistribution processes include residual enrichment of primary minerals, dissolution and active supergene enrichment in secondary phosphates and fluorcarbonates, and adsorption on to clays and oxyhydroxides, alongside mechanical transport through karst collapse, fluvial and eluvial processes. Residual enrichment is the dominant process, but dissolution-reprecipitation as authigenic (alumino-)phosphates resulting in the formation of anomalous REE patterns is a major control on final mineralogy. Adsorption onto clays is limited by the high pH of the local carbonatite interacting groundwater, but oxides can host a significant portion of the REE content. Overall, data support genetic models whereby the lateritic profile is not the product of a single continuous weathering event. REE-enriched profiles form through a repeated cycle of dissolution and collapse, accompanied by residual enrichment and dissolution-reprecipitation processes which control the final mineralogy and the potential for inter-element fractionations. Theoretical considerations indicate that dissolution-reprecipitation of phosphates would be limited in normal rainfall derived groundwater, and microbial processes must play a major role in mineral dissolution, confirmed by analysis of the soil microbiome at Longonjo. Geochronology of palaeo-systems indicates that an extended period is required for significant deposit formation, and correlates with periods of sea level fall as well warm palaeo-climates.

From Magma to Mineralisation to Groundwater: Deep Drilling a REE-Rich Carbonatite

Sam Broom-Fendley*[1]*, *Kathryn Goodenough*[2]*, Pauline Smedley*[2]*, Catherine Mottram*[3]

1University of Exeter, UK
2British Geological Survey, UK
3University of Portsmouth, UK

Carbonatite complexes form under some of the most extreme petrological conditions on Earth and can host large, high-grade rare earth element (REE) deposits. However, REE enrichment results from prolonged magma-fluid evolution, and REE-mineralised carbonatites are typically highly out of equilibrium with surface conditions, leading to rapid oxidation and alteration. Consequently, the structure and compositional evolution of carbonatites are difficult to constrain from surface exposures, particularly in relatively shallow systems. Carbonatites can also be a source of geogenic fluoride, posing risks to groundwater quality and human health, yet the controls on water-rock interaction, groundwater flow paths and residence times remain poorly understood.

Here we report ongoing work from the ICDP-funded REEDRILL project, which seeks to overcome the challenges of sampling REE-rich carbonatites and to investigate how fluid-rock interactions control mineralisation geometry and groundwater chemistry through time. We outline the project's objectives and planned drilling at the Songwe Hill carbonatite, Malawi. Existing shallow drillcore and deep geophysical data have informed the design of two drillholes to approximately 1200 m and 1450 m measured depth, respectively, providing two inclined sections through an inferred vertically zoned system. Doping drilling fluids with a tracer compound will allow assessment of contamination and evaluation of drilling-induced dissolution of pristine carbonatite minerals and impacts on groundwater samples. A comprehensive programme of fluid sampling and packer testing will further constrain the influence of carbonatites and associated alkaline rocks on local water resources, particularly as a source of geogenic fluoride. Combined with existing datasets, Songwe Hill will provide the deepest vertical section through a carbonatite complex available to the scientific community, improving genetic models for carbonatite-hosted REE deposits worldwide.

Potential role of molten salts and metaevaporites for IOCG deposit formation

***Michael Anenberg*[1]**

1Australian National University, Australia

Iron oxide copper-gold (IOCG) deposits host copper and gold, together with critical metals such as cobalt and the rare earth elements. Despite decades of research, there is no consensus on their formation, or even their classification. Many IOCG provinces are associated with sedimentary basins bearing evaporitic signatures, preserved as scapolite, chlorine-rich biotite and amphibole, or relict evaporite minerals. For example, the Gawler Craton in South Australia hosts the Olympic Province beside the Wallaroo Group, whereas the Cloncurry region in Queensland juxtaposes the Eastern Succession IOCG belt with the paleoevaporite-bearing Corella Formation. Deep drilling reveals metaevaporites retaining substantial chlorine in high-grade schists, while seismic sections suggest links between these metasedimentary rocks and IOCG deposits.

We propose that partial melting of evaporites during burial, metamorphism or magmatic heating generates molten chloride–carbonate–sulfate salts capable of mobilising metals and modifying surrounding rocks. These processes may resemble carbonatitic brine-melts and fenites, respectively. Molten salts can dissolve components poorly transported by silicate melts or aqueous hydrothermal fluids, and may react with silicates (akin to carbonatitic antiskarns). Direct evidence for the former presence of salt melts is mostly unknown, probably because they are highly reactive, dissolved by later fluids, or become consumed through wall-rock reactions. Their geological record may instead survive as mineral inclusions, unusual phase assemblages including refractory residues, reaction fronts, and geochemical signatures.

Deformation and recrystallisation as a mechanism for critical metal enrichment: coupled microstructural-geochemical insights from the Rajapalot Au-Co deposit

Lily Dickson*[1]*, *Taija Torvela*[1]*, Rob Chapman*[1]*, Sandra Piazolo*[1]

1University of Leeds, UK

Critical metals are often subordinate to other metals and are recovered as by-products. The geological processes that enrich them are still not fully understood, particularly in gold deposits. These systems can also record complex polyphase mineralisation and deformation histories, yet the influence of these processes on critical metal mobilisation and redistribution is rarely evaluated. Rajapalot, a Au-Co deposit in northern Finland, provides an opportunity to investigate these controls.

Coupled microstructural-geochemical mapping is an emerging but still relatively underused approach in ore deposit studies, and it offers a powerful means of resolving critical metal distributions. Here, we apply this methodology to determine how cobalt is redistributed during deformation and recrystallisation of pyrite, a mineral that hosts significant cobalt at Rajapalot and in many ore types.

Pyrite showing evidence of deformation and recrystallisation was analysed using correlative and quantitative EBSD and EMPA mapping. EBSD data were analysed to characterise strain distribution and accumulation, and the patterns were compared directly with cobalt distribution within individual pyrite grains. EMPA maps reveal distinct chemical domains, notably high-Co domains exhibiting primary oscillatory zonation and low-Co domains with homogeneous composition. Strain accumulation occurs in the high-Co oscillatory-zoned domains, whereas the low-Co domains are strain-free and adjacent to straight grain boundaries with 120˚ triple junctions, indicating grain boundary migration and annealing of the deformed pyrite.

Mass balance calculations for the two domains indicate that annealing of up to 35%, as observed in the studied samples, is sufficient to liberate enough cobalt to form >50 µm-sized cobalt minerals, provided cobalt is sequestered locally within newly forming minerals. These results demonstrate that deformation and subsequent annealing can release cobalt from pyrite and generate cobalt minerals that may be recoverable during processing. This highlights the broader importance of microstructural controls on critical metal behaviour in deformed, polyphase ore systems.

Diamonds to detect critical metal evolution in the mantle (DIADEM)

***Hannah S.R. Hughes*[1]**, *Nivea Magalhães*[2], *Karen V. Smit*[3], *Ian Butler*[4], *Iain McDonald*[5], *Ingrid Chinn*[6]

1Camborne School of Mines, University of Exeter, UK
2University of Exeter, UK
3University of the Witwatersrand, South Africa
4University of Edinburgh, UK
5Cardiff University, UK
6De Beer Group Services

Many ancient cratons are rich in valuable and critical metals that drive our modern world — from gold and platinum to copper, nickel, and cobalt. In the Kaapvaal Craton for example, the Witwatersrand Basin has produced a third of the world's gold, while the nearby Bushveld Complex holds 90% of the planet's platinum resources. But a crucial question remains unanswered: Why are some of Earth's cratons so rich in metals while others are not? Are these metals delivered in short-lived bursts during special geological events (a so-called 'Goldilocks Effect') or do they build up slowly over billions of years?

In our new DIADEM project, we will investigate how metals and sulfur are stored, redistributed, and transported through time beneath the Kaapvaal Craton of southern Africa. Nickel, cobalt, the platinum-group elements (PGE) and some other critical metals have a strong affinity for sulphur (chalcophile) in the Earth's mantle – these elements are mostly hosted in base metal sulphides (BMS).

BMS in mantle xenoliths and inclusions within diamonds are our only direct insights into the geochemistry of chalcophile elements at depth. However, at temperatures <1100^{0}C, BMS undergo subsolidus re-equilibration, fractionating inclusion composition. Traditional analytical techniques either partially sample BMS metal compositions (e.g., in xenoliths) or, in diamond inclusions, require complete extraction and consumption of the inclusion for a single analysis (often Re-Os to indicate age, without accompanying analysis of metals or stable isotopes). Here, we demonstrate that a homogenisation method designed to reverse the effects of subsolidus fractionation can be successfully applied to BMS inclusions in diamonds, enabling compositional, stable isotope and geochronological measurements to be made from single inclusions, permitting the geochemical history of chalcophile critical metals below cratons to be mapped through space and time. We present pilot study data showing differing metal contents between different diamond parageneses (eclogitic and peridotitic) [1].

References:

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Building a domestic critical minerals supply chain for the UK

***Jeremy Wrathall*[1]**

1Cornish Lithium, UK

Over the last ten years Cornish Lithium has built the foundations of a secure, domestic supply chain of refined, battery grade, lithium for the UK. Recent changes in geopolitics highlight the absolute requirement for a secure, domestic supply of critical minerals, given their role as the fundamental building blocks of modern technologies. Without such sovereign supplies the UK is vulnerable to disruption and the "choking off" of metals and minerals that enable technologies such as electric vehicles, power storage batteries and, most importantly, drones for defence.

Cornish Lithium is building a secure supply of refined lithium hydroxide for high power ternary batteries which are essential for defence and other industries. This has required innovation and delivery across all the topics that this conference sets out to discuss. i.e.

