PROGRAMME AND ABSTRACTS

Mineral Deposits Studies Group

Winter Meeting

5–7 January 2026

Cardiff, Wales

The conference was made possible through generous sponsorship from the following organisations.

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ERM Kingsrose

Croeso i Gaerdydd!

Welcome to Cardiff and the 48th AGM of the Mineral Deposits Studies Group

The technical meeting will open on Monday the 5th of January at 7 pm with an icebreaker at the *Parkgate Hotel* in central Cardiff, generously sponsored by SRK Exploration Services. Keynote talks, technical sessions, and poster sessions will take place on Tuesday 6th and Wednesday 7th of January. We have a very full programme of 37 speakers and 37 posters covering a wide range of topics including advances in exploration techniques, critical minerals, circular economy and sustainable resource exploitation, and mineral system studies. As part of this programme we are pleased to welcome four excellent keynotes from Prof Frances Wall (Cambourne School of Mines), Dr Thomas Lamont (University of Nevada-Las Vegas), Dr Martin Li (MDSG Early Career Lecturer; Imperial College) and Dr James Davey (SRK Consulting). All lunches and morning/afternoon refreshments, and the conference dinner are included in the registration cost. The main conference will be held at Cardiff University's beautiful *Main Building* on Park Place.

The conference dinner will take place on the evening of Tuesday the 6th of January at the *Royal Welsh College of Music and Drama*. Please arrive at 7 pm; you will receive a welcome drink and we will sit down to eat at 7:30 pm.

As always, the MDSG is committed to supporting students and early-career researchers within our community. There will be prizes for the Best Student Talk and Best Student Poster (sponsored and awarded by Rio Tinto), Best Student Masters-level Project (sponsored by the Applied Mineralogy Group), and the Best Mineral Systems Talk (sponsored by Halliburton). In addition, the generous contributions of sponsors have allowed us to maintain a low registration cost for students this year.

In conjunction with the main meeting, there are two **post-conference workshops** on **Thursday the 8th and Friday the 9th of January**:1)

- *Introduction to Mineral Resource Estimation* (presented by Richard Nicholls, MSA Group and supported by Seequent)
- *An Introduction to Prospectivity Mapping Based on a Mineral Systems Approach* (delivered by SRK Consulting)

These one-day courses provide practical training in key industry workflows and are available to both student and professional delegates.

Enjoy the meeting and the vibrant city of **Cardiff**!

The MDSG Cardiff 2026 Organising Committee
(mdsgcardiff2026@gmail.com)

Venue Information

Icebreaker at the Parkgate Hotel

The conference will kick off at 7 pm on January 5th with an evening icebreaker, sponsored by SRK Exploration Services. This will take place in the Postmaster Bar Suite at the Parkgate Hotel on Westgate Street in Cardiff. The hotel is a 10 minute walk from the University and a 5 minute walk from the central train station and most city centre hotels. A welcome drink and canapes will be served on arrival and drinks tickets will also be provided to delegates. A registration desk will be available at which you may collect your conference pass. Please enter the Parkgate via the main entrance and follow signs along the corridor to the right towards the Postmaster Bar Suite.

Conference and Workshops at Cardiff University Main Building

The conference and workshops will take place in Cardiff University's Main Building. Welcome coffee and registration will begin at 8:30 am on 6th January in the Viriamu Jones Gallery. This can be accessed via the main entrance from either the Park Place or Museum Avenue side of the building. Lunch, refreshments, and poster sessions will take place in both the VJ Gallery and the Council Chamber on the first floor; the latter will be signed from the VJ Gallery. In accordance with School of Earth and Environmental Science policy the food provided will be a mix of vegan and vegetarian options. Talks will take place in the Large Chemistry Lecture Theatre, which can be reached either by walking across the courtyard on the east of the building or via an indoor route. Signage will be available to aid navigation!

The workshops on the 8th and 9th January will be held in Main Building room 1.60A; this is on the first floor just south along the corridor from the council chamber and will be sign posted. Workshops will take place between 9 am and 5 pm and instructions for logging into IT facilities will be provided nearer the time.

A conference Wifi account has been created for delegates, to join 1) on your device, select CU-Wireless from the available networks, 2) when prompted, click "Conference" or "Guest" or on the login page, 3) enter the conference name and password provided below and connect.

Conference Name: MDSG 2026
Password: 875104

If you cannot connect, call IT Support on: 029 225 11111

A quite room, close to the VJ gallery and Council Chamber, has been booked for the duration of the conference for those who may feel the need for some space during the meeting. This will be clearly signed.

Conference Dinner at the Royal Welsh School of Music and Drama

The conference dinner will take place on the evening of Tuesday the 6th of January at the *Royal Welsh College of Music and Drama*. Please arrive at 7 pm; you will receive a welcome drink and we will sit down to eat at 7:30 pm. The RWCMD is 5 minutes walk from Cardiff University Main Building an 5-10 minutes from Cardiff City Centre.

PROGRAMME

Tuesday 6th January				
08:30	09:00	*Coffee and Registration*		*page*
09:00	10:45	**Advances in Exploration Geology.** *Chair: Antony Benham (MSA). Sponsored by MSA Mining*		
09.00	09.30	**Keynote**: An Updated Appraisal of the Mineral Prospectivity of the Arabian Shield	Davey, J., Price, J., Ward, L., Campodonic, M., Al Ghamdi, A., Sapanci, O., and Schlichta, T.	11
9.30	9.45	Privacy-preserving machine learning for prospectivity analysis using variogram and unsupervised learning	Sihombing, F.M.H. (STUDENT), Palin, R.M., Hughes, H.S.R. and Robb, L.	12
9.45	10.00	Application of Niggli Numbers in mineral exploration using ioGAS®	McDonald, I. and Sadikin, P.	13
10.00	10.15	Exploration Value Creation Across Scales	Lindsay, D.H.M. (STUDENT), Thebaud, N., Masurel, Q., Trench, A. and Hronsky, J.M.	14
10.15	10.30	The Significance of Magnetic Fabrics Preserved in Hydrothermally Altered Rocks	Latimer, B. (STUDENT), McCarthy, W., Mattsson, T. and Reavy, J.	15
10.30	10.45	Copper Kitchens: A New Framework for Sedimentary-Hosted Copper Exploration	Helps, P.A. and Nicoll, G.R.	16
10:45	11:15	*Morning coffee break*		
11:15	12:15	**Magmatic-Hydrothermal Mineralisation – I.** *Chair: Mizuki Ishida (NHM). Sponsored by Halliburton*		
11.15	11.45	**Keynote**: Porphyry copper formation driven by water-fluxed crustal melting during flat-slab subduction: Insights from the Laramide Belt, SW USA	Lamont, T.N., Cooper, F.J., Loader, M.A., Wilkinson, J.J., Roberts, N.M.W., Nathwani, C., Jowitt, S., Kemp, A., Bevan, D., Gorecki, A., Elliott, T., Gardiner, N.J., Tapster, S.	17
11.45	12.00	Modelling trace element evolution in arc magmas: implications for copper porphyry indicators	Soderman, C.R. and Weller, O.M.	18
12.00	12.15	Two tectonic settings for porphyry copper formation in the Northern Great Basin, USA	Bain, H.R. (STUDENT), Cooper F.J., Bevan, D., Lamont T.N., Elliott, T., Roberts, N., Bouvier, A. and Gorecki, A.	19
12:15	13:00	*Lunch*		
13:00	14:00	**Magmatic-Hydrothermal Mineralisation – II.** *Chair: Caroline Soderman (Cambridge University)*		
13.00	13.15	Using Detrital Zircon Geochemistry to Explore for Porphyry Copper Deposits: Combining Catchment Areas, Fertility Indicators and Multivariate Analysis	Ojeda, A. (STUDENT), Wilkinson, J.J., Vermeesch, P., Roberts, G., Cobenas, G. and Perkins, R.	20

13.15	13.30	Multi-phase petrochronology applied to porphyry-skarn mineralization: combining Re-Os molybdenite and U-Pb garnet, titanite, apatite and calcite geochronometers	Bowie, S. (STUDENT), Mottram, C., Kellett, D., Barrington, M. and Porter, S.	21
13.30	13.45	Controls on Skarn Development and Pb–Zn Mineralization at Keban, SE Anatolia: Insights from Fluid Inclusions, Stable Isotopes, and Mineral Chemistry	Kirat, E. and Mutlu, H.	22
13.45	14.00	Role of magmatic sulfides in the evolution of magmas associated with high-grade epithermal gold deposits: an example from southern Kyushu, Japan	Ishida, M., Jenner, F.E., Hammond, S.J., Cortes-Calderon, E.A., Broderick, C., Hosono, T., Shinjo, R. and Wilkinson, J.J.	23
14:00	14:45	***AGM***		
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15:45	17:00	**Granite-related Li and REE Mineralisation** *Chair: Chris Yeomans (NeoGeo Ltd) Sponsored by IAGOD*		
15.45	16.00	Unzoned Lithium Pegmatites: Fluid-saturated?	Nava de la Peña, J.S. (STUDENT), Gardiner, N.J. and Mangler, M.F.	24
16.00	16.15	The role of fluorine in the petrogenesis of Li-granites: a case study of the Li-granites of Cornwall, UK	Morris, M.C. (STUDENT), Weller, O.M., Soderman, C.R., Edmonds, M., Beard, C.D. and Yeomans, C.M.	25
16.15	16.30	The tectonic, thermal, and temporal controls on the production of lithium-enriched melts	Weller, O.M. and Copley, A.	26
16.30	16.45	Modelling redox constraints on tin granite genesis	Benson J. (STUDENT), Gardiner N., Palin R., White R. and Higgins O.	27
16.45	17.00	Alkaline Magmatism, Alteration and Anatexis: Key Processes in the formation of REE-Nb-Ta-Zr Roof-Zone Deposits	Rooks, C.J.W., Finch, A.A., Hutchison, W., Lewis, M.P. and Frangeskides, G.	28
Wednesday 7th January				
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09.30	09.45	Copper Smelting Slags from Cornwall: Critical Metal Content and Economic Potential	Tanciongco, A. (STUDENT), Jenkin, G.R.T. and Bird, P.	30
09.45	10.00	New pegmatitic rare earth element sources to diversify supply chains	Elliott, H.A.L., Deady, E., Partin, C. and Santos, C.	31

10.00	10.15	The critical role of carbonate mineral identification in accurate acid-base accounting for mine waste characterisation	Roberts, M., Pearce, S., Brookshaw, D., Grant, S. and Barnes, A.	32
10.15	10.30	Speciation, Distribution & Paragenesis of Carbonate Minerals at the Ikkari Gold Deposit, Finland: Implications for Block Modelling	de Kock, M-M., Wright, T., Roberts, M., Brookshaw, D. and Hartshorne, C.	33
10:30	11:00	*Morning coffee break*		
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11.00	11.15	Resolving the syn-genetic mineralization age of a metamorphosed Archean VHMS deposit using multiple geochronological approaches	Dana, C. (STUDENT), Hollis, S., Tavazzani, L., Chelle-Michou, C., Glorie, S., Kuwahara, S., Mimura, K., Yano, M., Ohta, J., Selby, D., Kato, Y., Pashley, V., James, M. and Podmore, D.	34
11.15	11.30	Critical metal presence in Archean VMS deposits: Case study of the Golden Grove deposits	Yin, A. (STUDENT), Hollis, S.P., Dana, C.D.P. and Hudson-Edwards, K.	35
11.30	11.45	Controls on precious and critical metal enrichment in VMS deposits of the Caledonian-Appalachian orogeny	Mongeau, P. (STUDENT), Hollis, S.P., Cooper, C., Piercey, S., McClenaghan, S., Joseph, G., Cartigny, P. and Butler, I.	36
11.45	12.00	Machine Learning Prospectivity Analysis for VMS Deposits in the Semail Ophiolite, Oman	Lambert, C., Scarlet, A., Ismail, A., Baines, A., Gines, J., Ford, K., Cihan, M., Samad Al Rawahi, A., Al Balushi, H., Kenchetty, P. and Al Humaidi, G.	37
12:00	12:45	*Lunch*		
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12.45	13.00	New insights into controls on Ni-Cu-Co sulfide distribution in the Arthrath deposit, Aberdeenshire, Scotland	Thompson, E.S., Holwell, D.A., Bacon, J., Frankland, O., Fowlie, B. and Gardiner, F.	38
13.00	13.15	Investigating country rock assimilation signatures in the Turfspruit Platreef Ni-Cu-PGE deposit, Northern Limb of the Bushveld Complex, South Africa	Barbieri, A. (STUDENT), McFall, K.A., Herrington, R.J., McDonald, I., Phetlhu, B. and Dunnett, T.	39
13.15	13.30	Newly discovered Cu-Ni-sulfide mineralisation in the 1.8 Ga Stendalen mafic intrusion, Ketilidian Orogen, South Greenland	Roper, M. (STUDENT), Holwell, D.A., Hamilton, M.A., Rasch-Christensen, A. and Gilbertson, J.	40
13.30	13.45	Tracing Nickel and Cobalt through the Processing Chain: A Forensic Geometallurgical Study of the Kevitsa Mine	Magalhães, N., Prado-Araújo, F., Rollinson, G., Vassilieva, E., Chipakwe, V., Crane, R.A., Andersen, J.C.Ø., Muchez, P. and Hughes, H.S.R.	41
13:45	14:30	*Poster Session (Day 2)* *sponsored by Society of Economic Geologists*		

14:30	16:00	**REE enrichment processes in the supergene and sedimentary environment** *Chair: Holly Elliot (BGS)*		
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15.00	15.15	Characteristics of Rare Earth Elements (REE) enrichment in carbonatite-derived weathered materials at Miaoya, China	Kumar, P. (STUDENT), Smith, M., Fendley, S.B., Li, M.Y. and Jalote, A.	43
15.15	15.30	Distribution and Geochemical Behaviour of Critical Elements in Pomalaa Lateritic Profiles, Sulawesi, Indonesia	Qodri, M.F. (STUDENT), Akane, I., Kotaro Y., Elwin, E., Abdul, B., Saefudin, J. and Akira, I.	44
15.30	15.45	Vanadium in Silurian Black Shale of North Gondwana: the Morocco case	Solomita, G., Bouabdellah, M., Idbaroud, M., Boni, M., Mondillo, N., Boukirou, W. and Balassone, G.	45
15.45	16.00	Supergene enrichment of carbonatite-hosted REE deposits: Development of the palaeolaterite at Sokli, Finland	Smith, M., Li, M.Y., Fendley, S.B., Wei Chen, Wall, F., Kumar, P., Rooks, C. and Grästen, T.	46
16:00	16:30	**Prizes & Conference Close**		

POSTERS

Potential strategic ore deposits on Mars: implications for in situ resource utilization	**Palin, R.M., Robb, L., Gardiner, N.J., Koopmans, L., Sihombing, F., Sayab, M., Wade, J. and Elardo, S.M.**	**48**
Metasomatism and metamorphism around the Loch Borralan Intrusion, Northwest Scotland	Goddard, I.[1] (STUDENT), Palin, R.M.[2], Searle, M.[2], Mackay-Champion, T.[2], Koopmans, L.[2], Wade, J.[2], Holdship, J.[2], Waters, D.[2] and Liu, J.[3]	49
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Structural Clues to UK and Ireland Molybdenum Resources	Rooney, L.A. (STUDENT), Mariani, E., McNamara, D., Lepley, B. and Bonson, C.	51
Constraining the age, geology, geochemistry, and VMS prospectivity of the Tallering Greenstone Belt, Yilgarn Craton, Western Australia	Turanski, Michaela (STUDENT), Hollis, Steve, Diers, Steffen, Dana, Cendi, Fitton, Godfrey, Tavazzani, Lorenzo, Chelle-Michou, Cyril, Glorie, Stijn and Morey, Brett	52
Characteristics of the Abetselo volcanogenic massive sulfide mineralization, western Ethiopian greenstone belt: the oldest known gold-bearing VMS in the Arabian-Nubian Shield?	Zewde, A. (STUDENT), Hollis, S., Smith, B., Dana, C., Tavazzani, L. and Chelle-Michou, C.	53
The rare earth element and fluorite deposit at Monte Muambe, Mozambique	Church, A.J. (STUDENT), Broom-Fendley, S., Simonet, C., Wall, F.	54
Micromineralogy of the Irgaity gold placer, Kazakhstan	Dolgopolova, A. , Omarova, G., Assubaeva, S., Seltmann, R., Tretyakov, A.V., Peregudov, V.V.4, Broderick, C., Salge, T., Tugambay, S.	55