- Innovation in understanding critical mineral systems and deposit geology
- New approaches to critical mineral exploration and targeting
- Geometallurgy, downstream processing and implications for mineral processing
- Circular economy along the mining value chain
- ESG and minimising environmental impact
- Supply chain mapping and minerals intelligence

Founder and Executive Chairman Jeremy Wrathall will cover all the above topics and highlight the innovations that have been required on the journey so far.

Liquid ores: the multi-commodity mineral potential of saline geofluids

***Konstantin Nazarov*[1]**, *Jon Blundy*[1], *Nick Hankins*[1], *Rick van der Ploeg*[1], *Mike Reynolds*[2]

1University of Oxford, UK
2Shell Research

The world's geothermal and oilfield brines may be the liquid ores of the energy transition: vast, continuously circulated flows of underexplored water carrying critical minerals that could complement conventional mining and strengthen supply security. Traditionally treated as waste streams, heat carriers or single-commodity lithium brines, saline geofluids have rarely been assessed as mineral systems in their own right.

We test that proposition against the GeoFluid DataHub, a compilation of 165,613 water-source records. Two findings emerge together. First, wherever broad trace-element suites exist, multi-element endowment is consistnent across independently characterised systems; and because elemental flux scales with concentration multiplied by fluid throughput, the enormous volumes moved by energy production convert modest concentrations into substantial annual elemental fluxes. In the best-constrained geothermal fields the theoretical gross value of the dissolved metal flux is comparable in magnitude to or often exceeds that of the associated electricity generation.

Second, the evidence base is far weaker than the sample count implies. Only 0.7% of records report twenty or more analytes; lithium is determined in 13,018 records, but germanium in 233, silver in 432, gold in 50 and tellurium in seven. Across United States wells lithium has been determined at 6.4–10.7% of sites and silver at 0.2–0.9%. The contrast reflects analytical history rather than geochemistry: these maps record where each element has been sought, not where it occurs.

These observations are sufficient to recognise saline geofluids as a prospective multi-commodity resource class, but not to forecast recoverable supply. Progress requires time-resolved multi-element characterisation coupled to reservoir geology and fluid throughput, together with long-duration extraction trials on authentic brines to overcome the technical challenges of recovering metals from dilute solutions with sustaiable technologies. Treating saline geofluids as reservoir-to-product mineral systems provides the framework within which their demonstrated endowment can be tested against recoverable supply.

Parys Mountain: An Old Mine, A New Mineral System

James McFarlane*[1]*, *Michael Wilkinson*[1]

1Anglesey Mining Plc, UK

Parys Mountain (Anglesey, Wales) hosts the UK's largest polymetallic Volcanogenic Massive Sulphide (VMS) Resource; 16.1 Mt at 0.98% Cu, 1.33% Zn, 0.71% Pb, 15 g/t Ag and 0.17 g/t Au. Copper extraction dates from the Early Bronze Age and it was reputedly the world's largest copper mine in the late 1700s. Copper is identified by the UK Government as a Growth Mineral supporting the clean energy and advanced manufacturing sectors, while zinc is included on the UK Critical Minerals list.

Despite extensive foundations from its long history of mining and exploration, the more recent work on the project has been episodic and is in need of re-evaluation. Newly restructured and with fresh management, Anglesey Mining is undertaking a complete technical reappraisal with a mineral systems approach to unlock the real potential of one of the UK's most unique and fascinating mining projects.

This is being achieved through a series of technical workstreams. Initially, a first-principles review of work-to-date – historical exploration data, geological interpretation, resource modelling and estimation – to reassess the geological and resource framework. Secondly, the prior lithogeochemical and stratigraphic work is being revisited using modern approaches to develop a higher-resolution understanding of lithostratigraphy, alteration, structure and controls on mineralisation. Third, a renewed metallurgical investigation is being used to develop a detailed understanding of deposit geometallurgy, including modern pre-concentration technologies and their potential implications for downstream processing and waste-stream management.

The central concept is a shift from a single deposit-centred interpretation towards an integrated mineral-systems model. Parys Mountain contains multiple documented mineralised deposits and, by reconstructing the model in this way, opportunities are appearing for material drill targets to grow the Resource base.

Further, the framework being developed also provides a basis for applying improved geological understanding to exploration across the wider system and even district scale.

Beyond Lithium Grade: A Geochemical Framework Enhancing LCT Pegmatite Project Evaluation, Exploration and Geometallurgy

***Radu-Gabriel Miron*[1]**

1SRK Exploration Ltd

With the rapid growth of the battery and electric vehicle sectors, lithium–caesium–tantalum (LCT) pegmatites have become a critical source of lithium. In these deposits, mineralogy, particularly the dominant lithium mineral species and associated by-products or deleterious phases, is as important as grade - it directly influences processing routes, recoveries and overall project viability.

LCT projects at early development stages commonly have well constrained lithium grade data, but mineralogical information is often sparse, qualitative and not systematically integrated with geochemical data. To address this gap, SRK Exploration developed a geochemical classification framework that uses routine multielement whole-rock assays to assess mineralogy and pegmatite fractionation. A structured series of hierarchical geochemical filters, element ratios and fractionation indicators are applied to sampling data to classify the degree of fractionation or crystallisation stage of pegmatites by their bulk mineralogy, infer lithium mineral species and inform on potential by-products and penalty elements.

The framework was initially developed as a rapid audit tool for project due diligence. However, applying it across pegmatite fields has demonstrated its value for exploration vectoring and targeting by identifying spatial fractionation trends and domains that are favourable for lithium-in-spodumene. Classification of drilling data identifies pegmatite groups and mineralogical zonation, supporting resource and geometallurgical domaining. The framework links geochemical signatures to the crystallisation process, itself critical to mineralogical characteristics and processing behaviour. It is not intended to replace conventional mineralogy; it is an additional tool that can provide earlier insights and allow rapid, low-cost interpretation of large amounts of data that is potentially more representative than that from more limited mineralogical sampling locations.

In this presentation, we will outline the methodology and demonstrate its application on various LCT pegmatite projects, highlighting how an assay-based mineralogical classification can inform and accelerate project evaluation, exploration targeting and geometallurgical decision-making.

Tectonic settings for porphyry copper formation in the Northern Great Basin, USA

***Hero Bain*[1]**, *Frances J. Cooper*[2], *Dan Bevan*[3], *Thomas N. Lamont*[4], *Tim Elliott*[5], *Nick M.W. Roberts*[6], *Audrey Bouvier*[7], *Adam Gorecki*[8]

1University of St Andrews, UK
2University College London, UK
3University of Western Australia, Australia
4University of Nevada, USA
5University of Bristol, UK
6Geochronology and Tracers Facility, British Geological Survey, UK
7University of Bayreuth, Germany
8BHP

Copper demand is rising rapidly, driven by its critical use in electric technologies which underpin the global green energy transition. Clustering of porphyry copper deposits (PCDs) in space and time within arcs implies that tectono-magmatic controls play an important role in their formation. If better constrained, these controls could help guide exploration.

In the copper-rich Laramide Porphyry Province (LPP) of Arizona, most PCDs are thought to have formed between ~75–54 Ma, synchronous with a relaxation of contractional stress during the onset of flat-slab subduction. However, in the adjacent Northern Great Basin (NGB: Nevada-Utah-Idaho), a lower copper endowment and longer, episodic history of PCD formation (~170–24 Ma) suggests the tectonic controls were different. To explain this difference and resolve the tectonic settings of PCD formation in the NGB, we compare the distribution of PCDs to the spatial-temporal history of crustal contraction, relaxation, and extension, as preserved in three metamorphic core complexes.

To constrain the timing of deformation we use in situ Rb-Sr dating of syn-kinematic micas that grew during contractional and extensional ductile shearing, and petrochronology of prograde metamorphic mineral assemblages: U-Pb monazite and allanite, and Lu-Hf garnet dating. Integrating our new geochronologic constraints, we identify two settings for PCD formation:

(1) Late Cretaceous slab-flattening: PCDs formed synchronously with peak metamorphism, crustal anatexis, and core-complex decompression. We suggest these are analogous to PCDs in the LPP, though far less abundant.

(2) Eocene-Oligocene slab-rollback: PCDs formed during a widespread volcanic flare-up and the initiation of core complex exhumation, but prior to substantial upper-crustal Basin and Range extension. This tectonic setting prevails in the time gap between slab-rollback and the onset of rapid extension. In the LPP there is no time gap between the two events, which may explain the lack of this later phase of PCD formation in the LPP.

Characteristics of chromite-bearing serpentinization in the Robusha Peridotite Massif, Tibet, and their relationship to regional tectonics

***Hongyuan Zhang*[1], *Junlai Liu*[1], *Chengyu Jiang*[1], *Kaixiang He*[1]**

1China University of Geosciences, Beijing, China

The chromite-bearing Robsha Peridotite Massif shows podiform plastic deformation of massive chromite, complicating mineral exploration. Ore bodies initially underwent a deep mantle-level emplacement stage (Stage I), involving the formation of layered chromite, plastic deformation of chromite, and igneous crystallisation of chromite-bearing peridotites such as harzburgite and dunite, followed by mylonitization and brecciation of peridotite. Subsequently, a crustal-level serpentinization stage (Stage II) occurred. This stage generally begins with a peridotite breccia (II-1), followed by the development of an outer shell of massive black to dark green serpentine (II-2). Upward in the sequence, serpentine colour varies, with local development of lens-shaped structures (II-3) and green fibrous zones (II-4). Kinematic analysis indicates that this period (II) is generally characterised by southward movement of the upper block, possibly due to two factors. One possibility is that it reflects oceanic core complexes across a mid-ocean ridge, with the original polarity of detachment. Vertical magmatic activity, evidenced by mafic rocks intruding into serpentine, also suggests extensional tectonics. Tectono-magmatic processes commonly result in the co-occurrence of ultramafic rocks, mafic rocks, serpentine, and ore bodies. Two distinct regional extensional stress fields are identified: one dominated by east-west and another by north-south upright joints. These stress regimes likely alternated, influencing areas below the Moho level.

Furthermore, horizontal joints host multi-stage and multi-type serpentine, representing multiple phases of north-south contraction. This is consistent with the kinematic polarity of the Indian plate's northward subduction and reflects the broader context of plate convergence. During the later stages of serpentinization, corresponding to the transition from oceanic to continental crust (Stages III–IV), the kinematic direction shifted to northward movement of the upper block, which is consistent with the Great Counter Thrust located south of the Gangdise granitic belt (GCT).

A Systems Approach to Viable Mineral Exploration

Matthew Grimshaw[1]

1Worth Discovery

Demand for the minerals needed for sustainable development is rising, while discovery rates continue to fall. The usual response is to invest more heavily in the same exploration activity or additional detection techniques. However, a viable discovery depends on more than geological prospectivity.

Exploration decisions are often framed as technical choices: a deposit model determines the appropriate geophysical survey, drilling method or sampling programme. In practice, these choices are shaped by the wider system in which exploration operates. Access, seasonal and environmental constraints, Indigenous rights and consent, permitting, tenure, water, infrastructure and logistics can determine not only when work can take place, but which methods are feasible and the quality of evidence that can be obtained.

This presentation sets out a systems approach to exploration viability. It shows how technical, operational and above-ground factors can be mapped as connected dependencies, allowing teams to identify bottlenecks, test scenarios and define practical actions earlier.

The convention of resolving the geology first and addressing the remainder later is no longer viable. A viable exploration target is considerably more than good geology.

Wednesday 18 November 2026

SESSION THREE: SUPPLY CHAIN MAPPING AND INTELLIGENCE

Understanding Resilience in Critical Raw Material Supply Systems

Lingli Zhou[1]

1Durham University, UK

Critical raw materials underpin modern economies and are indispensable for digitalisation, clean-energy transitions, and advanced manufacturing. At the same time, their supply systems are increasingly exposed to geological constraints, market concentration, geopolitical tensions, environmental and social pressures, and climate constraints. This work develops a geology-informed, system-level framework for understanding resilience in mineral-based critical raw material supply systems. By integrating concepts from economic geology, mineral economics, and resilience theory, it analyses vulnerabilities across upstream, midstream, and downstream segments of mineral value chains and examines how disruptions distribute through the integrated system. Building on this analysis, the work distinguishes between short-term engineering resilience, focused on buffering, redundancy, rapid recovery, and longer-term system resilience, which emphasises adaptation and structural transformation. A portfolio of resilience strategies is mapped across value-chain stages and time horizons, highlighting the complementary roles of technological innovation, diversification, governance, and sustainability. The framework is applied to selected critical raw materials, including cobalt, lithium, and rare earth elements, illustrating how material-specific geological, technological, and market characteristics shape vulnerability and resilience. The work demonstrates that resilient critical raw material supply systems require layered, material-specific strategies that combine short-term stabilisation with longer-term adaptive and transformative capacity.

Evolving the UK Criticality Assessment: New Ideas, New Needs

Christian Bishop[1], *Dr Pierre Josso[1], Dr Anastasia Kadochnikova[1], Isaac Watkins[1], Rowan Halkes[1], Dr Holly A L Elliott[1], Dr Narendra Singh[1], Tom Bide[1], Karen Kirk[1], Romaine Graham[1], Annabelle Luce[1]*

1British Geological Survey, UK

The 2024 UK Criticality Assessment was the most comprehensive process to discern the minerals which are crucial for the UK economy but are at risk of supply disruption, leading to a list of 34 critical minerals (see Mudd et al, 2024). The methodology adopted a risk management approach, incorporating four indicators for the global supply risk dimension and three indicators for the UK economic vulnerability dimension. Global supply risk incorporated production concentration by country (the higher of mining or smelting / refining and modified by an index of environmental, social and governance or ESG factors), trade concentration through imports, companionality (the extent to which a mineral is a by-product of a primary product) and recycling rates. UK economic vulnerability was determined through UK apparent consumption (based on value), UK net import reliance (based on mass and expressed as a percentage) and gross value added (representing the economic value of the use of a mineral). The extensive syntheses and analyses of mining, trade, economic and other data from 2018 to 2022 allowed the discerning of the 34 critical minerals for the UK context. There are, however, a variety of key challenges which needed to be explored for future UK criticality assessments. These include the need to consider climate risks for primary supply, alternative data sources or approaches for ESG inclusion, broader incorporation of trade codes which go further into the midstream and manufacturing, exploring the ability to model market volatility and trade restrictions, modelling economic links between sectors exposed to critical minerals supply disruptions, addressing corporate concentration as well as the ability to incorporate future supply scenarios (demand scenarios remain a future focus). The result of this research has been a range of improvements to the methodology for the next UK Criticality Assessment, providing a more comprehensive and policy-relevant approach.

Mineral Systems and Mineral Criticality: Exploring the Intersection of Policy and Prospectivity

Edward Bunker*[1]*, *Alexandra Scarlet*

1Viridien

Mineral criticality and mineral security have emerged as strategic priorities in recent years owing to the evolving geopolitical landscape and societal drivers such as the energy transition. Many major governments have published national critical mineral lists that highlight the minerals with greatest societal importance and domestic supply risk. These lists have helped to frame critical mineral supply as a national priority and inform policy decisions and government strategy. They also play a key role in raising public awareness of the societal importance of domestic mineral supply and exploration. Despite these virtues, criticality does not equate to commerciality, and critical mineral lists do not provide explorers or investors with guidance on how to meaningfully engage with the problem of securing domestic critical mineral supply.

Here, we explore the interface of mineral criticality with geological systems to better establish pathways through which critical mineral supply can be framed in the context of commercial opportunities. Firstly, we review existing critical mineral lists and discuss their limitations. We then discuss mineral co-occurrence, reviewing previous work to categorise mineral companionality, highlighting principal commodities that are systematically associated with companion elements. We then explore the geological systems that underpin these associations, arguing that critical mineral supply, in many cases, may be more effectively secured from mineral systems with economic companion elements, than through standalone exploration strategies for specific critical minerals. We synthesise this discussion by identifying geological systems with critical mineral associations and reframing the problem of critical mineral supply as an opportunity for reprioritisation of greenfield and brownfield exploration strategies, and mineral co-production. This work may aid in bridging the gap between critical mineral policies, geological realities and commercial priorities by highlighting opportunities to reassess supply risks, explore efficiently and maximise output from existing operations.

Critical minerals for digital technologies

***Holly Elliott*[1]**, *Gavin Mudd*[1], *Christian Bishop*[1], *Luz Ramos Cabrera*[1], *Edward Lewis*[1], *Richard Shaw*[1], *Pierre Josso*[1], *Craig Woodward*[1]

1British Geological Survey, UK

The digital revolution is rapidly integrating artificial intelligence (AI) and quantum computing technologies into everyday life. Our society and economy are becoming increasingly reliant on data and digital services, causing a growing need for data centres that store, process and manipulate this data. These technologies are key to future UK growth and security, and therefore designated as critical technologies and national infrastructure.

Increasing demand for these technologies is causing a subsequent increase in demand for raw materials. Digital technology components are becoming progressively more complex, expanding the range of materials beyond those previously used in classic computers, for example rare earth elements, niobium, lithium, and hafnium. Many materials must also meet very high purity or isotopic purity standards.

Many materials required for digital technologies have been designated as critical in the UK, due to their supply disruption risks and high economic importance. Many are recovered as by-products during the processing of primary commodities and therefore less responsive to market demand. These supply chains are typically juvenile and dominated by a small number of countries, making them vulnerable to disruption. Digital technologies also require similar element suites to other expanding sectors, including aerospace, defence, and renewable energy, potentially leading to future competition between sectors.

Digital technology supply chains are currently limited in the UK. Potential exists for domestic critical mineral production, developing additional sections of the supply chains, and production of high purity and isotopically pure materials. Recycling digital components could establish a secondary supply of materials not able to be extracted in the UK. However, the UK cannot become a world leader in the entire supply chain. International collaboration and strategic partnerships remain important to ensure access to components and raw materials. The UK therefore needs to build a portfolio of skills, materials, components, and processes with which to trade.

A Geology-Based Assessment of Mining Lease Adequacy and Land-Use Efficiency: A 3D Geological Modeling Case Study of a Manganese Deposit in the Eastern Ghats Mobile Belt, India

***Ahmed Koko Suleiman Dalbon*[1]**, *Edupuganti Naga Dhanamjaya Rao*[1], *Adibhatla Santha Ram*[1]

1Andhra University, India

Mining lease boundaries are often set by administrative considerations, with little regard for the orebody's geometry and the spatial requirements of mineral extraction. This can be particularly problematic in structurally complex manganese deposits, where variable orebody geometry and significant waste generation affect both mine development and land requirements. A geology-based approach has been developed and applied to assess the suitability of mining leases and support sustainable mine planning for the Sadanandapuram manganese deposit in the Eastern Ghats Mobile Belt, India. The methodology comprises borehole data, geological interpretation, 3D implicit modeling, geostatistical analysis, resource estimation, waste assessment, and mining land-use analysis. The geological model presents a discontinuous, lensoidal mineralized system with variable thickness and strong directional continuity. Declustering reduced the arithmetic mean Mn grade from ~26.9% to 23.7%. Variography showed anisotropic continuity of ~320 m in the major direction and 180-200 m across it. The modeled mineralized volume is approximately 17.078 million m^3, with approximately 11.122 million m^3 of modeled waste. Operational records also show large quantities of waste relative to ROM ore, emphasizing the importance of orebody geometry for stripping and land requirements. The lease area is 56.837 ha. Of this area, about 47.772 ha is under mining-related activities, and 9.065 ha is nominally unused. The results suggest that the adequacy of a lease should be viewed as a geological-operational property rather than a cadastral property. The proposed framework provides a practical foundation for incorporating orebody geometry, waste generation, land-use requirements, and mineral conservation for sustainable mine planning.