An Updated Appraisal of the Mineral Prospectivity of the Arabian Shield

Davey, J.[1], Price, J.[1], Ward, L.[1], Campodonic, M.[1], Al Ghamdi, A.[2], Sapanci, O.[2], and Schlichta, T.[2]

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[2]Ma'aden, Abo Bakr Siddiq Street, North Ring Road, Exit 6, P.O. Box 68861, Riyadh 11537, Kingdom of Saudi Arabia

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The Arabian Shield forms the eastern component of the Arabian-Nubian Shield (ANS), and represents one of the largest portions of exposed Neoproterozoic crust on Earth. Recent exploration interest and newly available high-resolution datasets, has highlighted the uncertainty of historic geodynamic models and related assessments of several mineral systems in the shield. This study builds upon a revised geodynamic framework developed by SRK and Ma'aden, focusing on mineral prospectivity mapping and target generation

Results demonstrate extensive metallogenic potential that is temporally, spatially and genetically diverse, reflecting a protracted history of tectonism and magmatism. The oldest metallogenic events (*ca.* 870 Ma) comprise primitive oceanic crust development and ophiolite obduction, preserving podiform chromite mineralisation along the Yanbu and Bi'r Umq suture zones. Bi-modal magmatism emplaced during the accretion of juvenile arc terranes during a period of plate reorganisation (*ca.* 700 Ma), are prospective for VMS, epithermal and magmatic Ni-Cu-PGE systems. Suturing of the Arabian Shield (*ca.* 660-620 Ma) resulted in the development of the N-S trending Nabitah Orogenic Belt, extending undercover along a newly interpreted arcuate geometry that trends northeast of the exposed shield. Voluminous post-orogenic felsic magmatism (*ca.* <620 Ma) exploited reactivated NE-SW trending pre-Nabitah translithospheric structures, resulting in evolved peraluminous and peralkaline granitic complexes prospective for Sn-W-Li-Cs-Ta and REE-Zr-Nb-Ta mineralisation. A series of volcanic arcs accreted to the ANS throughout pre- to post-Nabitah orogenesis demonstrate fertility for porphyry and epithermal mineralisation.

This study provides an updated understanding of the geological history of the Arabian Shield based on the integration of geoscientific datasets. The updated geodynamic framework, along with mineral system models for eight geologically permissible deposit styles, form the basis of the widest range of prospectivity maps and exploration targets generated to-date in the Kingdom of Saudi Arabia.

Privacy-preserving machine learning for prospectivity analysis using variogram and unsupervised learning

Felix M. H. Sihombing[1,2], Richard M. Palin[1], Hannah S. R. Hughes[3], and Laurence Robb[1,4]

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The value of machine learning (ML) for mineral exploration is becoming increasingly recognised by both academia and industry, although its efficacy varies significantly according to deposit type and the form of ML applied [1]. Mineral deposits within the continental crust are rare, limiting the usefulness of supervised ML approaches. In addition, their geological heterogeneity proves challenging for supervised learning, and models often perform poorly on unseen data. More importantly, the sensitivity of exploration data limits access, hindering the optimal training needed to address the heterogeneity issue. The application of privacy-preserving ML (PPML) techniques [2] can provide confidence for data sharing between data owners and data users, helping to remediate the challenges in applying ML for prospectivity analysis

Here, we demonstrate how variogram modelling, used PPML technique to transform and obscure sensitive data, combined with anomaly detection through unsupervised learning, can serve as a viable complimentary technique for determining prospectivity at a regional, orefield-scale during the early mineral prospecting stages. Additionally, we offered simple ML explainability technique to interpret the data and coupled the result with geological information. This method was applied to the United Kingdom (UK) to predict zones with metallogenic potential. This preprocessing technique preserves data confidentiality while enabling unsupervised learning algorithms to detect anomalous geological zones likely to host orefields that can be targeted for future exploration

[1] Yang F et al. (2024) Earth-Sci. Rev 258: 104941
[2] Xu R et al. (2021) arXiv:210804417.

Application of Niggli Numbers in mineral exploration using ioGAS®

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Niggli Numbers are values obtained from the major element analysis of a rock that utilize the concept of equivalent molecular numbers of component rock oxides (defined as the ratio of weight percentage of an oxide component to its molecular weight). Oxide or elemental data are combined and converted into 4 primary Niggli Number values (al, alk, c and fm), 3 secondary values (si, ti and p) and two ratios (mg and k) [1]. Niggli Numbers have the advantage that they can be calculated for any rock type or mineral without needing to take account of additional factors such the oxidation state of iron or the volatile content. McDonald [2] updated and automated the original Niggli calculation in Excel and demonstrated how different minerals and many applications relating to mineral and hydrocarbon exploration (e.g. alteration, magma contamination/fractionation, sedimentary provenance, etc.) could be represented and understood using vectors and trends on Niggli diagrams.

Following publication of the McDonald study in early 2024, there has been active collaboration with IMDEX to bring Niggli Number plots and functionality into the ioGAS® geoscience data analysis platform. Automated Niggli calculations and common binary plots were introduced in Version 8.2 in mid-2024, and Niggli ternary plots and a suite of useful reference rock suite (e.g. MORB, Collisional Margin basalts, andesites, dacites and rhyolites, Bushveld Complex rocks, etc.) were added when Version 8.3 was released this year. Examples of Niggli plots created using ioGAS® are shown in Figure 1. This presentation will illustrate more examples of the Niggli functionality that exists for users and more applications where Niggli Numbers may be useful for rapidly visualizing mineralogy and tracking processes linked to mineralization across a range of different deposit styles.

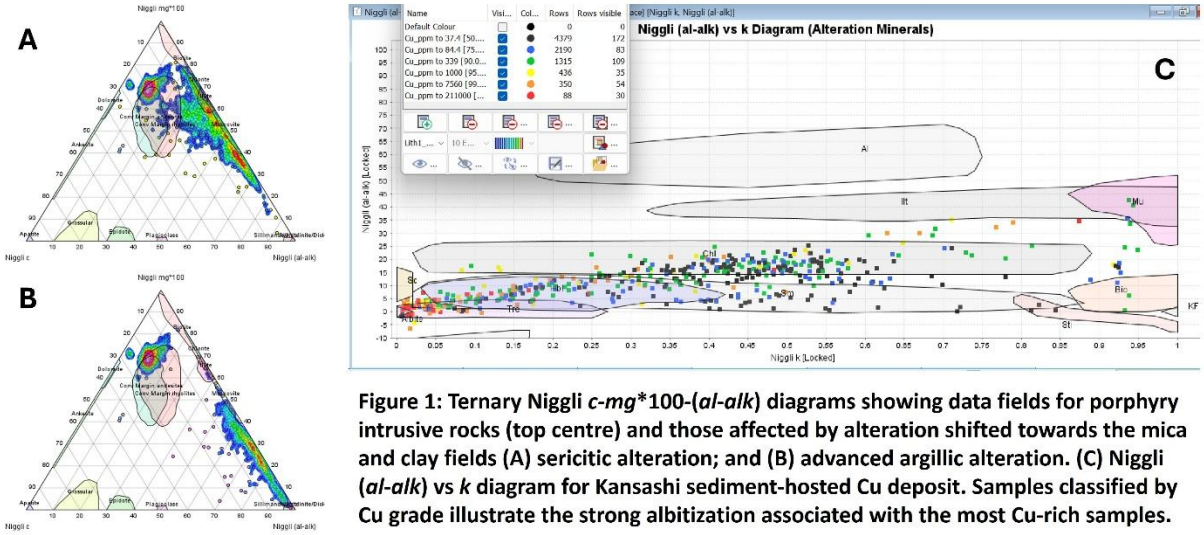

Figure 1: Ternary Niggli *c-mg100-(*al-alk*) diagrams showing data fields for porphyry intrusive rocks (top centre) and those affected by alteration shifted towards the mica and clay fields (A) sericitic alteration; and (B) advanced argillic alteration. (C) Niggli (*al-alk*) vs *k* diagram for Kansashi sediment-hosted Cu deposit. Samples classified by Cu grade illustrate the strong albitization associated with the most Cu-rich samples.**

References:
[1] Niggli P (1954) Rocks and Mineral Deposits, W.H. Freeman and Co, 559pp.
[2] McDonald I (2024) Chemical Geology, 650: 121915.

Exploration Value Creation Across Scales

Lindsay, D.H.M.[1], Thebaud, N.[1], Masurel, Q.[1], Trench, A.[2] and Hronsky, J.M.[2,3]

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Giant ore deposits are a product of predictable, hierarchically-scaled geological processes. Yet, global mineral deposit discovery rates are falling despite increases in expenditure and the adoption of machine learning and mineral systems approaches[1]. A key reason for decreasing performance is postulated as a poor understanding of whether the information in exploration datasets does, or does not, relate to the search space of interest[2].

To best optimise mineral exploration strategies, this study attempts to define combined technical-economic metrics for assessing exploration performance across scales and at each decision-making stage. The orogenic gold mineral system across the Yilgarn Craton is used as a case study area, given this deposit style has been extensively studied in the region and has a significant data repository[3]. The project will initially establish quantitative metrics for technical exploration performance, defined as 'area reduction' and 'endowment capture efficiency'. Effective exploration techniques should reduce the search area whilst retaining gold deposit endowment by an effective factor[3] (e.g. 60-80%).

Stage 2 of the project first establishes how 'feature importance' changes with scale. For example, how does the spatial association between gold mineralisation and major structural features (e.g. trans-lithospheric faults; regional fold axes) change from province to district-scale. Once scale-dependent feature importance is understood, and quantified, the optimal data layer for mapping these features will be assessed via data metrics such as signal-to-noise ratio (SNR). High SNR is expected to result in quantifiable high 'feature confidence' for the critical mappable features. The optimum data layer for mapping a critical feature may not be available in public datasets. Therefore, the next project phase assesses the value proposition of processing existing data vs collecting primary datasets, given that primary data can be tailored to high SNR that relates to the exploration question. The final project stages involve decision-tree expected monetary value modelling and exploration scenario analysis, used to assess the performance of different exploration strategies. For example, given high feature importance, high data SNR and a range of available datasets and/or primary acquisition strategies, is predictable value creation possible in mineral exploration?
This project provides a unique opportunity to evaluate exploration value creation using a multi-scale and multi-disciplinary mineral system approach. Research outcomes should help visualise the steps required to reverse the declining discovery trend and provide critical insight for national geological surveys in understanding the most effective pre-competitive datasets to acquire to aid domestic exploration efforts. Outcomes will also guide private companies in understanding quantitative metrics for data efficacy and best exploration practice. The envisaged research may also identify further research directions, e.g. identifying where feature importance knowledge (i.e. system geology) can be improved and reviewing 'big data' prospectivity mapping approaches in the context of value creation.

[1] McCuaig, T. C., & Hronsky (2017). The Mineral Systems Concept. Applied Earth Science. 126:77-78.
[2] Hronsky, J. M. (2009). The Exploration Search Space Concept. CET Q Newsletter. 8:14-15.
[3] Witt, W.K., Ford, A., & Hanrahan B. (2015). District-scale targeting for gold in the Yilgarn Craton. GSWA.

The Significance of Magnetic Fabrics Preserved in Hydrothermally Altered Rocks

Latimer, B.[1], McCarthy, W.[1], Mattsson, T.[2] and Reavy, J.[3]

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Anisotropy of Magnetic Susceptibility (AMS) and Anisotropy of Magnetic Remanence (AMR) are critical petrofabric tools commonly applied in investigating the evolution of volcano-magmatic, tectonic, and surface process systems. These highly sensitive techniques can distinguish multiple magnetic fabrics within individual samples, shown to be crucial in assessing archives of emplacement and deformation in intrusions where magmatic and tectonic processes occur concurrently or successively [1][2]. They have also been used to understand magmatic processes within layered igneous complexes associated with the concentration of economic mineral phases [3][4]. However, application of AMS and AMR to understand ore-forming processes in other deposit types is limited by the susceptibility of the mineral phases dominant in magnetic signals to hydrothermal alteration, potentially overprinting pre-existing petrofabrics. Despite being a well-known occurrence [5][6], the mechanisms and extent to which hydrothermal alteration modifies magnetic fabrics remains poorly constrained, raising concerns about the reliability of interpretations in studies involving hydrothermally altered rocks.

Our recent work assesses the significance of magnetic fabrics preserved in a hydrothermally altered fault zone that crosscuts a granitic pluton. Data were collected from unaltered granodiorite peripheral to the fault, the fault damage zone and the fault core to assess the impact of hydrothermal alteration on magnetic fabrics associated with magmatic and tectonic processes. Magnetic and hyperspectral data were used to characterise alteration distribution and intensity by quantifying changes in hydrous silicate and iron oxide phases. AMS and AMR fabrics were then measured and interpreted as either magma transport, tectonic, or hydrothermal alteration fabrics with context from field and petrographic data.

Our integrated hyperspectral-magnetic approach defines three alteration zones. Onset of hydrothermal alteration is identified from a subtle removal of white mica and low coercivity iron oxides (titanomagnetite) and the growth of new, high coercivity iron oxides (hematite) alongside chlorite and epidote. As alteration intensity increases, titanomagnetite and white mica are completely removed, with hematite, epidote and chlorite becoming predominant in the system. We note that changes to AMS and AMR fabrics occur in step with these changes in oxide and hydrous silicate mineralogy, with partial to complete destruction of tectonic and magmatic fabrics observed with increased alteration intensity. As these precursor fabrics are destroyed, they are replaced by a sub-vertical petrofabric defined by the alignment of hematite, interpreted as a product of hydrothermal fluid transport.

Our results demonstrate the ability to separate a record of fluids migrating across a fault corridor from underlying magmatic and tectonic events, providing a framework to the application of rock magnetism to examine mineralisation processes within hydrothermal settings.

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Copper Kitchens: A New Framework for Sedimentary-Hosted Copper Exploration

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Copper is fundamental to the Energy Transition, the drive to help mitigate climate change through a progressive global switch to lower carbon energy sources. It will be needed in ever greater abundance to support electrification and infrastructure upgrades, as well as provide the raw components for electric vehicles, renewable energy generation, and battery storage. Supply versus demand forecasts, along with declining ore grade and tonnage, particularly at near surface exploration depths pose a serious risk of a 'copper shortfall'. This supply gap, coupled with the prolonged timeline for predictions to discovery, and eventually to production, necessitates a shift in the mindset and tools that are used in the conceptualisation and exploration of copper, as well as all the other critical metals. Despite the larger size of typical porphyry copper deposits, sedimentary-hosted deposits are generally of higher grade, and are our focus here.

Over the past few years, we have been applying our experience in developing and employing hydrocarbon exploration workflows to aid subsurface mineral exploration, allowing for predictions to be made into the unknown – both deeper into the subsurface and in locations away from data control. These predictions are based upon robust tectono-stratigraphic frameworks built on diverse geological datasets, regional knowledge, and data-driven models. We have applied this approach to understand and predict the likely occurrence of critical components for sedimentary-hosted and porphyry copper, magmatic nickel, lithium and rare earth elements. These mineral prospectivity outputs can be used as a starting point to help generative teams understand and find mineral resources in the subsurface.