The potential supply of secondary minerals for UK's energy transition

***Jorge Torrubia*[1]**, *Evi Petavratzi*[1], *Richard Shaw*[1], *Narendra Singh*[1], *Tom Bide*[1], *Hannah Grant*[1], *Emma Raycraft*[1]

1British Geological Survey, UK

The UK Critical Minerals Strategy aims to meet 20% of critical mineral demand from recycling by 2035. Achieving this ambition depends not only on future recycling capacity but also on the pace of deployment of energy transition technologies, changes in material intensity and the operational lifespan of products containing critical minerals such as lithium, cobalt and rare earth elements.

This presentation draws on the study Future material demand and secondary supply potential for UK net zero technologies to assess the potential contribution of secondary supply potential to UK critical mineral demand up to 2050. The analysis quantifies the maximum secondary supply potential of 17 critical minerals embedded in batteries, traction motors and renewable energy technologies and compares this with projected UK demand. The analysis explores the key issues surrounding the feasibility of meeting UK Critical Minerals Strategy recycling target and outlines some of the key challenges and opportunities associated with developing a robust domestic circular economy for critical minerals.

Results indicate that for most minerals secondary supply is unlikely to contribute more than 20% of demand between 2030 and 2040. It is not until the 2040–2050 decade that this percentage reaches levels over 70%, as is the case with lithium, cobalt and rare earths. This reflects the long service lives of many energy transition technologies, meaning that significant quantities of critical minerals will not become available for recycling until the mid-2040s and beyond.

While the UK is unlikely to achieve the 2035 recycling target through end-of-life recycling alone, the findings suggest that potential of secondary supply to contribute to critical minerals security is significant from the mid- 2040. Strategic investment in the development of reverse value chain and associated infrastructure is therefore essential to maximise this future opportunity.

The Critical State of Global Copper: For Whom the Bell Tolls?

Gavin M. Mudd*[1]*, *Michiel van Dongen*[2]*, Simon M. Jowitt*[3]*, Pierre Josso*[1]

1British Geological Survey, UK
2Independant Consultant
3Nevada Bureau Mines & Geology

The role of copper in supporting many aspects of modern society remains strong despite its ancient history of use. Copper remains crucial for infrastructure, energy and especially electricity, information technology and a range of applications in chemicals, medical and other sectors. Since the Industrial Revolution, global copper production has risen steadily, driven by a successful mix of technological innovation, market demand and geological factors. At present, increasing demand for copper is being driven by the energy transition, especially the rapid growth in renewable energy and battery energy storage technologies, electrical grid upgrades and the inexorable rise of electric vehicles, as well as the emergence of giant-sized data centres to support artificial intelligence. This historical pattern of success, however, is increasingly competing with constraints such as declining ore grades, increasing mine wastes, land use competition, the energy-water-carbon nexus and social issues. Although copper is typically not designated as a critical mineral, the strengthening demand profile and headwinds are leading to calls for copper to be designated as critical to facilitate government policy and funding support. But are there really great difficulties facing the global copper sector – that is, are resources and reserves actually declining in concert with reducing productivity, leading to real prospects for global supply dwindling? Recent research has built a global database of copper resources and reserves for 2024, including annual production, co- and by-products and key case studies of the various copper projects which have faced difficulties in their development, including how some addressed these to succeed. The research shows that copper remains successful despite the headwinds, but the issues can be specific for each project, suggesting that careful attention needs to be taken for every proposed copper project and a comprehensive approach adopted to understand environmental, social and governance (ESG) factors which could affect project development.

Why by-product critical minerals are a stubborn problem

***Daniel J Smith*[1]**

1University of Birmingham, UK

A number of critical minerals are recovered as by-products from the mining and processing of major industrial metals (e.g. gallium from alumina refineries, tellurium from re-processing of copper refinery anode slimes). There are a number of compounding factors that place their supply chains at risk: small and opaque markets, poor inventories and trade data, monopolised production, inelastic supply, poor profitability… Metal mid-streams (smelters, refineries, and their intermediate and waste products) have been recognised as a priority area in critical minerals strategies, but the by-products will likely remain a stubborn issue. This presentation will outline some of the fundamentals of by-product recovery, and the challenging market conditions that make them a stubborn problem.

Don’t dig it up! In situ reprocessing and remediation of mine tailings to recover critical metals

Gawen Jenkin[1], *Cris Reven Gibaga[2], Sungano Mubaira[3], James Symons, Alex Tanciongco[1], Russell Swift, Jon Chambers[4], Yujie Yan[5], Rich Crane[5] John Henry Gervasio[2], Jessie O Samaniego[2], Carlo A Arcilla[2], Kate Tungpalan[6]) Vinicius De Oliveira[7], Mark Tibbett[7] and the PROMT consortium*

1Centre for Sustainable Resource Extraction, University of Leicester, UK
2Philippine Nuclear Research Institute, Philippines
3DEScycle, UK
4British Geological Survey, UK
5Camborne School of Mines, University of Exeter, UK
6University of the Philippines, Diliman, Philippines
7University of Reading, UK

Tailings are significant potential resources of unrecovered metals, especially in older facilities produced using less efficient mineral processing, and many initiatives are underway to recover metals, including those previously discarded but now classed as critical metals. Removal of toxic metals also serves to remediate the tailings and promote revegetation that stabilises them and reduces the risk of failure. The already finely ground material makes remining and reprocessing of tailings appealing but challenges include the risk of damaging the structural integrity of the tailings, handling costs, and the potential for release of contaminants. Reprocessing in situ is a potential alternative [1].

The PROMT project involved over 40 UK and Philippine researchers working together with mining companies to develop new science and sustainable technologies for in situ reprocessing and remediation of mine tailings, to recover metals, to develop soils and promote plant growth, and to allow the land to be reused. Here we describe a case study on a Cu-porphyry tailings facility at the Philex Padcal Mine in Benguet Province, the Philippines.

Using mesocosm experiments in the natural environment we have demonstrated how we can leach copper using an environmentally benign solvent combined with monitoring solvent infiltration using electrical resistivity tomography (ERT). These show a high proportion of the theoretically leachable copper can be leached in 8 days and demonstrate the use of ERT to monitor the leaching process itself. We also describe the outcome of mesocosm experiments that use applied electric fields to accelerate copper leaching by electrokinetics. The potential for upscaling and commercial application is explored.

[1] Jenkin GRT (2024) Mine Closure 2024 Australian Centre for Geomechanics:30-43 doi:10.36487/ACG_repo/2415_0.03

Mineral Resource Estimation for Critical Mineral deposits : Challenges associated with RPEEE in early stage projects

***Martin Pittuck*[1]**

1SRK Consulting (UK) Ltd, UK

When early-stage projects reach the Mineral Resource milestone, assessment broadens beyond geology and quantification of tonnage and grade. Reporting Mineral Resources in accordance with international reporting codes and standards requires discussion of the Reasonable Prospects for Eventual Economic Extraction.

Whilst not explicitly stated by the codes, this normally requires a conceptual level multi-disciplinary understanding incorporating technical and economic factors that facilitate an assessment of the overall project potential.

The assessment of RPEEE should consider the multi-disciplinary aspects critical to the individual project in question, initially ruling out any fatal flaws and thereafter defining the reporting criteria including mining limits and of cut off grade which is typically assessed on a combination of revenue and operating costs. RPEEE does not normally extend to capital costs and financial modelling.

For projects involving common metals and minerals, mining and processing metrics can be drawn from preliminary testwork combined with benchmarks using publicly available data and comparisons with analogous projects. Commodity price information can also often be drawn from publicly available information: including peer analysis, market commentary and freely available historical and forecast data.

Critical Mineral projects, however, often involve commodities for which there is little or no data in the public domain, companies in the same commodity space may not publish details about their bespoke technology or their offtake agreements for interim products. The markets for finished products may also be immature with particularly volatile trading prices.

Furthermore, the route to revenue may require vertical integration of mineral concentration and hydrometallurgical processing, involving novel processes where there may be limited or no commercial scale precedents.

This paper provides examples of how RPEEE has been addressed in Mineral Resource reports for early stage Critical Mineral projects to help them be considered in the market as investable assets whilst realistically conveying risks and opportunities.

From Waste to Resource: Phytotechnologies for Sustainable Mine Closure

***Rose Ridgeway*[1]**

1Mine Environment Management, UK

Mine waste facilities present significant environmental and geotechnical challenges, including impacts on biodiversity, metal contamination, and long-term stability issues. Globally, mining currently impacts an estimated 50 million km^2 of the Earth's surface. Impacts extend well beyond mine boundaries from contaminated air, soil, and water. As demand for critical minerals grows, so too does the volume of mine waste and associated risks of acid and metalliferous drainage. Sustainable rehabilitation strategies are needed to reduce environmental risks, restore ecosystems, whilst recovering value in mine wastes. We explore the role of phytotechnologies, including phytoremediation and phytomining, in the rehabilitation of mine waste facilities. New experiments show vegetation can help manage contamination while supporting geotechnical stability through erosion control offering circular economy opportunities. Integrating environmental and geotechnical objectives can provide more effective and cost-effective closure outcomes than treating them separately. Case studies from Europe, Australia, and Southeast Asia demonstrate the potential of plant-based solutions. Hyperaccumulator species such as Phyllanthus rufuschaneyi and Odontarrhena chalcidica can assist the recovery of critical and strategically important metals, such as nickel, from contaminated soils while improving soil conditions for future land use. Trials using Cichorium intybus (chicory) have shown the removal of cadmium, lead, and zinc from contaminated soils, while recent experiments show fast-growing and stress-tolerant species such as Bothriochloa macra, Austrodanthonia caespitosa, and Chrysopogon zizanoides help improve slope stability and reduce erosion in challenging mine waste environments. Key factors influencing success, including plant selection, climate and metal uptake characteristics are also be discussed. While phytotechnologies are not suitable for every site, they offer a practical way to combine remediation, ecological restoration, geotechnical stability and circular economy opportunities. These approaches can help turn mine waste from a long-term liability into a resource that supports environmental recovery and sustainable mine closure.