Previously, we have utilised a holistic mineral systems approach to map global prospectivity for sedimentary hosted systems, based on the geological model of Hitzman [1], showcasing some of the outputs for the German and Polish Kupferscheifer districts of the Zechstein basin [2]. We have now expanded our screening approach, through the concept of 'copper kitchens' – Phanerozoic sedimentary basins (or parts of) where the fundamental components of the mineral system (copper source, brine source and organic-rich reductant) may be present in different and variable temporal-stratigraphic configurations. This is achieved through the mapping of each component through to the prediction of lithological facies in a basin, via Gross Depositional Environment (GDE) maps, and assessing the nature of underlying basement from plate model-derived tectonic domain outputs [3].

The generated output maps, provide a rapid assessment of sedimentary basins that may have the critical components for the generation and precipitation of Cu-bearing fluids, at the global scale. The integration of tectonic data (e.g. geodynamic units, basin boundaries and faults) and basin contours help highlight where fluids, sourced from the kitchen areas, may migrate to. This approach has been validated via the incorporation of known deposit data. At the regional scale, we also utilise a holistic source-to-sink approach, examining paleo-drainage systems that transport copper-rich sediments from hinterland source areas into basin sinks. The UK is presented as a case study, integrating copper kitchen mapping with sample data from Parnell [4], which provides geochemical evidence for copper enrichment in specific sedimentary intervals. The results demonstrate the viability of our approach in identifying sedimentary basins that may be prospective for sedimentary-hosted copper mineralisation.

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[2] Helps and Nicoll (2024) Subsurface Insights, Feb:1-14
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[4] Parnell et al. (2021) Geofluids 2021:1-14

Porphyry copper formation driven by water-fluxed crustal melting during flat-slab subduction: Insights from the Laramide Belt, SW USA

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The prevailing view of porphyry copper formation along convergent plate boundaries involves deep crustal differentiation of metal-bearing juvenile magmas derived from the mantle wedge above a subduction zone [1,2]. However, many major porphyry districts formed during periods of flat-slab subduction when the mantle wedge would have been reduced or absent, leaving the source of the ore-forming magmas unclear. A key example is the Late Cretaceous-Palaeocene Laramide Porphyry Province in Arizona, which formed during flat-slab subduction of the Farallon Plate beneath western North America. By combining geochronology, thermobarometry, and isotope geochemistry to investigate the deep crustal processes taking place during Laramide porphyry mineralisation, we show that the Laramide granitic host rocks did not derive from the mantle wedge, but instead from a Proterozoic crustal source that was potentially pre-enriched in copper [3]. This source underwent water-fluxed melting between ~73 and 60 Ma, coincident with peak granitic magmatism (~78–50 Ma), porphyry genesis (~73–56 Ma), and flat-slab subduction (~70–40 Ma). Melting was driven by volatiles derived from the leading edge of the Farallon slab, without extensive magmatic or metallogenic input from the mantle wedge.

We propose that this melting occurred in a geodynamic 'sweet spot' located directly above the leading edge of the flat-slab at the point it was shallowing from a steep to low angle geometry. At this location, elevated crustal temperatures would have prevailed due to a combination of thickened crust above and laterally displaced mantle wedge to the sides. Volatiles released from the dehydrating flat slab would have moved upward into the Proterozoic lower crust, promoting crustal hydration and melting. Resultant rheological weakening may have caused the locus of contractional deformation to migrate eastward ahead of the leading edge of the flat slab, although on timescales >15 Myr, continual underthrusting would have ultimately cooled the North American crust. This may explain the systematic spatial-temporal patterns of mineralisation: (1) pre-mineralisation contraction and barren granitic magmatism related to steep subduction; (2) syn-mineralisation granitic magmatism and water-fluxed crustal anatexis during slab flattening; and (3) post-mineralization ore-barren magmatism, tectonic quiescence, and cooling related to continued underthrusting of the Farallon plate.

The Central Andes show similar spatial-temporal magmatic and mineralization trends, invoking a similar flat-slab regime associated with Late Eocene–Miocene porphyry copper formation. We therefore propose that other convergent plate boundaries with flat-slab regimes experienced a similar mechanism of ore formation triggered by volatile-mediated lower-crustal melting.

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[3] Lamont et al. (2024) Nat Geosci 17: 1306–1315

Modelling trace element evolution in arc magmas: implications for copper porphyry indicators

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Trace element ratios in arc magmas are widely used to infer petrogenetic conditions, particularly those associated with copper porphyry-forming versus barren systems [1]. For example, high Sr/Y, high La/Yb, and listric rare-earth element (REE) profiles in copper-mineralised arc magmas have been attributed to extensive amphibole (+/- garnet) fractionation and suppressed plagioclase crystallisation. These mineral assemblages are linked to hydrous, oxidised magmas crystallising at lower crustal pressures during crustal thickening [e.g. 2–4]. However, quantitatively linking whole-rock signatures to pressure, water content, or redox conditions remains challenging, as trace elements are sensitive to mineral assemblage and compositions, which both evolve during fractional crystallisation. While experiments provide insights into assemblages at selected conditions [e.g. 5], commonly used forward-modelling tools are unsuitable for amphibole-bearing arc magmas. Here, we integrate a recently updated thermodynamic model suite appropriate for arc systems [6] with dynamic (composition-, temperature-dependent) mineral-melt partitioning to track trace element evolution. Benchmarking the model against published experiments, including apatite saturation, shows that the methodology successfully reproduces phase assemblages and compositions.

We simulate fractional crystallisation of an average primitive arc magma across mid- to lower-crustal pressures (4–10 kbar), 2–4 wt% initial H_2O, and a range of redox conditions (~ 2 log units range in ΔFMQ). We demonstrate how mineral-specific vectors evolve in trace element ratio (e.g. Sr/Y, Dy/Dy*) and rare-earth element shape coefficient (λ) space. Results highlight that amphibole and garnet may produce overlapping λ-space vectors under deep, hydrous conditions—contrary to orthogonal vectors inferred using static (composition-, temperature-independent) trace element partitioning. Multiple petrogenetic paths can yield similar whole-rock trace element outcomes, particularly with poorly constrained primitive melt compositions. High Sr/Y, for example, commonly associated with porphyry systems, can form without particularly deep, hydrous, or oxidised conditions when dynamic partitioning behaviour is considered, if extensive fractional crystallisation can occur [7]. Overall, this combined phase equilibria and trace element model provides a powerful framework to test plausible petrogenetic conditions of arc magmas, allowing us to disentangle the effects of pressure, water, redox, and mineralogy, with implications for understanding indicators of Cu porphyry fertility.

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

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Copper demand is rising rapidly, driven by its critical use in the electric technologies that underpin the global green energy transition. Copper is primarily sourced from porphyry copper deposits (PCDs), which are magmatic-hydrothermal systems typically formed above subduction zones within compressional arcs. However, the tectonic controls on precisely where and when they form within an arc are poorly understood. Clustering of PCDs in space and time implies that tectono-magmatic controls play an important role. If better constrained, these controls could be valuable to guide exploration efforts, particularly during preliminary, terrane-scale investigations.

In the copper-rich Laramide Porphyry Province (LPP) of Arizona, most PCDs are thought to have formed over a 20 Myr period (~75–54 Ma), synchronous with a relaxation of contractional stress during the onset of flat-slab subduction [1]. 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 [2]) suggests the tectonic controls must have been different. To explain this difference and resolve the tectonic settings of PCD formation in the NGB, we compare the spatial-temporal history of crustal contraction, relaxation, and extension, to the distribution of PCDs. To avoid the widespread post-Laramide Basin and Range extension that overprinted much of the earlier deformational history, we focus on the pre-extensional deformation fabrics and metamorphic assemblages preserved within three exhumed metamorphic core complexes.

To constrain the timing of deformation we use *in situ* Rb-Sr dating [3] of syn-kinematic micas that grew during contractional (~55–47 Ma) and extensional (~101–95 Ma & ~47–30 Ma) ductile shearing, plus Lu-Hf dating of prograde garnets (~105 Ma and ~125 Ma). Comparing these new geochronologic constraints to PCD formation in the NGB, we identify two distinct settings for PCD formation:

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

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. The metal contents of PCDs in this setting show an evolution from more Au-rich to more Mo-rich, and are distinct from those in the LPP and (1). 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.

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Using Detrital Zircon Geochemistry to Explore for Porphyry Copper Deposits: Combining Catchment Areas, Fertility Indicators and Multivariate Analysis

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The growing global demand for copper underscores the need to refine exploration strategies for porphyry deposits, which supply more than 60% of the world's copper [1]. In recent years, several studies have proposed magmatic fertility indicators based on zircon geochemistry, however, very few have examined how these signals can be applied to detrital samples for exploration purposes, and none have tested such an approach at a regional scale.

This study uses a regional zircon dataset of over 79,000 analyses from 300 stream-sediment sampling locations. For each site, a catchment area was delineated to constrain the potential sources of the sediments reaching that point. Zircon fertility indicators related to magmatic water content and oxygen fugacity were evaluated within each catchment to assess the presence of porphyry-fertile magmatic suites.

Principal Component Analysis (PCA) and Multidimensional Scaling (MDS) were applied to characterise geochemical variability and to identify zircon populations that deviate from the regional geochemical background. These distinct populations show strong correlations with fertility indicators such as zircon Eu/Eu* and redox estimates (ΔFMQ). Clustering analysis, integrating multivariate and fertility parameters, grouped samples into porphyry-fertile and infertile clusters, providing a statistically objective classification.

A strong spatial correlation is observed between the areas identified as magmatically fertile and the locations of known porphyry deposits. Additional areas with similar geochemical characteristics but no known deposits define new zones of potential exploration interest.

This approach demonstrates that multivariate statistical analysis provides a powerful tool to identify fertility patterns in zircon geochemistry, complementing conventional fertility indicators and enabling the objective identification of fertile magmatic sources. Moreover, defining a catchment area for each sampling site allows these signals to be traced back to their possible source regions, offering a reproducible framework for regional-scale exploration targeting.

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Multi-phase petrochronology applied to porphyry-skarn mineralization: combining Re-Os molybdenite and U-Pb garnet, titanite, apatite, and calcite geochronometers

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Porphyry-skarn deposits host critical metals including iron, copper, gold, silver, molybdenum, tungsten, zinc, tin, lead, and rare earth elements, which are concentrated through magmatic-hydrothermal fluid processes. Skarns form at the intersection of magmatism, metamorphism, and metasomatism, and are therefore ideal geological systems in which to study the interactions between these processes. Although the evolution of porphyry-skarn deposits is fairly well documented, the longevity of both magmatism and hydrothermal activity remains unclear. Recent method developments mean it is now possible to directly date more unconventional minerals using the U-Pb system. Here, we apply a novel combination of in situ U-Pb geochronometers (zircon, garnet, apatite, titanite and carbonate), Re-Os molybdenite dating, and trace-element data to temporally track mineralizing processes from the magmatic to hydrothermal regime (~800ºC to ~200ºC).

This project focuses on a case-study ore deposit system in northwestern British Columbia, within the Canadian Cordillera. The Blue Property, owned and operated by Core Silver Corp., hosts a variety of mineralization styles (Mo-Cu porphyry, Zn-Cu-Ag skarn and Ag-Zn-Pb-Cu CRD) in several target areas, set within poly-deformed metasedimentary country rocks. Mineralized zones display evidence of multiple magmatic, faulting, and fluid-flow events that previously had no quantitative geochronological constraints. Multi-phase petrochronology across ~40 samples is used to test 1) the longevity and possible overprinting relationships within the case-study porphyry-skarn deposit; and 2) compare what processes are recorded by different geochronometers across a single mineralized system. New U-Pb datasets suggest that multiple pulses of igneous activity and porphyry mineralization are closely associated with at least two skarn events during the Paleocene, followed by ongoing faulting and fluid flow for a further ~20–30 Ma. Although garnet is shown to best record skarn processes, titanite and apatite provide constraints on country rock metamorphism as well as hydrothermal activity via variable secondary growth, recrystallization and/or diffusional resetting. In addition, calcite yields an extended lower temperature record of both syn- and post-mineralization fluid activity within skarn assemblages, veins, and brittle faults. More broadly, results suggest that hydrothermal fluid activity within porphyry-skarn deposits is complex, dynamic, and occurs over a protracted period of time compared to magmatic activity.

Controls on Skarn Development and Pb–Zn Mineralization at Keban, SE Anatolia: Insights from Fluid Inclusions, Stable Isotopes, and Mineral Chemistry

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The Keban Pb–Zn skarn deposit in the Elazığ district of southeastern Turkey formed within the Permo-Triassic/Permo-Carboniferous Keban Metamorphics and intruded by Late Cretaceous–Paleocene Keban Magmatics. Mineralization occurs as disseminated, vein-type, and massive types of ore hosted by alkali syenite porphyry, calc-schist, and dolomitic limestone. Three paragenetic stages of skarn development and ore deposition are identified: prograde (stage I), retrograde-sulfide (stage II), and supergene (stage-III).

The endoskarn contains grossular–andradite garnets (Grt 1 to 3), diopside, and plagioclase, while exoskarn includes grossular (Grt 4), pyroxene, and vesuvianite. Ore minerals include galena, sphalerite, chalcopyrite, magnetite, hematite, molybdenite, and pyrite accompanied in small quantities by pyrrhotite, arsenopyrite, manganese oxides, native gold, and sulfosalts. Mineral chemistry of garnets suggest that early Grt 1 formed from reduced fluids with low water–rock ratios, whereas Grt 2 and Grt 3 formed from more oxidized magmatic fluids with higher water–rock ratios. Later Grt 4 and vesuvianite reflect interaction with Al-rich residual fluids.

Depleted $\delta^{13}C$ and $\delta^{18}O$ from skarn calcites indicate strong influence of hydrothermal fluids and later mixing with meteoric waters. Fluid inclusion studies indicate that high-temperature magmatic fluids of stage I (473–572 °C; ~12 wt% NaCl eq.) were progressively diluted by low-salinity meteoric waters of stage II (230–524 °C; 0.8–6.6 wt% NaCl eq.). Based on FI trapping pressures and depths of the boiling system, the mineralization formed after boiling during the retrograde stage, in a shallow setting with low–moderate temperatures and low salinity, within the pressure and depth range of ~100–500 bar and < 1.5 km, respectively. $\delta^{34}S$ values of sulphides (−8.5 to +2.1‰) reflect a dominant magmatic–hydrothermal contribution to the ore-forming system. Spatial relations among the host rock, alteration zone and mineralization with high concentration of Fe, Mn, and Ga of sphalerite point to deposition at low to moderate temperatures in the distal part of the skarn system.

Role of magmatic sulfides in the evolution of magmas associated with high-grade epithermal gold deposits: an example from southern Kyushu, Japan

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Magmatic-hydrothermal systems that form porphyry and epithermal deposits are major sources of Cu, Au and Ag globally. Although it is increasingly recognized that oxidizing conditions and elevated concentrations of water, sulfur, and halogens in magmas are essential for the formation of porphyry deposits, the importance of these factors, particularly the role of magmatic sulfide, remains poorly constrained for epithermal systems. Because Au, Ag and Cu are highly compatible in magmatic sulfides, early sulfide crystallization has been viewed as detrimental to ore formation, unless sulfide saturation occurs late, after the exsolution of volatile phase enriched in chalcophile elements [1]. Conversely, the formation of magmatic sulfides may serve as an effective concentration mechanism, whereby subsequent cannibalism or remobilization of previously fractionated sulfides might help release chalcophile metals into magmatic-hydrothermal fluids [2]. Although our understanding of strongly oxidized, calc-alkaline mineral systems in thicker arcs has advanced considerably over the past decade, comparable studies of less oxidized, mildly calc-alkaline systems in thinner arcs, where sulfide saturation is likely more common, remain scarce. Here, we present data from Middle Quaternary volcanic rocks from Southern Kyushu that are temporally and spatially associated with the large, high-grade Hishikari epithermal gold deposit. These rocks contain phenocryst-hosted sulfide inclusions throughout the andesitic to rhyolitic compositional range, suggesting that sulfide saturation occurred at intermediate stages of magmatic differentiation. Modelling or the liquid-line-of-descent suggests that the magmas were only moderately oxidized (approx. FMQ +1) and relatively water-poor (approx. 2 wt% H_2O) during differentiation, with fluid saturation occurring during late-stage differentiation of magmas. The bulk Cu and Ag trends and decreasing Cu/Ag with decreasing MgO for andesitic compositions can be mostly explained by fractionation of monosulfide solid solution (MSS), which is consistent with the observed sulfide composition. However, the bulk Au concentration increases in the final stage of differentiation, and we will discuss the reasons for this in the presentation.