Unlocking Cobalt from Pyrite-Rich Mine Residues: What Diagnostic Oxidation Reveals About Metal Liberation

***Ummul Sultana*[1]**

1University of Queensland, Brisbane, Australia

Mine residues containing sulfide minerals represent a potentially important secondary source of critical metals, but their utilisation requires an understanding of how valuable metals are hosted and liberated during mineral transformation. This study uses diagnostic oxidative leaching to investigate cobalt liberation from a fine grained, pyrite rich material and to examine whether increasingly severe oxidation necessarily translates into improved metal recovery.

Ammonium persulfate (APS) was used as an atmospheric diagnostic oxidant, with single-dose, stepwise and continuous oxidant addition compared to pressure oxidation (POX) as a benchmark for extensive sulfide oxidation. Progressive oxidative treatment substantially increased cobalt liberation, with recoveries reaching approximately 77% under selected APS conditions. Controlled oxidant addition improved recovery relative to single-dose treatment, demonstrating the importance of maintaining oxidising conditions during progressive breakdown of the sulfide matrix. However, complete pyrite oxidation was not achieved.

Characterisation of the resulting residues provides insight into this limitation. Residual-persulfate and blank experiments showed rapid oxidant consumption and significant thermal decomposition, while X-ray diffraction identified persistent pyrite and formation of elemental sulfur in APS-treated residues. Surface analysis further indicated the coexistence of sulfur at multiple oxidation states. In comparison, POX produced substantially more complete mineral transformation, with disappearance of pyrite and elemental sulfur and formation of secondary iron phases.

The results show that cobalt liberation is strongly coupled to transformation of the pyrite matrix, but also demonstrate diminishing benefit from increasingly intensive atmospheric oxidation. Importantly, the APS experiments are considered as diagnostic tools for understanding mineral liberation rather than as a proposed commercial flowsheet. The findings highlight the value of combining diagnostic leaching with residue characterisation to identify the degree of mineral transformation required for recovery of critical metals from complex mine residues, while avoiding unnecessary reagent and energy demand.

Roadmaps for Critical Minerals Sustainability—What Can Be Achieved, Where and by When?

***Desire Runganga*[1], *Peta Ashworth*[2], *Bishal Bharadwa*[3]*j*, *Helen Cabalu*[4]

1Western Australia School of Mines, Australia
2Curtin Institute for Energy Transition, Australia
3University of Calgary, Canada
4Curtin University, Australia

This paper assesses the extent to which science and innovation have kept pace with critical minerals sustainability ambitions. It tests whether there is sufficient Knowledge of: (i) the Source of harm; (ii) the current Status; (iii) the Contexts in which the harm occurs; (iv) defined sustainability Ambitions; (v) technology Readiness to address the harm; and (vi) Pathways towards achieving those ambitions (K-SSCARP). The test is applied across environmental dimensions, including acid mine drainage, tailings, water, emissions, biodiversity, mine closure and traceability. Findings suggest that we do not yet know what levels of environmental performance can be achieved, by when, or in which mineral-producing countries. Hence, there is a lack of roadmaps that translate sustainability ambitions into measurable targets, timelines, technologies and implementation pathways. Therefore, there is a need to develop national and global roadmaps that define achievable performance today and establish scientifically informed and context-specific targets for 2035 and 2050, together with the technologies, interim milestones, investment and enabling conditions required to reach them.

Integrating Socio-Political Impacts on Local Mining Communities into Low-Carbon Technology Production Systems to Facilitate a Just Transition

***Diana Rincon Valbuena*[1]**

1University of Warwick, UK

The global rush for Critical Raw Materials (CRMs) to meet Western decarbonisation, digitalisation, and security agendas reinforces asymmetric governance models that prioritise state-business alliances over mining communities. Although voluntary frameworks such as ESG, OECD due diligence, the EU's CRMA, and other initiatives to promote sustainable and responsible mining exist, structural integration remains incomplete and key gaps persist. This creates a clear disconnect between Global North sustainability metrics and Global South territorial challenges, leaving community protection largely dependent on corporate will.

To address these disparities, this study moves beyond conventional voluntary standards by arguing for the integration of localised socio-political impacts directly into clean technology production systems as an essential design variable. Utilising the Social Life Cycle Assessment (S-LCA) framework, aligned with UNEP (2020) and ISO 14075 (2024), this research analyses the integration of 81 literature-extracted impacts across six core dimensions.

Preliminary findings from a global panel of 10 experts show that impact integration varies by dimension. While Human Rights, Local Employment, and Community Development are considered more often, their integration remains generalised and driven by investment trends, overlooking critical site-specific, long-term impacts such as territorial fracture, localised inflation, and socio-environmental degradation. Conversely, Cultural Heritage and Governance remain under-addressed, while Health and Safety focuses almost exclusively on physical operational hazards, neglecting psychological or systemic epidemiological risks.

Furthermore, expert interpretations indicate that integration priorities vary by mining region. In Africa, supply-chain scrutiny prioritises child labour; in Latin America, water access is the dominant biophysical risk; and in the Asia-Pacific, land expropriation is paramount. In contrast, North American and Australian priorities shift towards workplace culture and social pathologies. Ultimately, this research provides a framework for delocalising current practices, arguing that clean technology systems must adapt to territorial realities to account for the true socio-political cost of the energy and digital transition and, in doing so, facilitate a just transition.

Industry-Academia Outreach: Engaging Future Professionals in Responsible Critical Minerals Development

Ben Lepley[1]

1ERM

Delivering the critical minerals required for the energy transition depends not only on geological potential and technical and economic feasibility, but also on attracting new professionals to the minerals and mining industry. As expectations for responsible resource development increase, the sector needs a diverse workforce that can navigate trade-offs, build stakeholder confidence and deliver responsible mining.

This presentation examines how interdisciplinary industry–university outreach can support skills development to expand the potential workforce. Drawing on workshops with students at two UK universities, we try to show that mining, contrary to public perceptions, is a key contributor to sustainable development.

The workshops moved beyond traditional career talks by encouraging critical thinking amongst students with diverse discipline backgrounds. They compared four real-world lithium projects, weighed competing priorities and considered how professionals balance risks and opportunities through the lens of sustainable development. This approach demonstrated how decisions on mining projects require complex trade-offs between a multitude of aspects including environmental and social impacts, geological potential, engineering and technology readiness and investment requirements.

The presentation postulates that such engagement is critical not only for providing a wider understanding, but also for future capability and reputation building for the critical minerals sector. The interdisciplinary approach to the workshop helps to challenges perceptions and strengthen awareness of wide ranging issues. By exposing students to real world challenges and encouraging them to apply their learning to solving them, the workshops supported academic learning and employability skills.

Building the next generation of professionals not only an educational challenge, but is critical for a more sustainable future. It requires honest, participatory and interdisciplinary engagement that acknowledges the sector’s challenges while demonstrating its essential role in the energy transition. Outreach of this kind can help develop a technically capable, morally conscious workforce that drives responsible mining.

Co-creating a roadmap for responsible nickel production in the Philippines

Rowan T Halkes[1], *R E Delina-Agillon[1], E Mills[1], I R Shaw[1], M de Jongh[1], A Lacinska[1], A Winson[1], G Mudd[1], H Napier[1], T Bide[1], K M Goodenough[1]*

1British Geological Survey

Nickel is essential to the energy transition, but increasing production can intensify environmental and social pressures. These challenges are particularly relevant to the Philippines, the world's second-largest nickel ore producer, where laterite deposits occur within biodiverse, climate-change and multi-hazard exposed landscapes, including areas inhabited by Indigenous communities[1,2].

This study presents a stakeholder-led roadmap for responsibly developing the Philippines nickel industry. The roadmap was developed by the British Geological Survey through a review of published evidence, site visits and workshops. We engaged with stakeholders from government, industry, academia, civil society and Indigenous organisations. Workshop findings were analysed using a political, economic, social, technological, legal and environmental (PESTLE) framework and mapped against the United Nations Resource Management System principles[1,3].

Although the study identified a strong legislative foundation and examples of effective practices, range of challenges were also highlighted including biodiversity loss, catchment-scale impacts, greenhouse-gas emissions, environmental baseline data, tailings management, regulatory implementation, meaningful community participation and post-mining outcomes1. These pressures could increase as the Philippines seeks to expand domestic processing[1,2].

The roadmap proposes practical actions across the mine life cycle. Priorities include catchment-scale assessment of cumulative impacts; improved biodiversity and environmental baseline data capture; transparent and participatory monitoring; integration of climate and multi-hazard risk planning; greater use of life-cycle assessment and lower-carbon energy; meaningful engagement and benefit sharing; and nature-positive rehabilitation linked to community transition planning. Complementary opportunities include furthering recovery of co-products, repurposing mine wastes and developing lower-impact technologies[1].

The work demonstrates how geoscience, stakeholder knowledge and systems-based resource management can be combined to translate broad ESG ambitions into locally grounded actions for responsible critical-mineral supply.

1:Halkes R T, et al. Responsible nickel roadmap for the Philippines. BGS; 2026. Forthcoming.

2: Domingo J PT, et al. J Clean Prod. 2024;468:143114.

3: UNECE. United Nations Resource Management System: principles and requirements. 2022.

Estimating global extractable copper in subvolcanic brines

Michele Paulatto*[1,2]*, *Matthew Jackson*[1]*, Haiyang Hu*[1]*, Laura Crisp*[3]*, Andrew Berry*[3]*, Amanda Bustin*[4]*, Roger Beckie*[4]*, Adam Pacey*[5]

1Imperial College London, UK
2Rio Tinto Centre for Future Materials
3ANU
4UBC
5Rio Tinto Exploration

Copper (Cu) is an essential material for electrification and the energy transition but conventional supply from mining and recycling is predicted to meet only 70% of the world's growing demand by 2035 (IEA2025). The extraction of Cu from hot saline fluids associated with active volcanoes (subvolcanic brines) offers a new source with lower environmental impact than traditional mining (Blundy2021). We build a global database of geophysical and borehole data and use a probabilistic volumetric approach to estimate for the first time the potential Cu available in subvolcanic brine reservoirs. We predict a lognormal Cu resource distribution with a 10th percentile (P10) of 0.4 Mt a P90 of 50 Mt and a median (P50) of 4.6 Mt. These results suggest that the largest brine resources are potentially comparable to the largest conventional mines currently in operation, offering a globally significant supply. We envisage net-zero Cu production (self-powered by geothermal energy produced as a by-product) with almost no surface footprint. Future research should develop exploration methods to locate the largest and highest-grade reservoirs and resolve technical barriers in drilling, production and separation.

POSTER PRESENTATIONS

Porphyry Prospectivity Mapping and Targeting on the Arabian Shield

Alex Tunnadine*[1]*, *Stephen Johnson[2], Steve Garwin[3], Ali Sholeh[1], James Davey[1], Jamie Price[1], Mark Campodonic[1], Mohammed Rashed Al Somali[4], Zaid Al Mowaled[4], Thiago Schlicta[4]*

1SRK Consulting (UK) Ltd
2SRK Consulting Australasia Pty Ltd
3Steven L Garwin Pty Ltd
4Maaden - Saudi Arabian Mining Company

Growing demand for critical and base metals has renewed interest in underexplored regions such as the Arabian-Nubian Shield. Geodynamic studies by SRK Consulting and Maaden provide a refined framework for understanding the tectonomagmatic evolution and metallogenesis of the shield. This project utilised our renewed understanding of the Arabian Shield to assess prospectivity for porphyry copper-gold systems and derive exploration targets and workflows across the shield.

Previous explorers have questioned the shield's prospectivity for porphyry systems due to its implied low preservation potential. As such the region has relatively low exploration maturity for porphyries, despite confirmed occurrences on both the Nubian, and Arabian sides proving the inherent fertility to form, and capability to preserve, porphyry systems.

This study adopts a mineral systems approach, integrated with knowledge-driven prospectivity mapping to identify and rank porphyry targets across the Shield.

Mineral systems frameworks were developed based on our understanding of the key processes underpinning porphyry formation in the shield, these frameworks supported the development of interpretive and objective evidential layers that included preservation proxies, fertility indicators, favourable structural architecture, appropriate magmatic systems and possible trap locations.

Model inputs were weighted, within a fuzzy logic workflow following field validations to assess their relative importance in the local context. Assessment of prospectivity results against known porphyry occurrences provided important feedback to the modelling process and informed model refinement and improvement.

Resulting prospectivity maps informed the delineation of search spaces at a number of scales. These were ranked in terms of data maturity and prospectivity allowing prioritised, targeted exploration plans to be developed.

This work demonstrates potential for porphyry formation and preservation across key terranes on the Arabian Shield, beyond the known prospects. The prioritised matrix of targets at a variety of scales allows an idealised exploration pathway based on both exploration maturity and prospectivity.

A Century of Copper Slag Generation: Global Production Trends and Implications as a Secondary Resource of Critical Metals

***Alexandria Tanciongco*[1]**, *Gawen RT Jenkin*[1], *Philip Bird*[1]

1Centre for Sustainable Resource Extraction, University of Leicester, UK

Copper smelting generates large quantities of metallurgical slag that can retain Cu and other valuable and critical metals, making these materials potential secondary resources for metal recovery [1,2]. Recent global assessments have estimated copper slag generation over the past two to three decades [2,3], but its longer-term historical production and geographic distribution remain poorly constrained. This study reconstructs global copper slag generation from 1928 to 2021 using reported country-level copper smelter production and slag-to-copper ratios assigned according to dominant smelting technologies and changes in smelter capacities through time. The reconstructed dataset is evaluated alongside major historical changes in copper production and the development of global smelting infrastructure.

An estimated 1,419 Mt of copper slag was generated globally between 1928 and 2021, with approximately 36.8% produced since 2000. Slag generation increased substantially over the study period and shifted geographically alongside changes in global copper smelting, particularly towards Asia in recent decades. Differences in smelting technologies through time has shown influence to the residual metal content and resource potential of accumulated slags [4]. From a circular economy perspective, copper slags represent a large secondary material resource with potential to be reintegrated into metal supply chains through the recovery of Cu and associated critical metals, with quantification of their scale and distribution providing a basis for identifying countries where more detailed slag inventory, characterisation and resource assessment should be prioritised.

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Unlocking Cornwall's Geothermal-Lithium Resources: Fault Reactivation, Fluid Flow and Permeability Evolution Through Time

***Catherine Mottram*[1], *Will McKenzie*[2], *Robin Shail*[3]**

1University of Portsmouth, UK
2Cornish Lithium
3Camborne School of Mines, University of Exeter, UK

Understanding the timing and evolution of fault-controlled permeability is critical for the development of geothermal energy and lithium-bearing geothermal brine resources in southwest England. Cornwall hosts some of the UK's most promising geothermal-lithium prospects, yet the structural controls governing fluid circulation remain poorly constrained. In particular, the post-Variscan tectonic evolution of the region has received relatively little attention, despite evidence that fault reactivation has played a key role in creating and modifying permeable pathways.

Here, we present results from a pilot study integrating K-Ar fault gouge dating, U-Pb carbonate geochronology, structural analysis, and petrographic observations to investigate the post-Variscan structural history of Cornwall and its implications for permeability evolution. Sampling targeted lode and cross-course parallel faults, and fracture networks that are known or inferred to influence fluid flow. K-Ar ages from syn-kinematic fault gouges provide direct constraints on episodes of fault movement, while U-Pb ages of carbonate vein fills record the timing of fluid circulation associated with fracture development and reactivation.

The new geochronological dataset reveals multiple post-Variscan episodes of brittle deformation and fluid flow, demonstrating that fault systems in Cornwall have experienced a prolonged and complex history of reactivation. Integration of age constraints with structural relationships allows periods of permeability creation, enhancement, and sealing to be distinguished, providing the first temporal framework linking deformation and fluid movement across key fault networks. The results suggest that inherited structures acted as long-lived fluid conduits, but that permeability was episodically renewed through reactivation and fracturing, generating pathways for hydrothermal circulation.

These findings provide important new insights into the tectonic and hydrothermal evolution of Cornwall and highlight the value of combining fault gouge and carbonate geochronology to reconstruct permeability histories. The resulting framework has direct implications for targeting productive geothermal reservoirs and lithium-bearing brines, while offering broader lessons for fault-controlled geothermal systems worldwide.

Critical raw material potential of volcanogenic massive sulphide (VMS) deposits in the UK

***Hannah Grant*[1]**, *Kathryn Goodenough*[1], *Eimear Deady*[1], *Steven Hollis*[2], *Tom Bide*[1], *Mark Coope*[3], *David Currie*[1], *Pierre Josso*[1], *Alicja Lacinska*[1], *Katie McFall*[4], *Mark Patton*[3], *Richard Shaw*[1]

1British Geological Survey, UK
2University of Edinburgh, UK
3Geological Survey of Northern Ireland, UK
4University College London, UK

Critical raw materials (CRM) are commodities that are economically important and at risk of supply interruption. The UK government aims to ensure that the UK has reliable and sustainable access to the CRM required to support economic growth and the transition to net zero. An important part of this is understanding the UK's domestic mineral resources. Although the UK geology is well-known, and there has been extensive historic mining and exploration for precious and base metals, there is currently relatively little understanding of the potential for many of the CRM in the UK. In 2023, the potential UK prospectivity for CRM was assessed using a minerals system approach, and CRM prospectivity maps produced at a national scale, identifying optimal target areas for more detailed surveys. Multiple focus areas identified UK potential for volcanogenic massive sulphide (VMS) deposits as they can contain significant amounts of CRM both as major metals or potential by-products.

VMS deposits are hydrothermal (and magmatic) submarine deposits preserved on land during orogens. They are major sources of base and precious metals and have been mined for over a thousand years in the UK. The majority of known UK VMS deposits are hosted within the Caledonian-Appalachian orogenic belt extending from Norway, through the UK and Ireland, to northeastern Canada. Although the potential of polymetallic VMS deposits as a viable economic resource for many CRM is considerable, the deportment and processes controlling CRM enrichment and fertility in UK and Irish VMS deposits, compared to some of the largest VMS deposits in the world in Canada is poorly understood. A project funded through a UK-Canada sustainable critical minerals research partnership aims to enhance exploration techniques through evidence-based targeting methods and facilitate more efficient mining through a greater understanding of VMS CRM deportment and fundamental enrichment processes across orogenic belts.

Iron Recovering from Fluorspar Tailings via Magnetizing Roasting and Magnetic Separation: A Sustainable Waste Minimisation Approach

Kemane Kgwete*[1]*, *Murray Bwalya*

1University of the Witwatersrand, South Africa

To support zero-waste mining, this study looks at a sustainable way to recover valuable iron from low-grade fluorspar process tailings. Because the iron in this waste is mostly weakly magnetic hematite, standard magnetic separation does not work well, meaning the mineral properties must be changed first.

To improve the magnetic properties, waste samples undergo magnetizing roasting to transform the weakly magnetic hematite into highly magnetic magnetite. The material is then processed using low-intensity magnetic separation. The testing focuses on how key operating conditions affect the overall reaction rate and separation success. Specifically, it evaluates roasting temperature, roasting time, reductant dosage, particle size, and magnetic strength.

Changes in the minerals and elemental composition are tracked using WD-XRF, XRD, and SEM-EDS. Finding the best settings for these conditions creates a reliable method to turn a major mine waste stream into a usable, valuable byproduct.