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Unzoned Lithium Pegmatites: Fluid-saturated?

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Pegmatites are important multi-resource (Li-Ta-Sn) mineral deposits and now the major source of battery-grade lithium. Classic petrological models propose that pegmatites evolve fluid-undersaturated, with the magmatic-hydrothermal transition occurring only at very late stages of crystallisation [1]. However, these models were developed to account for the textures characteristic of zoned pegmatite systems. In contrast, the saturation conditions of *unzoned* Li-rich pegmatites, which currently constitute a major proportion of actively explored and mined Li-rich deposits, remains poorly addressed. Early fluid saturation could explain the chemical homogeneity of unzoned pegmatites, as it enhances elemental mobility and limits fractionation, and may therefore be a key control on the formation of economically viable Li deposits.

Here, we test this hypothesis using two Li-rich pegmatite systems, the Eastern Harare Pegmatite Group in the NE Archean Zimbabwe craton, as case studies of unzoned, petalite(±SQI)-albite pegmatites. We study apatite as a proxy for volatile behaviour during crystallization: high-resolution, in-situ volatile (SIMS) and trace-element (LA-ICP-MS) apatite compositions are used to build a robust volatile paragenetic model supported by a well-stablished thermodynamic framework [2].

Our results demonstrate that unzoned Li-rich pegmatites likely crystallized from melts that were fluid-saturated from the early magmatic stages onward, implying that the magmatic–hydrothermal transition in these systems is not a late-stage event, but rather an early and continuous process. These findings suggest that unzoned pegmatites follow petrologic pathways fundamentally different from those predicted by experimental models developed for zoned pegmatites. This has important implications for interpreting the paragenetic evolution of petalite- and spodumene-albite type pegmatite systems and highlights the need to revisit the P-T-X conditions typically assumed in experimental studies of pegmatite formation, as pegmatite melts may crystallize in the persistent presence of a fluid phase.

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The role of fluorine in the petrogenesis of Li-granites: a case study of the Li-granites of Cornwall, UK

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Demand for lithium (Li) is increasing due to its importance for green energy. Granitic melts derived from anatexis of metasedimentary rocks, particularly biotite-dehydration reactions, are an important Li source. However, exploration is hampered by poor understanding of their formation. Many questions remain about the genesis of these Li-enriched melts, with competing models suggesting extreme fractionation of generic sources [1], multi-stage melting models [2], or invoking unique sources, such as biotite-rich restites formed after an initial melting stage [3]. The central factor determining the viability of these models is the choice of partition coefficients ($D^{mineral/melt}$) used to describe Li behaviour. This choice is not straightforward as literature values can vary by over an order of magnitude for a given phase, and are commonly composition- and temperature-independent (i.e., fixed values). Here we use thermodynamic modelling implemented in MAGEMin [4] coupled with the spectrum of relevant published *D*s, including a dynamic $D_{Li}^{biotite/melt}$ which varies with biotite composition and temperature [5], to quantify viable Li enrichment scenarios during partial melting and fractional crystallisation.

Our approach is applied to the Li-rich Cornubian granite batholith and demonstrates the sensitivity of magmatic Li enrichment models to choices of *D* for modally-significant, Li-poor phases (e.g. quartz), as well as phases thought to dominate the Li budget (e.g. biotite). We show that economic Li enrichment may result from extensive fractionation with the application of selective partition coefficient suites used in some existing modelling (for example where $D_{Li}^{quartz/melt} = 0$, and $D_{Li}^{plagioclase/melt} / D_{Li}^{alkali\text{-}feldspar/melt}$ as ≤ 0.02). However, such values are not always supported by experimental or natural studies, and their use for volumetrically-dominant phases likely results in an overestimation of Li enrichment at a given melt fraction during both melting and fractional crystallisation.

Alternatively, we present a new model for the development of some Li-rich granitic magmas (such as the Cornubian batholith) via dehydration melting of fluorinated biotite, due to the substantial $D_{Li}^{biotite/melt}$ increase in a fluorinated system [5] and higher-temperature fluorinated biotite stability [6]. This model [7] reconciles the common observation of fluorite in Li-rich granites, the frequent occurrence of late-orogenic Li deposits, and provides a mechanism for extensive fractionation due to the depolymerising effect of fluorine in silicate melts [8].

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The tectonic, thermal, and temporal controls on the production of lithium-enriched melts

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Increasing demand for lithium-ion batteries, coupled to the desire for diversified supply chains, has driven ongoing attention in the formation of, and exploration for, lithium (Li) ores. Many of the world's important hard-rock lithium deposits are pegmatites and granites derived from partial melting of sedimentary protoliths. Partial melting of metasedimentary rocks is dominated by muscovite- and/or biotite-breakdown reactions. Muscovite is only stable in appreciable quantities for pelitic (mud-dominated) compositions, whereas biotite is a major phase across a wide range of metasedimentary compositions. Furthermore, biotite has been documented to be the most important host of lithium in metasedimentary rocks, consistent with most estimates of its mineral-melt partitioning value being higher than for other potentially important lithium hosts, such as cordierite and muscovite. Therefore, biotite breakdown reactions represent the most important source for the generation of lithium-rich melts.

This study examines the tectonic controls on the temperatures achieved in mountain belts, as a means to understand the conditions required for biotite-breakdown melting reactions in metasedimentary rocks, and therefore the range-scale patterns of lithium mineralisation [1]. Such conditions are most readily achieved in mountain belts with (i) large crustal thicknesses, (ii) high radiogenic heating rates, and (iii) slow convergence. The first two factors indicate an important role for geological history, in terms of creating a strong foreland to support the thick mountain belt, and assembling sufficiently radiogenic lithologies. The third factor—slow convergence—is generally incompatible with uplift outpacing erosion to develop thick mountain belts, but this paradox is resolved by, and explains, most lithium deposits being formed late in the history of mountain belts, at times of slowing convergence rates. Our results explain why lithium deposits are more prevalent in preserved Precambrian mountain belts, formed during times of higher radiogenic heating. The general approach we outline can also be applied to other critical metals provided that melting in continental mountain belts is an important factor in their distributions, regardless of the lithologies involved and the temperature range of importance (e.g. tin, tungsten, tantalum, and others).

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Modelling redox constraints on tin granite genesis

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The majority of the world's tin resources occur as magmatic–hydrothermal cassiterite (SnO_2) associated with "tin granites" [1,2]. Tin granites are typically S-type melts derived from metasedimentary sources and are enriched in Sn relative to both average continental crust and unmineralised granites [3]. Petrogenetic models for Sn enrichment invoke varying contributions from fractional crystallisation, source Sn enrichment, and biotite breakdown [3,4,5].

A defining feature of tin granites is their reduced oxidation state: they fall within the ilmenite series ($Fe_2O_3/FeO < 0.5$), in contrast to the oxidised magnetite series granites associated with Mo and Cu systems [6]. Redox state is fundamental because Sn^{4+} is compatible in Ti-bearing minerals (e.g., biotite, Ti-magnetite), whereas Sn^{2+} is incompatible in major rock-forming minerals and therefore preferentially enriched in melts during anatexis or crystallisation [7]. However, how the processes of melting and crystallization affect the oxidation state of tin granite magmas and by extension their ability to concentrate Sn is not well constrained.

We use phase equilibria modelling to examine oxidation state evolution during both crustal melting and subsequent fractional crystallisation, to test the compatibility of different petrogenetic models with generating ilmenite series granites. Ilmenite series granites can only be produced through partial melting of highly reduced pelites. Melting conditions consistent with forming an ilmenite series melt lie in a redox "transition zone" where both Sn^{2+} and Sn^{4+} are stable; therefore, Sn partitioning is highly sensitive to small changes in the oxidation state of the source. As a result, Sn enrichment during partial melting is underestimated when fixed partition coefficients are assumed.

In contrast, fractional crystallisation drives progressive melt oxidation through biotite removal, creating a trade-off between Sn enrichment and increasing oxidation state. Consequently, petrogenetic models which invoke extreme (>90%) fractional crystallisation are inconsistent with generating reduced ilmenite series melts characteristic of tin granites.

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Alkaline Magmatism, Alteration and Anatexis: Key Processes in the formation of REE-Nb-Ta-Zr Roof-Zone Deposits

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Alkaline igneous rocks are renowned for hosting deposits of the critical raw materials deemed essential for the green energy transition, such as the Rare Earth Elements (REE) and Nb. Despite their importance, deposit models for these systems vital for guiding exploration are underdeveloped.

The Motzfeldt Complex of southern Greenland's Gardar Igneous Province hosts REE-Nb-Ta-Zr mineralisation of the alkaline silicate roof-zone subtype of alkaline igneous hosted REE-HFSE deposits (High Field Strength Element e.g. Nb, Ta, Zr) [1][2]. This study utilises field observations, transmitted light petrography, SEM, EPMA and LA-ICPMS to investigate controls on mineralisation from magmatic through hydrothermal stages.

Our investigation reveals a complex interplay between alkaline igneous metasomatism, known as fenitisation, and metamorphism. Geochemically bland quartz arenite country rock rafts and xenoliths detached at the roof of the magma chamber, reacted with fenite fluids enriched in alkalis, REE and HFSE and were contact metamorphosed by the heat of the surrounding magma. This transformation resulted in spotted albite-biotite hornfels with REE and HFSE minerals such as monazite, zircon and aeschynite-(Y) concentrated within biotite spots. Partial melting of this rock generated a HFSE-Na-enriched melt which mixed and mingled to varying degrees with the surrounding magma dependent upon temperature and degree of crystallisation controlled by depth within the roof-zone. Assimilation of the metasomatites by the Motzfeldt magma allowed concentration of REE and HFSE in the roof-zone which would otherwise have been dispersed through the country rock [3].

This work shows the benefits of collaboration between academia and industry in increasing our understanding of mineral systems for critical raw materials, guiding decision making in exploration for these complex and important modern resources.

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Towards a Circular Economy for Critical Minerals

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The circular economy (CE) offers a sustainable alternative to the traditional linear economy by focusing on reducing waste and keeping products and materials in use for as long as possible while regenerating natural systems [1]. It requires a fundamental shift from the 'take, make, dispose' model to a more sustainable system where materials are reused, repaired, refurbished, and remanufactured.

CE solutions are a key part of security of supply of critical minerals. If they are looked after well, metals are super sustainable materials that can complete many cycles of use and re-use. In Met4Tech we researched a whole systems CE – starting from geological exploration and encompassing the whole value chain. We produced UK roadmaps towards a better CE for lithium-ion battery materials (Li, Co) and rare earth magnet material [2] and the principles in these roadmaps apply to many materials and technologies.

So, starting at the beginning, in exploration, besides the obvious reworking on mine waste, more consideration could be given to potential co- and by-products, even from the first exploration desk studies. Moreover, mines should not be considered in isolation but as part of a symbiotic industrial ecology with adjacent industries such as farming, manufacturing and recycling as well as their local communities. We use the term CE geo-models for this extension of the traditional models [2,3].

Other interventions on the inbound cycle or 'forward loops' as we called this in our roadmaps, are also important. It is the manufacturing steps that set up materials, components and products for a long life in a CE but unfortunately second life is rarely high on the agenda in these manufacturing stages.

Too often also the term 'circular economy' is used to mean 'recycling' but recycling materials is the lowest value 'loop of last resort' in the CE hierarchy. It is better to use the other reverse loops of re-use and remanufacturing that maintain the materials at higher value. Having said this though, recycling is essential to capture materials and keep them in circulation, and a key intervention to ensure security of supply for critical raw materials. To go with this, geological views of anthropogenic resources will be needed more in the future.

The 'perfect circle' diagrams often used for CE are fiction. Pragmatic solutions now often combine primary (mined) raw materials with secondary (recycled) materials, and this is likely to expand. Also important is integrating CE into sustainability frameworks. When discussing UN Resource Management System, for example, we have been adding the CE principles as a fourth and key consideration alongside the principles relating to Environmental, Social and Governance.

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Copper Smelting Slags from Cornwall: Critical Metal Content and Economic Potential

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Global demand for copper and critical raw materials continues to rise, driven by the growth of renewable-energy infrastructure and advanced technologies [1]. This has led to increases in primary copper production and the accumulation of metallurgical waste. Since 1928, copper smelting alone has produced over 400Mt of slag, with annual output rising from ~4.3Mt to >34Mt by 2021. Early slags typically retain 1-20 wt.% Cu due to lower recovery efficiency. Despite this, many historical slag deposits remain poorly characterised, including those from nineteenth-century smelting in Cornwall and Swansea [2].

This study investigates historical copper slags from Cornwall, where mineralogical and geochemical analyses reveal a characteristic assemblage of spinifex-textured fayalite with magnetite or Fe-Al spinel, hosted in an amorphous silica-rich matrix. Copper (bulk content 1-2 wt.%) occurs primarily as sulfide phases (chalcopyrite or chalcocite), while some samples contain Cu-Sn±Bi alloy phases (25-90 at.% Cu, 4-10 at.% Sn), rimmed by chalcocite and hosting 3-5 µm Bi-rich blebs (>85 at.% Bi). This alloy assemblage represents a previously undocumented copper-slag mineralogy and likely reflects the Sn-rich and Bi-bearing character of Cornish ores [3].

The enrichment of critical metals in these slags makes them promising candidates for reprocessing. Prior studies rely on strong mineral acids or toxic reagents, achieving non-selective recoveries of around 75-90% [4] which highlights the need for more selective and environmentally benign extraction methods. Using a conservative 80% assumed recovery, selected Cornish slags, particularly from Hayle, may yield an estimated £66–£471 per tonne in recoverable metal value, with contributions of ~45% from Cu, 25% In, 15% Sn, 15% Zn, and the remainder from other metals.

To assess reprocessing potential, ongoing work will integrate automated SEM-based mineral liberation analysis with leaching experiments. These results will support a geometallurgical framework for evaluating metal deportment and the processability of historical slags as unconventional critical metal resources.

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New pegmatitic rare earth element sources to diversify supply chains

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The global drive to achieve net zero goals is causing pressure to decarbonise energy and transport systems to reduce carbon dioxide emissions and dependence on fossil fuels. Achieving a low-carbon society will require a large supply of a variety of raw materials to manufacture the green technologies required to limit climate change [1]. Rare earth elements (REE) are recognised as a critical raw material by both the UK [2] and Canadian governments due to their integral role in the manufacture of permanent magnets required for both wind turbines and electric cars. All modelling scenarios predict that demand for REE is expected to grow and surpass supply in the near future [3].

The UK lacks suitable geology to produce economic deposits of REE and is therefore completely reliant on imports and strategic global relationships. The majority of global REE are sourced from four deposit types: carbonatites, alkaline-silicate rocks, ion adsorption deposits, and placer mineral sands [4]. Production of REE is geographically limited, with China producing nearly 69 % of REE in 2024 [5]. Mine production is beginning to diversify, however, over 90 % of processing and separation occurs in China [3]. This geographical concentration and dominance of reagent production in China enables the country to influence REE prices, causing a risk to global supply chains, and being the predominant factor affecting REE criticality [4].