Critical metal by-product recovery on site: a case study for co-extraction of bismuth, tellurium and tungsten using Deep Eutectic Solvents at Björkdal Gold Mine

***Lara Tritton*[1]**

1University of Leicester

Bismuth, tellurium and tungsten are widely classed as critical metals due to their strategic importance and limited supply. It is crucial to diversify the sources of these metals, whilst minimising environmental impact. By-product recovery at operational gold mines could be a promising part of the solution, as gold deposits are often enriched with other rare metals[SD(1.1]. Recovery of by-products from existing mines would increase supply and reduce the need for new mines, avoiding additional environmental impact and long lead times. Unrecovered by-products may report to tailings, metallurgical wastes or facility emissions, incurring penalty fees and adding to the environmental burden of mines.

This work is a case study with Björkdal Gold Mine in Sweden. It investigates geometallurgical properties of Bi, Te, and W minerals, tracing these through mineral processing, and testing a recovery process involving environmentally-benign Deep Eutectic Solvents (DESs).

Samples from the mineral processing input and outputs underwent both detailed mineralogical characterisation, and bulk geochemical analysis. Automated SEM-EDS revealed near-total deportment of both bismuth and tellurium into tsumoite (BiTe), and 100% deportment of tungsten into scheelite. The characteristics of both tsumoite and scheelite differed greatly between the different concentrates and the tailings, with grain size, grain liberation, and susceptibility to froth flotation the key parameters for recovery. Two concentrates had promising tsumoite characteristics for a tailored DES-based recovery with an oxidising agent. Dissolution rates were examined through optical profilometry, which, together with the mineralogical data, informed observations from bulk leaching experiments. Efficient, selective leaching of Bi and Te is possible even at 30°C. Although scheelite does not leach, a multi-step process can produce a tungsten-rich residue.

Digestion Method Controls on Using Geochemical Data for Rock Classification: Insights from the Camp Creek Cu-Mo-(Au-Ag) Porphyry Deposit, Northwestern British Columbia, Canada

***Maxwell Long Porter*[1], *Shaun Barker*[2]**

1Imperial College London, UK
2MDRU – Mineral Deposit Research Unit, The University of British Columbia, Canada

Lithogeochemistry routinely supports lithology classification and alteration domaining classification where visual lithology identification is challenging. Four-acid digestion (4AD) with an ICP-MS finish is the dominant method used by commercial laboratories owing to its low cost, rapid throughput, and low detection limits, but it can incompletely dissolve refractory minerals that host high-field-strength elements (HFSEs) and Ti. The Late Cretaceous Camp Creek Cu-Mo-(Au-Ag) porphyry deposit in northern British Columbia is hosted by hornblende-quartz-biotite-plagioclase porphyry phases that are difficult to distinguish in the field due to limited cross-cutting relationships. Previously, 4AD-derived Zr/Ti ratios defined three units: shallow Porphyry Z (PZ); Porphyry Y (PY); and deeper Porphyry X (PX), the main mineralized host. To test this classification, we compare the recovery of Zr, Hf, Nb, Ta, Ti, and Ba across lithium borate fusion (LBF), portable X-ray fluorescence (pXRF), and 4AD. Shortwave infrared spectroscopy identifies pyrophyllite and paragonitic white mica (± diaspore) alteration in PZ, and muscovite-phengitic white mica in PY and PX. Ti released during biotite breakdown forms titanite in PZ, but fine-grained, refractory rutile along former cleavage planes in PY and PX. Relative to LBF and pXRF, 4AD systematically under-reports the HFSE and Ti. The deficit in Ti, Nb, and Ta is alteration-controlled, increasing from ~13% in PZ to ~55% in PY. Zircon-hosted Zr and Hf are under-reported in all phases (up to 82% in PX), reflecting a primary compositional control that distinguishes PX. While the refractory behaviour of rutile is well documented, its expression through the titanite-to-rutile transition as a mappable, alteration-driven four-acid signal represents a new contribution. We recommend routine pXRF on every pulp, paired with fusion analysis of ~10% of samples to constrain absolute HFSE concentrations. These results refine lithology and alteration models at Camp Creek and can be applied to guide geochemical classification in porphyry systems.

Carbonatite-Hosted REE Prospectivity Mapping Under Label Scarcity

Miaozhou Tang*[1]*, *Chetan Nathwani*[1]*; Ross Smail*[2]

1Imperial College London, UK
2Getech

Carbonatite-hosted rare earth element (REE) deposits are geologically rare and spatially clustered, making data-driven prospectivity mapping challenging when confirmed occurrences are scarce and reliable negative sites are unavailable. Conventional discriminative machine learning approaches such as Random Forest typically treat sampled background locations as negative examples, an assumption that may be inappropriate in frontier terranes where undiscovered mineralisation may be present.

The Deviation Network (DevNet) is investigated as an anomaly-based alternative. It requires only known occurrences and an unlabelled background pool, avoiding the need to designate confirmed negative sites. The model uses a deviation loss to pull background samples toward a fixed Gaussian reference while treating known occurrences as anomalous. The approach is evaluated against a Random Forest baseline across three Canadian terranes, Cordillera, Superior and Grenville, using gravity and magnetic data and their derivatives, alongside two independent feature sets: GLCM texture descriptors capturing the spatial morphology of carbonatite-related anomalies, and proximity-to-structure features computed separately from fault, margin and worm datasets. Both models use the same disjoint background pool and are evaluated using cross-validation, with an analysis of which features drive model predictions.

Results show that DevNet does not uniformly outperform Random Forest, and performance is dependent on the number of labelled occurrences in each terrane. Random Forest achieves stronger performance in Cordillera, where labelled occurrences are more numerous, whereas DevNet achieves higher average precision in the more label-scarce Superior region. Independent spatial validation shows DevNet's highest-favourability predictions in Superior coinciding with the Kapuskasing Structural Zone, a documented carbonatite corridor not represented among the training occurrences.

In conclusion, DevNet's value lies not in uniformly outperforming discriminative classifiers, but in providing a negative-free framework for target generation under severe label scarcity. This makes it a practical option for early-stage critical-mineral exploration in geologically underexplored terranes.

Challenges of Limiting the Number of Input Variables in Machine Learning: A Case Study on the Prediction of REE-Bearing Phosphorites

***Nasreddine Tahar Belkacem*[1]**

1Ouargla University, Algeria

This study assesses the impact of input variable reduction on machine learning prediction of rare earth element (REE) content in phosphorites from the Gafsa-Metlaoui Basin, Tunisia. Random Forest (RF) and XGBoost regressors were evaluated using a geochemical dataset of thirty-seven samples characterized by nine major oxides. Feature engineering was also applied to generate geochemically meaningful interaction variables. Using the complete nine-oxide feature space, XGBoost achieved a test-set R^2 of 0.9445 (RMSE = 23.39; MAE = 16.35), outperforming Random Forest (R^2 = 0.8092). In contrast, a constrained model based on only four oxides available at the deposit (SiO_2, MgO, CaO, and P_2O_5) achieved a substantially lower R^2 of 0.554. The results demonstrate that reducing the number of input variables can significantly decrease predictive performance when informative geochemical features are excluded. SHAP analysis further highlights the importance of engineered interactions, particularly MgO/TiO_2. These findings emphasize the critical role of input feature selection and geologically guided feature engineering in machine learning-based prediction of REE enrichment.Keywords— artificial intelligence, geoscience, feature engineering, machine learning, rare earth elements, phosphorite, XGBoost, Random Forest, SHAP

Fingerprints of Nickel Exploration in the Pulivendla-Vemula (P-V) sill in Cuddapah Basin:Geological Complexity and Discovery Potential

***P V SUNDER Raju*[1]**

1CSIR-National Geophysical research institute

The increasing global demand for nickel, driven by its critical role in stainless steel production and emerging battery minerals technologies, has intensified exploration efforts in geologically diverse terrains. This study focuses on the Cuddapah Basin, a Proterozoic sedimentary basin in southern India, which presents a complex geological framework with promising yet under-explored potential for nickel mineralization. Through an integrated approach combining lithological mapping, geophysical surveys, and geochemical analysis, this paper present fingerprints of geochemical and geophysical signatures to target Nickel Exploration. The preliminary findings indicate the presence of ultramafic intrusions and favourable host rocks such as picritic sills which are typically associated with nickel sulfide deposits. The western margin of the Proterozoic-aged Cuddapah Basin contains gabbro and plagioclase bearing sills within the Tadapathri formations These sills have 4-28% MgO and 30-1050 ppm Ni and they are characterised by elevated Th/Nb which is indicative of contamination by upper crustal material. The low MgO ma!c magmas have one to two orders of magnitude viscosity higher than the picritic sill they are emplaced all along the Cuddapah basin margin. No Ni-Sulphide mineralization is known in this belt, but trace interstitial sulphide is present. The following features of the Pulivendla-Vemula sill complex indicate that the rocks are prospective for magmatic sullfde exploration:1. Tholeiitic lavas and sills were emplaced during extensional intra-cratonic rifting at a time of major Ni ore formation at ~1.9 Ga metallogenic epoch i.e late Proterozoic-Archaean in age.2. Un-deformed fresh differentiated ultramafic sills have a range in Ni concentration over a narrow interval of forsterite content with primary olivine 3. These sills and other sills in the footprint of regional magnetic and gravity anomalies possibly contain feeders where immiscible magmatic sulfides may have formed. correlating between Werner depth

estimations and seismic data, particularly in pinpointing fault zones. These zones act as critical conduits for fluid migration from the mantle to the surface, playing a vital role in both tectonic interpretation and mineral exploration 4. Despite the absence of magmatic sulfide mineralization and magmatic breccias, there is untested potential within the basin stratigraphy for the development of intrusions which have a magnetic and density signal, possibly in association with a structural break as well as a diagnostic electromagnetic signal from highly conductive sulfide mineralization. However, the geological complexity, including structural deformation and metamorphic overprints, poses significant challenges in locating economically viable deposits. The study underscores the importance of advanced exploration techniques and multidisciplinary data integration to improve discovery success rates. Ultimately, this work contributes valuable insights into the Ni-mineral prospectively of the P-V Picritic Sill in western margin of Cuddapah Basin and highlights its potential as a frontier region to relook for nickel exploration in India.