The petrogenesis of REE-enriched (Nb-Y-F) pegmatites is poorly understood compared to Li-Cs-Ta pegmatites. REE-enriched pegmatites are typically thought to be associated with peralkaline granites sourced from melting of the lower continental crust and/or the mantle. The REE-enriched pegmatites in the Wollaston Domain of Saskatchewan, Canada, have no clear local granite source. Two pegmatite endmembers can be found in this domain; one U-dominated and one REE-Th dominated. However, little is known regarding the source or formation mechanisms of these pegmatites. This project aims to develop a source-to-sink geomodel to determine the formation processes of the REE-enriched pegmatites in Saskatchewan. The shape and size of pegmatites can make exploration problematic, although high U-Th contents do make them detectable using radiometric methods. In addition, this project aims to explore methods and indicators that allow the targeting of REE-enriched pegmatites over barren U-enriched endmembers. This presentation divulges preliminary results determined through fieldwork and petrographic studies of these deposits.

Developing a secure, resilient, and diverse REE supply chain with high environmental, social, and governance standards is a key priority for both the UK and Canadian governments. Developing a deeper understanding of the REE-enriched pegmatites in Saskatchewan could provide a supply of monazite into the Rare Earth Processing Facility built by the Saskatchewan Research Council. This will have a global impact by aiding in the diversification of the supply of REE and creating a more resilient global supply chain, reducing dependence on Chinese production. Whilst understanding the formation and exploration methodologies of these deposits is applicable on a global scale to similar deposits, such as in Namibia and Mongolia.

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The critical role of carbonate mineral identification in accurate acid-base accounting for mine waste characterisation

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Accurate characterisation of mine waste materials is central to predicting acid metalliferous drainage (AMD) and designing effective waste management strategies. While Acid-Base Accounting (ABA) techniques such as the acid neutralisation capacity (ANC) [1] and Net Acid Generation (NAG) [2] tests provide a practical framework for estimating the characteristic of AMD, the reliability of these predictions is fundamentally dependent on assumptions regarding the mineralogical composition of the sample. In the methodologies of many ABA analyses carbonate minerals are often grouped together and predicted to all contribute equally to neutralisation; however, not all carbonates contribute equally, and some—particularly siderite ($FeCO_3$)—can complicate interpretations when not properly identified.

Siderite poses unique challenges for ABA because it behaves in a significantly different manner from more reactive carbonates such as calcite and dolomite. During total inorganic carbon analyses, siderite may be incorrectly quantified as a major neutralising phase, despite its limited ability to consume acid under typical environmental conditions. Furthermore, siderite dissolution can release ferrous iron, which subsequently oxidises to ferric iron, generating acidity rather than neutralising it. Such acid generation is typically commensurate with the amount of neutralisation potential (NP) from the release of carbonate. Thus, rendering siderite net neutral with respect to ABA. This secondary acidity can lead to overestimation of a material's neutralisation potential (NP) and underestimation of net acid-generating potential (NAG), resulting in false predictions of non-acid-forming behaviour. In addition, siderite's relatively slow reaction kinetics and sensitivity to redox conditions complicate both static and kinetic test interpretations. Such effects are not limited to siderite, other carbonates such as ankerite [Ca(Fe,Mg)(CO3)2] and rhodochrosite (MnCO3) can also introduce complicating factors to ABA predictions.

This presentation highlights the importance of incorporating robust mineralogical techniques—such as X-ray diffraction, electron microprobe analysis, and scanning electron microscopy—into routine ABA workflows to reliably detect and quantify carbonate and sulfide mineral phases. Case studies are presented illustrating misclassification outcomes when siderite and other minerals are not identified, and suggestions are provided on adapting ABA methodologies to account for such cases. By improving mineralogical resolution, the predictive accuracy of AMD assessments can be greatly increased. This in turn can reduce environmental risk, and support more informed mine planning and closure decisions.

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Speciation, Distribution & Paragenesis of Carbonate Minerals at the Ikkari Gold Deposit, Finland: Implications for Block Modelling

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The Ikkari gold deposit, located in the Central Lapland Greenstone Belt of northern Finland, consists of a structurally complex volcano-sedimentary sequence that has undergone greenschist facies metamorphism and several hydrothermal alteration events [1,2]. A variety of carbonate minerals are present - mainly dolomite, siderite, and calcite [2] - which are important for evaluating the deposit's overall acid mine drainage (AMD) characteristics including acid-neutralising potential (NP) [3]. While calcium- and magnesium-rich phases (calcite and dolomite) can act as effective buffers to potential acidity, iron-bearing carbonates (e.g. siderite) can exhibit more complex net-buffering characteristics, depending on their oxidation state [4].

This study investigates the speciation, paragenesis and distribution of these carbonate minerals to assess whether the mineral domains are more closely associated with ore and waste zones or with lithological units at Ikkari. Ca, Mg, and Fe served as the primary elements for carbonate identification. Whole-rock geochemistry alone is not suitable for carbonate phase identification due to the presence of silicates and oxides. Accordingly, representative samples were selected and analysed using a combined application of petrographic analysis, Raman spectroscopy, micro X-ray fluorescence, and thin section staining, alongside validation from X-ray diffraction (XRD) and scanning electron microscopy (SEM). Drill core samples were analysed to develop paragenetic sequences, and ternary Ca-Mg-Fe diagrams were used to classify the different carbonate assemblages [5].

The outcome of this research intends to build a more comprehensive geological understanding to further support and inform the environmental characterisation block model and associated risk assessments.

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Resolving the syn-genetic mineralization age of a metamorphosed Archean VHMS deposit using multiple geochronological approaches

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Accurately constraining the timing of mineralization is critical for understanding syn-genetic stratiform systems such as volcanic-hosted massive sulfide (VHMS) deposits. This study integrates multiple geochronological methods to determine the age of syn-genetic mineralization and subsequent magmatic, metamorphic, and deformational overprints at the King VHMS deposit in Western Australia [1]. Concordant ages from U–Pb zircon dating of felsic volcanic host rocks (2725 ± 10 Ma), a Re–Os pyrite isochron (2730 ± 26 Ma), and Pb–Pb galena model ages (ca. 2714–2718 Ma) collectively constrain the timing of syn-genetic mineralization. Pyrrhotite formed by metamorphic desulfidation of pyrite yielded a younger Re–Os age of 2652 ± 32 Ma, overlapping with prograde metamorphism dated by in situ Lu–Hf garnet analysis at 2680 ± 28 Ma. A Re–Os age from massive sulfide ore (2664 ± 23 Ma), representing a mixture of pyrite and pyrrhotite, is geologically meaningless due to metamorphic re-equilibration, underscoring the limitations of bulk Re–Os dating in high-grade metamorphic terranes. Quartz monzonite intrusions that crosscut the deposit and correspond to regional M2 metamorphism yield weighted-mean U–Pb zircon ages of ca. 2676–2665 Ma and host minor molybdenite mineralization with Re–Os ages of ca. 2650–2655 Ma. Together, these results establish the King Zn deposit as the earliest phase of VHMS mineralization associated with the development of the Kalgoorlie–Kurnalpi Rift (KKR), significantly older than other VHMS systems in the Eastern Goldfields. The study further shows that syn-genetic pyrite can retain its Re–Os isotopic signature through amphibolite-facies metamorphism, enabling direct dating of VHMS deposits in high-grade Archean terranes, whereas Re–Os ages in pyrrhotite record prograde metamorphism and provide a tool for identifying metal remobilization events [2].

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Critical metal presence in Archean VMS deposits: Case study of the Golden Grove deposits

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The Yilgarn Craton of Western Australia hosts many Volcanogenic Massive Sulfide (VMS) deposits, of which only a handful have been mined. These include the Gossan Hill and Scuddles deposits that are both part of the Golden Grove mining camp in the 2.9 billion year old lower greenstone sequences of the Youanmi Terrane. Both deposits contain two ore zones that have been mined for Cu, Zn, Au and Ag, with 15.9 Mt and 10.5 Mt of ore for extracted at Gossan Hill and Scuddles, respectively. In order to explore the further economic potential from the ore extracted from these deposits, by products (especially critical metals) could be considered.

Using laser ablation inductively coupled plasma mass spectrometry, sulfide minerals were analysed for their trace critical element contents to understand their deportment from deposit scale to single crystal scale. The trace critical metal concentrations (e.g., Co, In, Sb, Cd) of dominant sulfide minerals (pyrite, chalcopyrite, sphalerite, galena, pyrrhotite) across the deposits vary between the two ore zones. High trace In concentrations have been observed in chalcopyrite. Two distinct generations of pyrite have been recognised with different critical metal concentrations (e.g. Sb). Two generations of sphalerites are distinguished by trace Cd contents when their physical properties under optical microscopy or EDS work prove difficult to tell apart. These data will contribute to a better understanding of the Yilgarn VMS deposits and of Archean VMS deposits globally.

Controls on precious and critical metal enrichment in VMS deposits of the Caledonian-Appalachian orogeny

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Volcanogenic massive sulphide (VMS) deposits not only host significant quantities of base metals (Zn, Cu, Pb) of which there is growing global demand but can also be enriched in precious metals (Ag, Au) and a number of critical metals (e.g., Co, Ga, Bi, In, Sb) crucial for renewable technologies.

The Caledonian-Appalachian orogenic belt hosts a large number of VMS deposits in arc and ophiolite sequences of varying age, host stratigraphy, magmatic affinity, and tectonic setting. World-class deposits occur on both sides of the Iapetus Suture upon Laurentian and Gondwanan affinity crust. Within these arc systems, regional-scale to intra-deposit controls on precious and critical metal enrichments are poorly understood. Controls on the latter may reflect footwall leaching, a magmatic volatile contribution, and/or fluid conditions.

The Tyrone Igneous Complex (TIC) of Northern Ireland represents a late arc-ophiolite system that accreted to the margin of Laurentia during the Middle Ordovician. It is now recognized to be a direct correlative to the VMS-rich Annieopsquotch Accretionary Tract of Newfoundland, host to the world-class Buchan's deposits. The precious metal enrichment varies significantly within and between deposits, and their critical metal potential is largely unknown. This study aims to improve the understanding of controls on mineralization within the Caledonian-Appalachian orogeny, to provide a detailed assessment of their precious and critical metal potential and to contribute to their global exploration and development efforts.

We present new deposit paragenetic characterisation and sulphide trace element data (SEM, EPMA, LA-ICP-MS) combined with multiple sulphur isotope data (SF_6^+ IRMS), highlighting the differences in geochemical signatures of the various mineralized occurrences found within the TIC. This data, integrated with existing and new geochronological data will enable to place these sulphide occurrences within a robust geodynamical framework, improving the targeting of prospective lithologies.

Machine Learning Prospectivity Analysis for VMS Deposits in the Semail Ophiolite, Oman

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The Semail Ophiolite in Oman represents one of the world's largest and best exposed ophiolitic successions. Even though numerous volcanogenic massive sulphide (VMS) deposits were discovered, the area remains largely underexplored. Exploration within the belt is challenged by heterogeneous and inconsistent legacy datasets, including variable-scale geological mapping and limitations of geophysical data. This study develops a data-driven, machine learning (ML) approach using standardised, satellite derived inputs, to predict VMS prospectivity across the Semail Ophiolite at regional scale.

A boosted-tree ML algorithm was trained and validated on 147 positive and 142 negative labels, defined using a mineral system based geological framework that integrated spectral, structural, stratigraphical and lithological evidence. Input datasets were derived primarily from an ASTER Bare Earth model, combined with multispectral and hyperspectral imagery (Sentinel-2, EMIT, PRISMA) and digital elevation models (DEMs). From these, alteration mineral indices (e.g., ferric iron, clay, silica, hydrothermal alteration) were generated alongside a supervised lithological classification distinguishing key ophiolitic units (e.g. basalts, gabbros, sheeted dykes). Structural features, including faults, fold axes, and extrusive contacts, were manually interpreted from optical and DEM datasets and reconciled with published geological maps (1:50,000; 1:100,000; 1:250,000). The structures were subsequently classified into orientation domains relevant to fluid pathways for VMS formation.

The ML model underwent iterative refinement through subject matter expert review and cross-validation to ensure geological plausibility. Independent validation using Cu–Pb–Zn occurrences, excluded from model training, showed that 73.5% of known deposits fall within the "Medium-High" to "Very High" prospectivity zones. The resulting probability heatmap was segmented into seven classes and revealed coherent, spatially meaningful patterns that align with known mineralised trends while highlighting previously underexplored zones beneath limited sedimentary cover.

This approach reduced the regional search space for surface VMS mineralisation by approximately 95%, providing a quantitative, bias-reducing, and interpretable framework for prioritizing exploration targets and 2026 field campaigns. Notably, the workflow demonstrates how ML can be applied to derive consistent geological proxies (e.g., lithology, alteration, structure) directly from remote sensing data, bypassing limitations of incomplete or inconsistent mapping datasets. This study demonstrates the viability of combining machine learning, remote sensing, and expert geological interpretation to enhance exploration efficiency. By directly relating geological features to pixel-based spectral representations, we demonstrate a fundamental approach to mineral prospectivity modelling in ophiolite terranes.

New insights into controls on Ni-Cu-Co sulfide distribution in the Arthrath deposit, Aberdeenshire, Scotland

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The Arthrath intrusion, located in Aberdeenshire, is one of a number of mafic-ultramafic intrusions within north-east Scotland, collectively termed the 'Younger Basic' suite [1], which are prospective for Ni-Cu-Co sulfide mineralization [2]. The emplacement of these intrusions is associated with a change in subduction direction, and subsequent closure of the Iapetus Ocean, during the Grampian episode of the Caledonian Orogeny from 470 – 480 Ma [3].

At Arthrath, sulfide mineralisation is located within both olivine-rich and olivine-poor gabbroic rocks, with a range of sulfide textures present from disseminated and blebby, to net-textured and massive domains [4]. Aberdeen Minerals has completed three drilling campaigns at Arthrath, most recently in the summer of 2025. These campaigns have identified several pulses of both sulfide-rich and sulfide-poor magmas, and have revealed certain key characteristics in common with major Ni-Cu sulfide deposits including Voisey's Bay [5], Canada, and Nova-Bollinger [6], Australia. These well documented deposits therefore provide useful analogues to guide exploration.

Detailed downhole geochemical analysis from bulk assays, observations from drillcore, and both silicate and sulfide mineral chemistry studies, reveal a more clearly defined magmatic stratigraphy within the Arthrath intrusion than previously thought. The identification of sharp magmatic contacts between mineralized and barren portions of the intrusion, as well as more diffuse contacts between variably mineralized domains, has furthered understanding of the controls on Ni-Cu-Co sulfide distribution, and aided the development of a more comprehensive exploration model at Arthrath.

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Investigating country rock assimilation signatures in the Turfspruit Platreef Ni-Cu-PGE deposit, Northern Limb of the Bushveld Complex, South Africa

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The Northern Bushveld Complex, South Africa, hosts the world's largest deposit of platinum-group elements (PGEs), known as the Platreef. The down-dip extension of the Platreef in the Turfspruit Farm has an indicated mineral resource of 2 g/t of 4PGE (Pt + Pd + Rh + Au), 0.16 wt% Cu grade, and 0.34 wt% Ni grade hosted in pyroxenites, harzburgites and gabbronorites. Each stratigraphic unit at Turfspruit varies in thickness, and the relationship between Ni, Cu, and PGE grade is often unclear and decoupled. The thickness of mineralisation is also heterogeneous, averaging 15m at a 2g/t 4PGE cutoff but ranging from 2m to 93m across the reserve.

The Turfspruit lithologies intrude and assimilate the reactive sedimentary country rocks of the Transvaal Supergroup. These consist of dolomites, shales, banded iron formations (BIFs), and silicate sedimentary rocks, each of which makes up different areas of the footwall. While previous work has shown evidence of sedimentary contamination throughout the mineralized unit [1], the relationship between the assimilation of these different country-rock lithologies and the thickness and geometallurgy of the overlying mineralisation is still poorly understood.

Detailed core logging and sampling was performed on 6 drill cores, representing the mineralisation above each of the different footwall lithological zones, to investigate the effect and relative importance of assimilation of each footwall lithology. The assimilation of these lithologies formed a complex 'Footwall Assimilation Zone' (FAZ) that underlies the mineralisation-bearing units and consists mainly of metasomatised hornfels and calc-silicates. Areas of more cryptic assimilation, where the footwall was buffered, creates cyclical norites within the mineralised zones. Petrographical and SEM-EDS (TIMA) analyses of 45 samples from the five distinct footwall zones revealed the presence of calcite xenoliths of varying diameter (~0.4 mm to ~1.5 mm) in samples from the hornfels footwall zone, the Buffered Zone, and the calc-silicate zone. Calcite veins also infill cracks of base metal sulphides in the same samples, often associated with arsenide minerals which replace/overprint the primary base metal sulphides.

Niggli numbers calculations [2] were done on whole rock geochemistry from the sampled drill cores. This revealed carbonate assimilation to have a stronger input in the calc-silicate footwall zone, but to be present with varying degrees of intensity in all the drill cores, even those km away (laterally) from the calc-silicate footwall zone. This shows correlation with Cu grade, highest in the para-pyroxenites of the calc-silicate assimilation zone, while no such correlation was found with PGE grade, which is still heterogeneous in the mineralisation. Coupled with petrological results this suggests that calc-silicate assimilation may have the strongest influence, and that this influence is not confined to the areas of the deposit directly above the dolomite footwall.

Mineralogical analyses of PGE host minerals and their distribution will be presented, which will further shed light on the potential remobilisation of PGE by country rock assimilation.

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Newly discovered Cu-Ni-sulfide mineralisation in the 1.8 Ga Stendalen mafic intrusion, Ketilidian Orogen, South Greenland

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The Stendalen layered mafic intrusion, Greenland, is a 17.5 km^2, ca. 1300m thick, saucer-shaped meta-gabbroic intrusion hosting magmatic Cu-Ni-Co sulfide mineralisation. Stendalen lies within forearc sediments of the accreted Ketilidian orogenic belt on the southern margin of the North Atlantic craton. Zircon U-Pb geochronology of the intrusion has yielded a precise primary crystallisation age of 1804 +/- 1.5 Ma; placing Stendalen within the latter stages of the calc-alkaline Julianehåb igneous complex magmatism and indicating that emplacement occurred immediately prior to the Ketilidian deformation recorded in the forearc. The mineralisation is considered an atypical magmatic sulfide occurrence, having formed in an arc setting. It appears to share characteristics with similar deposits in the Svecofennian orogenic belt (e.g. Kleva, Älgliden, Espedalen), including low PGE tenors. This is the first study assessing the petrography and mineralisation of the intrusion, utilising drillhole data, field-mapping, petrographic, micro-XRF and SEM-EDS analysis.

Petrographic analysis shows the intrusion is dominated by plagioclase, clinopyroxene and hornblende which was largely recrystallised during peak HT-LP Ketilidian metamorphism. The intrusion is underlain by S- and graphite-bearing metasediments which are potentially integral to the generation of mineralisation. The intrusion is extensively crosscut by peraluminous, syn- to late-tectonic granites and granodiorites. Early drilling results reveal that the upper section of the intrusion contains minor disseminated sulfides and towards the base, the gabbro is taxitic and displays a variety of sulfide textures. The sulfide assemblage comprises pyrrhotite-chalcopyrite-pentlandite with Cu>Ni. The timing of emplacement relative to metamorphism and deformation raises the possibility of sulfide re-mobilisation, currently under investigation.

Tracing Nickel and Cobalt through the Processing Chain: A Forensic Geometallurgical Study of the Kevitsa Mine

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Nickel (Ni) and cobalt (Co) are critical metals for low-carbon technologies, particularly for batteries in electric vehicles (EVs). As global EV adoption accelerates in both developed and emerging economies, the demand for Ni and Co is projected to rise sharply. At present, most Ni and Co production is concentrated in a few countries, notably Indonesia for Ni and the Democratic Republic of Congo for Co, leaving Europe highly dependent on external supply. The ENICON project seeks to address this strategic vulnerability by exploring the potential of Europe's low-grade Ni-Co geomaterials and developing new pathways for their enrichment and refining within Europe.

Within this framework, forensic geometallurgy, where detailed mineralogical, textural, and chemical characterisation is applied to "trace" target metals through each processing stage, provides enhanced diagnostic insight to maximise Ni and Co recovery and improve understanding of their distribution and composition within waste. Namely by linking micro-scale features - such as grain size, mineral associations, and inclusion textures - to macro-scale metallurgical performance, this method identifies where and why Ni and Co are lost or sub-optimally recovered. These insights allow targeted adjustments to improve overall Ni and Co recovery.

At Kevitsa, a Ni-Cu-(PGE) magmatic deposit in northern Finland, this approach is applied across the entire ore processing flowsheet, from unprocessed ores to final concentrates. The Kevitsa intrusion, an ultramafic–mafic body emplaced into the Central Lapland Greenstone Belt at ~2.06 Ga[1], hosts disseminated sulphide mineralisation dominated by pentlandite, pyrrhotite, chalcopyrite, and minor pyrite. Cobalt is of particular interest, commonly associated with pentlandite and pyrite, but its distribution and deportment are complex and may reflect multiple generations of sulphide mineralisation.

The sulphidic ores investigated in this study contain, in addition to sulphides, magnetite and chromite as the main Ni- and Co-bearing phases, with additional Ni hosted in olivine. The Ni-Co in these phases are typically lost during processing. Other losses may occur due to grain size, as smaller fractions favour agglomeration, which sometimes retain minerals of interest (pentlandite, chalcopyrite). Despite the blending of different rock types in the feed material, the mineralogy and mineral compositions are relatively uniform throughout the processing chain. We also identified that a significant concentration of platinum group elements in the mineral concentrate materials, with further studies needed to assess economic potential. However, the Co grades obtained in this study are lower than those reported for other Ni–Co concentrates from Finland, such as those from the Hautalampi mine.

The ENICON project is funded by the European Union Horizon Europe Programme (GA number 101058124) and co-funded by the UK Research and Innovation through Innovate UK. Kevitsa mine is owned and operated by Boliden Group.

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Formation of regolith-hosted heavy rare earth element deposits through weathering

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Rare earth elements (REE) are critical to the modern society, specifically to the transition to a zero-carbon society and numerous high-tech applications. They are the key components to make permanent magnets for wind turbines and electric vehicles. Currently, the world's majority of the rare earth production comes from carbonatite-related deposits, however, the more demanding but scarce heavy (H)REE are mainly sourced from the regolith-hosted deposits in South China. These deposits can also be easily processed, enabling a low-cost mining operation.

Granites and syenites are the main protolith and REE source for the formation of regolith-hosted HREE deposits. These protolith often experienced extensive hydrothermal alteration with F and CO_2-rich fluids that altered the primary, refractory xenotime, monazite, zircon and niobates to much more weathering susceptible REE-fluorcarbonates, such as synchysite-(Y) and bastnäsite-(Y). In the same process, the bulk REE concentration was also highly elevated, favouring later supergene enrichment for the ore formation.

During weathering, REE released from decomposition of the parental minerals would be adsorbed as ion-exchangeable complexes by clay minerals, mainly kaolinite and halloysite, for the ore formation. Recrystallisation of these clay minerals occurs during progressive weathering, significantly increasing the size and crystallinity, and decreasing the surface area and cation exchange capacity. Collectively, the adsorption capacity of the clay minerals decreases with weathering. That favours REE desorption in shallow regolith of higher degree of weathering and vertical transport of REE to greater depth, at where clay minerals of higher adsorption capacity favour ion-adsorption REE enrichment for the ore formation.

Characteristics of Rare Earth Elements (REE) enrichment in carbonatite-derived weathered materials at Miaoya, China

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Rare earth elements (REE) are very important in many high technologies, especially in green energy generation and low carbon transport, along with other critical metals [1]. REE are mostly hosted within carbonate-dominated carbonatite rocks and their weathered materials, e.g. Bayan Obo, China; Araxa, Brazil; Ambadongar, India; Miaoya, China; Mt Weld, Australia; etc. However, the global distribution of REE are limited, as only a few nations control the reserves, and this has created geopolitical issues. Among currently known deposits, REE resources in weathered materials derived from carbonatites are not well studied.

Weathering mechanisms are enhanced under tropical conditions, yet the processes vary between localities [2]. Here, we study 2 sites to investigate the inception of carbonatite weathering under different tectonic settings and climatic conditions. The Miaoya carbonatite and syenite complex (MCSC) in China, dated to ~440 Ma, consists of syenites and carbonatites, where carbonatite intruded the syenites in the form of stocks and dykes [3]. The Ambadongar carbonatite complex (ADCC) in India, dated to ~64 Ma and intruding the basalts of the Deccan volcanism, is a well-known REE deposit associated with carbonatite-type rocks [4]. Both sites host REE minerals formed under hydrothermal conditions. However, the surrounding rocks and geomorphic conditions differ as a result of contrasting climatic and geological settings. Therefore, comparing these two sites will highlight geochemical, mineralogical and climatic factors influencing supergene REE enrichment.

Field observations at the MCSC show a high degree of variation, as the complex is exposed within the compressional regime of the South Qinling Belt [5], where carbonatites are fresh in places but altered along river terraces. Mineralogical and geochemical analyses using XRD, SEM-EDS, EPMA, CL imaging, ICP-MS and ED-XRF were carried out on MCSC samples. Additionally, the BCR sequential extraction procedure was used to investigate REE fractionation in the collected samples.

The chondrite-normalised plots for the MCSC carbonatites show LREE enrichment, and a similar trend is observed in their weathered materials. However, the REE variation with depth in the carbonatite-based profile shows Ce anomalies near the top of the profile, which reduces at greater depth. Additionally, the sequential leaching experiment indicates a higher proportion of reducible REE, while the proportion of resistant REE decreases with depth. SEM-EDS and EPMA analyses show a localised distribution of microscale REE carbonates (bastnäsite, synchysite) and REE phosphate (monazite), together with apatite. Dissolution textures and increased proportion of silicates evidence the intensity of weathering, as grain boundaries show dissolution and reprecipitation processes. Additionally, the ED-XRF analysis of MCSC bulk samples reports higher CaO wt.% in the fresh material, shifting to higher SiO_2 wt. % in the weathered material. The increase in silica and alumina oxides shows weathering transformation, which is later represented by the increasing chemical index of alteration.

Overall, the REE enrichment in the MCSC weathered samples occurs mostly as fluorcarbonates together with apatite. The formation of montmorillonite and iron oxides reflects the dolomitic origin. Further work will include isotopic analysis of iron oxides and secondary carbonates to further understand the weathering processes. The collected data will be compared with known regolith-based REE deposits, including Sokli, Finland and Longonjo, Africa.

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Distribution and Geochemical Behaviour of Critical Elements in Pomalaa Lateritic Profiles, Sulawesi, Indonesia

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Nickel laterite deposits are important sources of Ni and Co, and also contain critical elements such as Sc, REEs, and PGEs. Indonesia, despite being one of the world's largest producers of lateritic nickel, has limited studies on these elements. This study investigates their vertical distribution, geochemical behavior, and enrichment mechanisms in laterite profiles from Pomalaa, Southeast Sulawesi. The Pomalaa area lies within the East Sulawesi Ophiolite Belt, one of the most structurally complex regions in Southeast Asia. this area is divided into three geomorphological zones: Northern (NA) with steep terrain and weakly serpentinized harzburgite bedrock, Central (CA) with lowland zone and moderately serpentinized harzburgite bedrock, and Southern (SA) with undulating terrain and serpentinite bedrock. Profiles show a typical sequence of red limonite, yellow limonite, earthy saprolite, rocky saprolite and bedrock. Ni and Co are enriched in the earthy saprolite (up to 2.48 wt% NiO in CA and 0.28 wt% CoO in SA, linked to serpentinization and influenced by topography. Serpentinized ultramafic rocks release Ni and Co during weathering, which are incorporated into secondary phases such as goethite. Regarding topography, steep terrains in NA tend to enhance leaching and downslope transport, while flatter terrains in CA favor the accumulation and retention of Ni and Co. REEs and Sc are concentrated in the yellow limonite, associated with Fe-Mn oxyhydroxides, while PGEs are enriched in the limonite zone, reaching 356 ppb in NA. Mass balance (τ) calculations reveal major leaching of Mg and Si in limonite, while Fe, Cr, and PGEs show residual enrichment. These results indicate that enrichment in Pomalaa is controlled by protolith composition, geomorphology, and weathering intensity, involving residual processes, adsorption, and redistribution. Pomalaa thus represents a promising unconventional resource of critical elements, though its economic potential requires further evaluation.

Vanadium in Silurian Black Shale of North Gondwana: the Morocco case

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As part of the critical metals group, vanadium is an essential commodity for the low- and zero-CO_2 energy system, notably due to its key role in vanadium redox flow battery technologies. Vanadium mineralization displays a broad geological spectrum, from magmatic accumulations in mafic–ultramafic intrusions such as the Bushveld, to sediment-hosted deposits. Black shale-hosted alone may contain nearly 80 % of the world's potential V resources, although only <2 % are currently considered economic (notably in China, Kazakhstan, and Australia).

During Silurian, thick anoxic black shale successions rich in graptolites, and variably enriched in V and associated metals [1], developed across the North Gondwana margin, from NW Africa [2] to southern Europe and the Middle East. Morocco preserves some of these basins [3], which have been made object of preliminary investigation.

Our study integrates whole-rock geochemistry and mineralogical characterization, to constrain both major and trace element concentrations and metal-hosting phases within Silurian black shales of the Anti-Atlas and Western Meseta. The mineral assemblage includes quartz, illite/muscovite, chlorite, pyrite (euhedral and framboidal), Fe-Mg-Mn carbonates, and carbonaceous matter, with minor feldspar, galena, chalcopyrite, gypsum, zircon, monazite, and apatite.

The Moroccan black shales show heterogenous V contents (160 - 860 ppm) and up to 3 wt % TOC. Compared to other coeval Silurian successions of North Gondwana, Morocco black shales have also anomalous values of Sb, Ba, Se, Mo, As, Mo, F, Cu, Ni, U, and REEs (avg. 330 ppm with Y and Sc). Vanadium is principally hosted in rutile, reaching up to 2 wt % V_2O_3, whereas unlike Sardinia equivalents [1] V-bearing illite has not been identified so far. Carbonaceous matter contains minor S and Cl. Expanded sampling across additional Moroccan areas is underway, to refine metallogenic comparisons with other North Gondwana black shale provinces.