New Exploration Guides for Mn and Rare Earth Element Mineralizations Associated with Central Saharan Cenozoic Anorogenic Volcanism

Riad Ben El Khaznadji[1], Abderrahmane Bendaoud[1]

1Université des sciences et technologie Houari Boumediene, Algérie

The growing global demand for critical raw materials highlights the necessity of establishing modern, targeted exploration models for strategic metals such as Rare Earth Elements (REE) and Manganese (Mn). Cenozoic intraplate anorogenic volcanism in the Central Sahara, particularly within the Tuareg Shield (e.g., Hoggar Massif), represents a highly promising yet under-explored target for high-value mineralizations. This study establishes integrated structural, petrological, and geochemical exploration vectors for Mn and REE deposits associated with peralkaline volcanic and subvolcanic complexes.

Structural architecture exerts a primary control on mineralization distribution. The emplacement of highly differentiated peralkaline magmas (phonolites, trachytes, and agpaitic syenites) is strongly localized along reactivated Pan-African lithospheric discontinuities, notably the 4°50'E and 8°30'E mega-shear zones. These deep-rooted structures facilitated both the ascent of mantle-derived parent melts and extreme fractional crystallization. REE enrichments (combining light and heavy REE facies) are predominantly concentrated within late-stage felsic domes, ring complexes, and magmatic-hydrothermal breccias. In contrast, Mn mineralizations develop as structurally controlled vein networks, stockworks, and hydrothermal replacements linked to late-volcanic fluid circulation.

Key exploration guides derived from this framework include:

Structural Vectors: Intersections of reactivated Pan-African shear zones with Cenozoic intraplate fracture networks.

Petrological Indicators: Highly evolved peralkaline/agpaitic felsic facies, volcanic plugs, and associated hydrothermal vein systems.

Geochemical Signatures: High concentrations of High Field Strength Elements (HFSE), pronounced REE anomalies, and distinct Mn-Fe hydrothermal halos.

This multi-scale exploration model provides an operational vectoring tool to locate economic REE and Mn mineralizations across Saharan intraplate volcanic provinces, opening new prospects for critical mineral discovery in North Africa.

Is AI really helping Geoscience Microscopy?

***Rich Taylor*[1]**

1Zeiss

The incorporation of AI into Geoscience workflows of any kind is a controversial subject amongst geologists.

The very nature of our subject is framed around the natural complexity of the samples themselves, and the multi-scale observations that underpin our interpretations. We also need a both complete flexibility for understanding any individual sample in great detail, and automation in processing large numbers of equivalent sample data. This combination of flexibility and automation is troublesome for both the hardware and software provided by traditional microscopy and microanalysis vendors.

So where are we at with AI?

What role is AI providing in Geoscience microscopy?

What is the interplay between powerful, but more generic high-end software, and more bespoke but specific academic software?

More importantly, how can we leverage both in the best way?

Light, Electron, and X-ray microscopy (LM, EM, and XRM) are all seeing the emergence of various AI technologies, most importantly different flavours of deep learning neural networks. These techniques are often at their best when they are integrated in a way that does not require much user input, simple “click button” methods or “Everyday AI”.

More importantly, these methods should be used in the areas of our workflows where we have the biggest or most constraining bottle necks, rather than in the areas that require geoscience training and expertise. Here we will look at some of the latest techniques involved in common Geoscience workflows, especially the essential image segmentation required for upscaling our interpretation across increasingly large datasets. Instance segmentation, data compression, super-resolution, and image enhancement are all examples of where AI can support the geologist rather than replace them, enabling better datasets, better projects, and better databases from which to make our essential interpretations.

Consensus Prospectivity Mapping and Uncertainty Assessment of Graphite Deposits: A Multi-Workflow Machine Learning Approach

***Suchitra Behera*[1]**

1Indian Institute of Technology Bhubaneswar, India

The requirement for critical minerals, specifically graphite, has peaked due to its usefulness in energy storage, electric vehicle production, lubricants, refractories, and advanced technologies. However, exploration of new graphite deposits using conventional mineral exploration techniques is time-consuming, requires manual integration of varied geological, geophysical, and geochemical datasets, and is less reliable. The increasing availability of geoscientific datasets has encouraged the use of machine learning techniques in Mineral Prospectivity Mapping. The study area falls over the Eastern Ghat Mobile Belt and is characterized by graphite-bearing khondalite suite, charnockite suite, resulting in an optimal region for further graphite exploration using data-driven approaches. This study exhibits a mineral prospectivity mapping based on the machine learning technique to identify the graphite prospective zone while calculating the model uncertainty. Multiple datasets of geological, geophysical, and geochemical predictor layers were integrated along with the known graphite deposits. To explore the impact of model selection, negative sampling strategies, and feature group designs on the graphite prospectivity prediction, multiple machine learning algorithms and modeling workflows were prepared. The multi-workflow models were prepared in order to check the sensitivity of the prospectivity prediction to modeling parameters. Predictions from the accepted workflows were compiled to form a consensus prospectivity map instead of depending on single model predictions. The mean estimated probability score across the model was utilized to depict the consensus prospectivity map, while the spatial prediction uncertainty was quantified by the standard deviation. High confidence graphite prospective zones were marked by high prospectivity and a comparatively low uncertainty score. The results show that a multiple model ensemble lowers the model-specific bias and delivers a more robust representation of the graphite prospectivity zone compared to the single classifier model.

Beyond Sulfide Oxidation: New Pathways for Cu, Au and Sulfur Recovery from Complex Concentrates

***Ummul Sultana*[1]**

1The University of Queensland, Brisbane, Australia

The increasing processing of complex sulfide resources presents challenges extending beyond the extraction of the primary target metal. Hydrometallurgical treatment can effectively liberate valuable metals from sulfide minerals; however, the resulting changes in sulfur speciation can strongly influence downstream metal recovery and residue management. This creates an opportunity to consider sulfide oxidation and subsequent residue treatment as an integrated resource-recovery problem rather than independent processing stages.

This work explores this concept through laboratory studies of pyrite- rich and copper- gold sulfide materials. Previous oxidative-leaching experiments on pyrite-rich mine tailings demonstrated that controlled oxidation can substantially improve liberation of associated cobalt, while the extent and mode of oxidant addition strongly influence metal extraction and dissolution of the iron- sulfur matrix. These observations highlight the importance of controlling, rather than simply maximising, sulfide oxidation.

Building on these findings, proof-of-concept work is being extended to finely ground copper- gold sulfide concentrate treated by atmospheric oxidative leaching. Copper dissolution is accompanied by the formation of an elemental-sulphur-rich residue containing unrecovered gold, raising an important downstream question: should the residual sulfur be removed, further oxidised, or utilised as part of the subsequent recovery process?

Three potential gold-recovery pathways are therefore considered: conventional cyanide leaching following sulfur management; glycine-assisted low-cyanide leaching to reduce the impact of residual copper and cyanide consumption; and an exploratory cyanide-free route based on lime- sulfur synthetic solution chemistry, in which polysulfide/thiosulfate species may provide an alternative gold lixiviant. Preliminary proof-of-concept experiments are used to assess the opportunities and limitations of these approaches.

The study proposes a broader framework for processing complex sulfide resources in which oxidation severity, sulfur deportment and downstream metal recovery are considered together. Such an approach may enable recovery of multiple value streams while reducing the requirement for complete sulfide oxidation and improving utilisation of sulfur-rich process residues.

Mineralogical Controls on Nickel Redistribution during Lateritic Weathering: Insights from the Batu Putih Ni Laterite Deposit, Sulawesi, Indonesia

***Yu Shen*[1]**

1China University of Geosciences, Wuhan, China

Ni-laterite deposits represent an increasingly important source of Ni for the global energy transition, yet the mineral-scale processes controlling Ni redistribution and high-grade ore formation during ultramafic weathering remain incompletely understood. Here, we investigate a ~24 m-thick lateritic profile from the Batu Putih Ni deposit, Sulawesi, Indonesia, using field observations, X-ray diffraction, whole-rock geochemistry, SEM–EDS, and electron-probe microanalysis.

The profile records a systematic mineralogical transition from Fe-(oxyhydr)oxide-dominated laterite in the upper section to mixed Fe–Mg–Si assemblages across the transition zone, and finally to serpentine- and Ni-bearing Mg-silicate-rich saprolite at depth. Whole-rock geochemical profiles show strong depletion of Mg and Si in the highly weathered upper horizons, accompanied by residual enrichment of Fe and Al. Nickel displays a contrasting pattern, with relative depletion in the laterite and pronounced enrichment in the transition and saprolite zones. Mass-balance calculations further indicate net Ni gains in the lower profile.

Mineralogical observations show that Ni is hosted by several secondary phases, including Ni-bearing serpentine, talc-like/kerolite–pimelite-type Mg–Ni silicates, Mn–Ni–Co oxides, and locally Ni-rich silica-bearing assemblages. These relationships indicate that Ni enrichment is not controlled by a single mineral phase, but instead reflects progressive release, downward transport, and re-fixation during lateritic weathering. The transition from Fe-dominated to Mg–Si-dominated mineral hosts appears to be a key control on high-grade saprolite ore formation.

These results highlight the importance of mineralogical transformations and fluid–rock interaction in governing critical-metal redistribution within lateritic weathering profiles, and provide insights into the formation and exploration of high-grade Ni resources in tropical ultramafic terrains.

Keywords: Ni-laterite deposit; critical minerals; garnierite; nickel redistribution; mineralogical controls; Sulawesi