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Supergene enrichment of carbonatite-hosted REE deposits: Development of the palaeolaterite at Sokli, Finland

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Carbonatites are the dominant source of light REE. However, two of the highest-grade carbonatite-hosted REE deposits - Tomtor, Russia, and Mount Weld, Australia - are in deeply weathered carbonatite. Weathered carbonatite offers the potential for major supergene enrichment, lower energy cost for mining and beneficial element fractionations both between the REE and actinides, and within the REE as a group. The Sokli carbonatite is part of the Devonian Kola alkaline province, and consists of a vertical carbonatite pipe, ~2km in diameter, surrounded by a halo of metasomatically altered ultramafic rocks and fenite. Bedrock REE mineralisation is hosted by late stage REE-Sr-Ba rich dolomite carbonatite [1]. However, the deposit is capped by ~100m of carbonate-free laterite. Lithologies include friable laterite including crandallite minerals and pyrochlore, bands of cemented phosphate rock dominantly composed of carbonate-fluorapatite and goethite, and clay-rich laterite formed of phlogopite altered to vermiculite. Bulk rock analyses indicate enrichments in the REE of 10 to 100x compared to bedrock. There is little fractionation in the REE relative to bedrock, which could indicate residual enrichment of bedrock REE minerals. However, sequential extraction and electron microprobe analyses indicate element fractionation between minerals, including the development of positive and negative Ce anomalies. The mineralogy includes residual monazite-(Ce), but also widespread development of secondary monazite (with significant Ca and S contents), rhabdophane-(Ce) and florencite-(Ce) ($REEAl_3(PO_4)_2(OH)_6$), alongside secondary REE-poor apatite, and the incorporation of the REE into oxides and weathering derived silicates. Residual pyrochlore, on the other hand, shows evidence of alteration increasing K and Ba contents and development of structural vacancies. The dominant mineralising processes are inferred to be dissolution and re-precipitation of REE minerals alongside residual enrichment and alteration. U-Pb dating of secondary apatite generations defined by CL textures indicates at least some of the weathering period was Miocene, and mineralisation hence may be related to warm paleoclimate. However, weathering extended over ~20Ma from 30Ma to 9Ma, and hence can be related to enhanced weathering through the Oligocene to Miocene as a result of global base level fall. Textural observations indicate comparable processes at other sites including Tomtor and Dong Pao (Vietnam) although REE mineralogy varies with site. Further work will focus on identifying if a common timing exists for high latitude carbonatite-laterite REE deposits, the structural transformation of REE mineralogy during dissolution-reprecipitation, inter-mineral element fractionation, and the conditions of weathering.

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POSTERS

Potential strategic ore deposits on Mars: implications for *in situ* resource utilization

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The discovery and utilization of natural resources on Mars will be crucial for supporting the sustainability of future human exploration and habitation. Decades of data obtained from fly-by missions, orbiters, landers, and rovers suggests that Mars hosts a range of minerals and metals [1], many of which are vital for building infrastructure, life support systems, and spacecraft for further interplanetary travel. Ore-forming processes on Earth are well understood, allowing many parallels to be drawn with features observed on the Martian surface. As Mars is broadly chondritic in composition, mafic volcanic rocks and magmas forming probable large igneous provinces, such as in the Tharsis Region, should be enriched in chalcophile elements (e.g., Ni, Co, Cu, PGE, and Au), akin to terrestrial examples. These elements play critical roles in the production of electronics, catalysts, and batteries. Weathering and erosion of lavas during the Noachian (4.1–3.7 Ga) and Hesperian (3.7 to c. 3.3–2.9 Ga) periods, when Mars recorded an active hydrological cycle, would have generated placer and lag deposits containing heavy minerals such as magnetite, ilmenite and zircon in fluvial and deltaic environments. Such deposits represent concentrated and easily obtainable sources of Ti, Fe, Cr, and Zr, which have critical uses in construction. Interactions between ascending sulphur-rich magmas and descending or trapped subsurface water in the fractured Martian upper crust likely promoted formation of acidic volcanic–hydrothermal systems, producing sulphate minerals similar to those observed in mid-ocean ridge or crater lake environments on Earth. Chemical sediments, such as evaporites, would have formed during loss of the Martian hydrosphere and will likely host halogens and alkali earth metals that have important uses for chemical engineering and agriculture. Finally, given the importance of meteorite impacts in shaping Mars' geological history and their close association with high-grade ore systems on Earth (e.g. Sudbury), we predict that a wide range of progenetic, syngenetic, and epigenetic ore deposits exist within the shallow Martian subsurface, particularly in and around large craters present in the southern highlands. Importantly, we argue that ore deposits uniquely associated with plate tectonic processes on Earth are not expected to occur on Mars since it never established a mobile lid geodynamic regime [2]. Tapping into Mars' ore resources is essential for ensuring the viability and sustainability of exploratory missions, enabling a self-sufficient presence on Mars, and facilitating the future of interplanetary exploration. Additionally, new investigations of the geological processes that control mineralization on Mars are also likely to advance our understanding of terrestrial deposits.

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Back to Programme

Metasomatism and metamorphism around the Loch Borralan Intrusion, Northwest Scotland

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Rare Earth Elements (REEs) have been identified by the UK's 2025 Critical Minerals Strategy, as being a key suite of metals required for the UK's energy transition, though currently, the UK does not produce any REEs[1]. However, the Loch Borralan Intrusion in Northwest Scotland has been identified as having elevated levels of REEs within the syenite body itself[2]. Research by Martin et al. in 1978 identified evidence of fenitisation accompanied by Light Rare Earth Element (LREE) enrichment within the metamorphosed quartzites present in the metamorphic aureole, though previously, no thorough investigation of the marble region of the aureole has been undertaken. This project aims to characterise the marbles that form part of the metamorphic aureole of the Loch Borralan Intrusion, and explore if they may also contain elevated levels of REEs.

Our work finds that there is evidence of pervasive fenitisation in the marbles surrounding the intrusion, though the lateral extent of this is limited by rapid consumption of sodic and potassic ions upon their release from the intrusion. We also find extensive veining, caused by non-fentitising fluids expelled by the intrusion during cooling. We examined the petrological and geochemical characteristics of the metasomatic lithologies, performed petrological modelling to ascertain the T-XCO_2 conditions associated with the formation of the veins, and carried out chemical potential modelling to quantify the chemical gradients present across the syenite-marble boundaries.

The next phase of our work will examine a second sample suite of the newly-identified fenites, to ascertain the REE profiles of 10 µm apatite crystals identified only within the fenite aureole, and to assess if the fenites could exhibit enrichment in REEs.

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Mineralisation and metal deportment in the Redmoor deposit, Cornwall

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The Redmoor deposit, located underneath the historical Redmoor mine workings between Kelly Bray and Callington, Cornwall, is an untapped tin, tungsten, and copper resource. The resource is a polymetallic sheeted vein system (SVS) that steeply dips to the NNW over 550m and strikes WSW – ENE for roughly 1km [2]. The SVS developed adjacent to the Kit Hill granite, which has been described as a G2 muscovite granite: fine- to coarse-grained, with variable phenocrysts [8]. Previously, Dangerfield and Hawkes [3] described the granite as a coarse-grained megacrystic rock, with small megacryst variants. The granite has been dated as the one of the oldest stocks in the Cornubian Batholith, with U-Pb monazite ages ranging from 293.7±0.6 Ma to 281.7±0.8 Ma and in-situ U-Pb cassiterite ages ranges from 290.5±2.8 Ma to 288.5±2.9 Ma [4, 9].

Mineralisation at Redmoor is exogranitic situated in the Devonian 'killas' metapelites and metapsammites – fine to medium grained slates and shales – with interbedded metabasite. No mineralisation has been observed within the granite [1]. This contrasts with the mineralisation at sites such as Cligga Head, Cornwall; St Michael's Mount, Cornwall; and Hemerdon, Devon - where the mineralisation is primarily endogranitic. Although broadly classified as an SVS, mineralisation styles at Redmoor are diverse and include greisen bordered veins (with and without tourmaline), quartz-tourmaline breccias, skarns, and polymetallic quartz-chlorite-sulphide lodes (formed in fractures or fissures in existing rock formations) [1, 6]. There are also Pb-Ag-Zn bearing N – S cross course veins which post-date the granite [1, 7]. The main oxide and sulphide minerals are arsenopyrite, löllingite, wolframite, cassiterite, stannite, chalcopyrite, sphalerite, and pyrite, with muscovite, quartz, tourmaline, kaolin, and chlorite as associated gangue minerals [1]. Generally, tungsten concentrations are higher in proximity to the granite, whilst copper and tin are richer more distal from the granite [2]. It is also high in UK critical metals such as indium and gallium [1, 5].

There has been limited research into the genesis of the deposit. It is assumed to be a structurally controlled, multi-phased mineralisation event; however, with the vast amount of mineralisation styles, phases, differing metal concentration localities, the potential for multiple fluid injections and fluid mixing, and potentially more than one granitic source involved, more investigation is required.

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Structural Clues to UK and Ireland Molybdenum Resources

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Society is built on rock from which we source critical minerals (CM) that are essential for renewable energy infrastructure (wind turbines, solar panels, batteries), transport, mobile devices and medical equipment. Due to complex combinations of economic, geopolitical and logistic factors, CM are at risk of short supply. Materials recycling is moving forward, but significant amounts of CM are needed to tackle global environmental challenges and net zero. Molybdenum (Mo) is a rare heavy trace element that is recognised as an important mineral in the UK Criticality Assessment [1]. It is used in steel alloys to improve their strength and wear resistance, and as a catalyst in the evolution reaction of hydrogen. It is essential for life as it enables nitrogen uptake in animals and plants. Molybdenite (MoS2) is the main ore of molybdenum. In the UK, Mo is associated with orogenic, magmatic, and hydrothermal ore deposits and it is typically a by-product of copper and gold mining [2].

Previous studies have focussed on the geochemistry and dating of Mo, however there is a clear gap in our understanding of the controls of regional structures and associated deformation mechanisms on Mo occurrences and microstructures. The project will fill this gap through field mapping of structures and sampling in the Galway Granite Complex, western Ireland [3], the Newry Igneous Complex [4] and Curraghinalt orogenic deposits [5], Northern Ireland, and in south-west Scotland or the central-western Grampian Highlands [2], where Mo occurrences have been reported. Advanced quantitative analyses of microstructures, mineralogy and timing of events will help determine those deformation mechanisms that may have concentrated Mo-bearing minerals in each of the regions of interest.

Early assessment of Environmental, Social and Governance (ESG) risks associated with potential Mo extraction will be undertaken in regions of high Mo concentrations. Data will be gathered through review of publications, reports and interviews and results will complement the project outcomes on Mo prospectivity, providing a sustainability framework for Mo from the early stages of discovery.

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Constraining the age, geology, geochemistry, and VMS prospectivity of the Tallering Greenstone Belt, Yilgarn Craton, Western Australia

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The Tallering Greenstone Belt is located in the Youanmi Terrane of the western Archean Yilgarn Craton [1] [2]. The greenstone belt has experienced greenschist-to-amphibolite facies metamorphism across its length, and has been historically exploited for Fe-ore by Mount Gibson Iron Ltd. from banded iron formations (BIFs) [2]. Recent efforts have now shifted towards VMS exploration given the occurrence of thick sequences of massive sulfide mineralization underlying the units of the BIF [2]. This study presents the first detailed account the age, geology, and geochemistry of the Tallering Greenstone Belt. The research objectives guiding this investigation include characterizing the host stratigraphy, determining its tectonic-magmatic evolution, characterizing the type and intensity of hydrothermal alteration, and identifying geochemical and mineral-chemical halos to sulfide mineralization. These were achieved through core logging of diamond drill holes, petrography, Scanning Electron Microscope (SEM) analysis, whole rock geochemical analysis, and trace element analysis of garnet, white mica, and chlorite using Electron Probe Mirco-Analysis (EPMA) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). U-Pb zircon and Lu-Hf garnet geochronology was also completed to determine the age of the host stratigraphy and timing of peak metamorphism, respectively.

This investigation revealed that the Tallering Greenstone Belt is composed of a calc-alkaline, largely volcaniclastic stratigraphy. It is dominated by andesitic rocks with lesser basalt, dacite, and rare ultramafic rocks. Overlying meta-sedimentary rocks to massive sulfide mineralization include thick sequences of BIF and polymict conglomerates. The volcaniclastics were dated to c. 2.74 Ga using U-Pb zircon geochronology. A minor zircon population at c. 2.94 Ga is consistent with existing geochronology, suggesting the presence of a large regional unconformity in the greenstone belt. Most of the sulfide mineralization observed is composed of pyrite and pyrrhotite, though minor sphalerite, galena, and chalcopyrite were observed. Hydrothermal alteration in diamond drillcore is extensive and consistent with the distal portions of a VMS system, and it includes largely sericitic and chloritic assemblages. Mineral assemblages, whole rock geochemistry (e.g. Eu/Eu*), and garnet trace element geochemistry (e.g. Heavy Rare Earth Element (HREE) abundance) distinguish footwall from hanging-wall alteration across the system. Massive sulfide mineralization is associated with increased Mn contents in garnet in the laser ablation and EPMA data. Whole rock geochemical data from RC drilling suggests the NE area is increasingly prospective. Lu-Hf garnet analysis revealed ages of ~2.0 Ga, suggesting that peak metamorphism is likely associated with the Glenburgh Orogeny [3].

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Characteristics of the Abetselo volcanogenic massive sulfide mineralization, western Ethiopian greenstone belt: the oldest known gold-bearing VMS in the Arabian-Nubian Shield?

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The Abetselo VMS mineralization is hosted by a metamorphosed, bimodal volcanic sequence in the western Ethiopian greenstone belt of the Arabian Nubian shield (ANS). Although the ANS is well known for its VMS deposits, the western Ethiopian region remains underexplored. This study provides the first comprehensive characterization of the mineralization, including the age of volcanic host rock, mineral paragenesis, lithogeochemistry, mineral chemistry, and short-wave infrared (SWIR) spectroscopy.

The host stratigraphy is steeply-dipping, overturned, and metamorphosed between upper greenschist to lower amphibolite facies. The stratigraphic footwall is dominated by lower, coherent basaltic volcanic rocks and overlying andesitic volcaniclastic rocks with minor dacite units. The stratigraphy of the ore horizon consists of sericite-quartz-kyanite andesite, silica-rich exhalite, and kyanite-bearing sericite-quartz-feldspar dacitic volcaniclastic rocks. The hanging wall sequence is dominated by quartz-plagioclase-sericite-biotite andesitic volcaniclastic rock. New U-Pb zircon geochronology has constrained dacite volcanic rocks from the host stratigraphy to 882 ± 4 Ma, making Abetselo the oldest known VMS-type mineralization in the ANS. The mineralization is interpreted to have formed in a continental volcanic arc setting, hosted by FI-FIIa, high LILE, low HFSE intermediate volcanic sequences.

The ore mineralogy is predominantly pyrite with minor chalcopyrite. Gold-enrichment is interpreted to be synvolcanic. It was mobilized during regional metamorphism to grain boundaries and fractures and during a late orogenic vein overprint along a high-strain corridor.

Four hydrothermal alteration assemblages are recognized corresponding to stratigraphic sequences: (i) epidote-carbonate in the deep footwall; (ii) chlorite-sericite-quartz-pyrite ± kaolinite ± andalusite in the stringer zone; (iii) quartz-pyrite-sericite-andalusite-kyanite-kaolinite in the ore horizon; and (iv) carbonate-sericite-silica-epidote-pyrite ± kaolinite in hanging wall sequences. Detailed mineralogy and geochemistry reveal that the mineralization is enveloped by aluminous alteration (interpreted as the metamorphic equivalent of advanced argillic alteration) characterized by strong silicification, and porphyroblasts of kyanite and andalusite, and alkali metal leaching (Na, K, Ca, Mg, Mn).

SWIR spectral analysis allows the identification of key hydrothermal alterations and systematic chemical variations in white mica and biotite. The ore horizon is characterized by Na-rich (paragonitic) muscovite, while the hanging wall is phengitic white mica. Phlogopite occurs proximal to ore lenses, whereas biotite occurs in the distal hanging wall and deep footwall sequences. The concentration of F increases toward the ore horizon in both phyllosilicate minerals.

The rare earth element and fluorite deposit at Monte Muambe, Mozambique

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Rising demand for the Rare Earth Elements (REE) has increased focus on the formation of REE deposits. Carbonatites, alongside alkaline-silicate rocks, form the main ore type mined worldwide[1]. However, carbonatite formation mechanisms remain uncertain, and REE mineralisation processes are not fully understood. In this study, we present work on the Monte Muambe Carbonatite-hosted REE-deposit, Mozambique, which is being developed by Altona Rare Earths for its REE, fluorite, and gallium potential. Monte Muambe is considered part of the Chilwa Alkaline Province of Malawi, which comprises over 20 alkaline syenite, granite, and carbonatite intrusive complexes, many of which host significant REE resources[2]. Situated 'over the border' in Mozambique, Monte Muambe is much less well known that its Malawian counterparts. The complex intrudes Karroo sediments and volcanic rocks of the Zambezi basin, which range from Early Jurassic to Late Carboniferous in age[3].

The Monte Muambe carbonatite complex hosts a variety of lithologies, including multiple generations of carbonatite. These include both relatively unevolved, REE-poor calcitic compositions, and more evolved REE-rich ferroan compositions, and are interpreted to be consanguineous. Associated units include pyroclastics, which pre-date the carbonatites; fenites; and breccias. In addition to REE mineralisation, fluorite-rich veins and dykes occur in carbonatite and adjacent fenites, with the latter containing notable associated gallium enrichment. Other rock types recognised at Monte Muambe include Karroo-age sedimentary rocks, including coal measures of the Moatize formation, and arkosic sandstones of the Cádzi formation[3]; and mafic dykes, which all pre-date the intrusive and extrusive components of the complex.

We have studied the lithologies of the complex through a mix of fieldwork, detailed petrography, and analysis of core assays, which has allowed us to document the evolution of the Monte Muambe carbonatite complex. We will discuss the lithologies present at Monte Muambe, the exploration being undertaken by Altona Rare Earths, and the ongoing work to address the evolution of the complex.

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Micromineralogy of the Irgaity gold placer, Kazakhstan

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Gold placer deposits in drainage systems make historically a substantial contribution to the gold production of Kazakhstan. Until now, major mining enterprises (Bakyrchik, Vasilkovskoye, Suzdal, etc.) dominated the gold sector. However, less explored placers remain commercially viable targets for small-scale mining by the junior sector.

The understanding of deportment of gold as refractory or invisible gold incorporated in the lattice of sulphides, arsenides, tellurides, selenides etc. deserves in-depth studies using modern analytical methods. It has been established that refractory gold represents the initial gold source, where tectonically controlled fluid circulations in a metamorphic basement dominantly of carbonaceous rocks (black shales) lead to the release of gold from the lattice of carrier minerals to form free gold. Nano-/micro-inclusions of free gold in carrier minerals represent a second group, subject of this study.

Gold placers of the studied region are localised within the Cenozoic sediments overlaying the Palaeozoic basement. The Irgaity placer deposit is situated in the eastern part of the North Jungar gold-bearing zone in the Almaty region and hosted in Quaternary sediments. It is located at the junction between the North Jungar synclinorium and the Alakol depression and is framed by the Alakol-Jungar and Sandyktas-Sholak long-lived faults. The placer is composed of alluvial and alluvial-proluvial gravel-pebbles, boulder-pebbles with sandy loam and loamy filler, with interlayers and lenses often embedded within cross-bedded sands and gravels and rarely loams and clays. Based on the geomorphological relief, the deposit is classified as a terrace placer, which is associated with the alluvium of the preserved basement terraces in the mountainous part of the region.

Free gold of 20 microns to 1 mm in size is present in the gold-bearing sands and is associated with pyrite, chalcopyrite and arsenopyrite; these sulphides may be potential carriers of finely dispersed gold. In samples, which contain significant amounts of free gold, red garnet is predominant and can serve as an indicator mineral of placer sands in this area. Gold has high fineness of 98-99%, sometimes with small impurities of silver (0.6%) and iron (0.6%).

A processing flow sheet has been developed and successfully applied to concentrate micro-gold of the placer at the bench scale. A key feature of the flowsheet is the three-stage disintegration and enrichment of sand using conventional deep-fill sluices and centrifugal units. Gold-bearing concentrates from each processing stage have been analysed using Tescan TIMA and Bruker FEI-SEM at the Imaging and Analysis Centre (IAC) of the Natural History Museum London that allowed efficient and precise identification of free gold and gold-silver alloys in gold-bearing phases across polished thin sections and mounts. Future investigations of this project will focus on microprobe analyses of sulphides and quantitative analyses of all gold-bearing phases identified by TIMA.

Acknowledgements

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Magnetite oikocrysts in anorthosite bounding Bushveld magnetitite layers

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Monomineralic layers of magnetite in mafic intrusions are important sources of critical metals; it is estimated that the Bushveld's magnetitite layers host 45% of global reserves of vanadium [1]. However, the petrogenesis of the Bushveld's Upper Zone, comprising magnetitites, anorthosites and norites, is debated. Intercumulus oikocrysts of pyroxene and olivine within anorthosite, colloquially termed 'mottles', have been reported in the Bushveld and other layered intrusions [2]. We present evidence from subspherical regions of interstitial magnetite or biotite within anorthosites bounding the magnetite layers (Fig. 1a) for silicate immiscibility and carbonated fluids in the Upper Zone.

We analyse magnetite mottles, biotite mottles and adjacent unmottled anorthosite in thin section to probe the formation mechanism of mottles within anorthosite in the Bushveld's Upper Zone. Samples were collected from Magnet Heights, eastern Bushveld, and Rhovan mine, western Bushveld. In magnetite mottles, Fe-Ti oxide almost completely encloses anhedral, rounded plagioclase grains and polycrystalline clusters. This texture closely resembles patchy net-textured sulfide ores, which form when immiscible sulfide melt infiltrates silicate mush [3]. Most mottles show symplectites between magnetite and plagioclase, frequently with a biotite substrate (Fig. 1b), which in Skaergaard have been attributed to reaction between silicates and Fe-rich immiscible liquid [4]. Biotite mottles contain carbonate cores and blocky, dendritic oxides. Preliminary results are therefore consistent with silicate immiscibility and hydrous, carbonated fluids within the Upper Zone of the Bushveld.

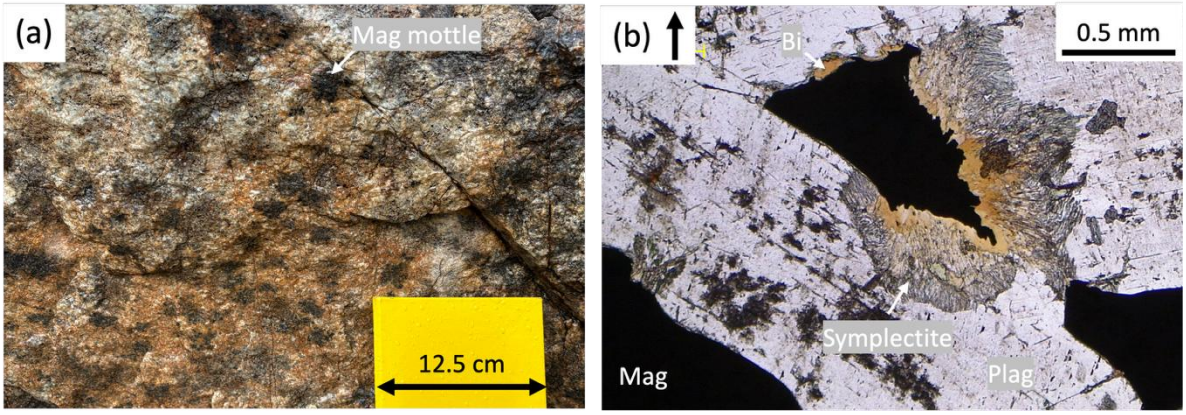

Figure 1: (a) Field photograph of subspherical magnetite (Mag) mottles at Magnet Heights, eastern Bushveld; (b) type 1 symplectite between magnetite and plagioclase (Plag) with a biotite (Bi) substrate, in plane polarised light.

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Fluid evolution of cassiterite-dominated lode systems in SW England

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Southwest England hosts a world-class Sn-W-Cu-As-Zn-Pb-Li ore field associated with the Cornubian Batholith and overlying Devonian metasedimentary and metabasic igneous rocks [1]. The magmatic-hydrothermal mineralisation is localised in steeply dipping ENE-WSW extensional faults (lodes), which exhibit mineral zonation as a function of distance from the granite source [2]. A resurgence in exploration drilling across historic mining districts by several companies has provided an opportunity to reassess the ore and alteration mineralogy paragenetic sequence and fluid evolution of the magmatic-hydrothermal system at depth. Establishing the key controls of ore precipitation and zonation patterns within deeper lodes will aid exploration and support resource expansion.

This study integrates core logging, petrography, µXRF imaging, microthermometry, and LA-ICP-MS fluid inclusion analyses to reassess the mineral paragenetic sequences, and character of mineralising fluids within lode systems from the Callington, Pool and Carn Brea mining districts. Recent drilling by Cornwall Resources, west of the Kit Hill Granite, has confirmed a mineralogically complex, Sn-W-Cu sheeted vein system [2] with the following ore paragenesis: {1} quartz (Qz)–tourmaline (Tur); {2} Qz–wolframite and greisenisation; {3} cassiterite (Cst)–Qz; {4} Qz–As–Cu–Zn polymetallic minerals; and {5} Qz–fluorite (Fl) cross-course. In contrast, the Pool and Carn Brea districts, explored by Cornish Metals, are typical lode systems [2]. Recent drilling in the Mylor Slate Formation and underlying Carn Brea Granite indicates a six-stage paragenesis [3]. At shallower levels, cassiterite is hosted by a Qz–Tur/chlorite (Chl) assemblage [4], whereas at deeper levels, Cst is either {A} massive cassiterite, with no clear vein structure, or {B} Cst within Fl–Qz±Chl veins; both cut earlier Tur breccia.

The microthermometry of fluid inclusions hosted by Cst, Fl and Qz identifies overlapping magmatic–hydrothermal, meteoric fluid and basinal brines contributions across the districts. In the Carn Brea district, Cst {A} formed from high-temperature (300–400°C), high-salinity (19.5–20.9 wt.% eNaCl) H_2O–CO_2–NaCl fluids. These fluids show episodes of cooling and rejuvenation during Cst formation which, when combined with fluid geochemical data, suggest that precipitation was due to mixing and dilution by low temperature meteoric water and calcium chloride (cross-course) brines. The inferred primary magmatic fluids show enrichment in Sn and Cu at all stages, with a strong association with Li, Pb and As. Cst within veins in the Pool, Carn Brea {B} and Callington {3} contains both moderate-high temperature (210–375°C), moderate salinity (6.2–11.6 wt.% eNaCl) magmatic-hydrothermal fluid; and a low temperature (125–250°C), low salinity (0-0.5 wt.% eNaCl) meteoric fluid, that mixed prior to Cst precipitation. Geochemically these are similar Li-rich magmatic fluids to those within {A}, carrying high levels of Sn–Cu–As–Zn throughout lode systems, with the highest Sn recorded at 1.2 wt.% within a secondary fluid inclusion in Fl. Combined with cathodoluminescence textural evidence, these results indicate that Cst precipitated through repeated episodes of dilution of waning magmatic-hydrothermal fluids and meteoric waters ± calcium chloride (cross-course) basinal brines.

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Mineralogical aspects of magmatic Ni-Cu sulfide mineralisation at Arthrath, Aberdeenshire

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The Arthrath intrusion, located ~25km north of the city of Aberdeen, is one of a number of Caledonian aged mafic-ultramafic intrusions within northeast Scotland. The intrusion is hosted by hornfelsed Dalradian metasedimentary rocks, and is primarily made up of a thick, olivine-poor gabbronorite core, with some olivine-bearing peridotites and norites flanking the gabbronorite. Magmatic Ni-Cu-Co sulfide mineralisation is concentrated in the gabbronorites and lesser olivine norites and displays textures that range from disseminated interstitial blebs, to net-textured and massive sulfides.

Disseminated sulfides hosted within phlogopite-bearing gabbronorites are made up of pyrrhotite-pentlandite-chalcopyrite and have Ni/Cu ratios typically of 0.5 to 1.5. More massive sulfides, which include net-textured, sulfide-matrix breccias and massive sulfides are primarily made up of pyrrhotite, with pentlandite as loops and flames, occasional pyrite, but very little chalcopyrite. These massive sulfides have Ni/Cu ratios typically of up to 10. Some minor Cu-rich stringer veins extend from the massive sulfide into the host rock and in addition, mm-scale chalcopyrite-carbonate veins with hydrothermal alteration selvages are common.

The disseminated sulfides with Ni/Cu ratios around 1 are interpreted to represent a primary sulfide assemblage. Where there is evidence of significant sulfide accumulation, the preserved massive to semi-massive sulfides are primarily Fe-Ni sulfide, which would imply a 'missing' component of Cu-rich sulfide in a fractionated sulfide system over a scale of 10^{1-2} metres. Whilst some Cu sulfide is present in hydrothermal veins, indicating some fluid mobilisation of Cu, there remains the possibility of discovering further fractionated magmatic Cu-rich sulfide accumulations at Arthrath.

Towards "Critical Geometallurgy" of post-subduction mineral resources: investigating the Newmont Lake magmatic-hydrothermal deposits, British Columbia

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Critical metals such as tellurium (Te), bismuth (Bi), antimony (Sb), and platinum group metals (PGMs) are essential for the green technologies that will underpin the global energy transition and achieve net zero. However, despite forecast increased demand, the current market value of many critical metals is too low to make their extraction economically viable as the sole product of a mine. Te, Bi, Sb and PGMs are often associated with more abundant and economical metals such as copper (Cu) and gold (Au) in post-subduction magmatic-hydrothermal mineral deposits, and therefore have the potential to be extracted as by-products during processing of the ore. Efficient recovery of these critical metals as by-products can secure future supplies, while at the same time minimising the environmental impact through enhanced extraction efficiency. However, we have a poor understanding of where within deposits these by-products are hosted – mineralogically, spatially, and physically – and what controls this distribution and their concentrations, impeding the design of processing techniques to recover these vital resources. Understanding the processes governing critical metal enrichment in post-subduction Cu and Au deposits is therefore key to developing predictive geometallurgical models to enable effective by-product extraction.

Here we provide a research-in-progress update on our work investigating the controls on critical metal enrichment in post-subduction magmatic-hydrothermal deposits within the Canadian Cordillera, British Columbia. Our focus is the Newmont Lake area, which contains porphyry Cu deposits and epithermal Au deposits associated with the same Late Triassic (219 – 215 Ma [1]) silica-undersaturated alkaline post-subduction intrusions that produced the neighbouring Cu-Au-(Te-PGM) Galore Creek deposit. These include the McLymont epithermal Au deposit, which contains potential by-products Cu and Te; and the Burgundy porphyry Cu deposit, which contains potential Te, Zn, Bi and PGM by-products.

We will be applying ore mineralogy, fluid and melt inclusion analysis, geochronology, and thermochronology to a recently-collected sample suite to test whether fluids exsolved from alkaline magmas are favourable for critical metal transport; how semi-metal melts in hydrothermal systems can control final mineralogy and grade distribution; and how cooling and exhumation affect the mobilisation and concentration of fluids and critical metals.

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Seeking Geochemical and Mineralogical Evidence for a Hidden Porphyry System Below the Lorne Plateau, Argyll, Scotland

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The Lorne area of Argyll, Scotland, has seen over 60 years of commercial mineral exploration and is currently being explored for Cu-Au-Mo porphyry mineralisation by Western Gold Exploration Ltd [1]. The area is unique for ancient metamorphic belts because a ~375 km^2 palaeosurface of variable thickness and permeability is preserved beneath volcaniclastic cover [2] of variable thickness and permeability. The identification of mineralisation below cover remains a significant challenge for exploration programs and may have been overlooked in both Argyll and worldwide. This study seeks to understand whether if distal hydrothermal signatures in the Lorne can be detected within more permeable units of the volcaniclastic cover.

The target lithology is the Silurian/Devonian Kerrera Sandstone Formation, a series of fluviatile and lacustrine sandstones and conglomerates that sit unconformably on the palaeo-landscape of the Dalradian Supergroup and at the base of and interfingered with the Lorne Plateau Lavas (LPL) [3]. The LPL constitute a lateral extensive sequence of Late Silurian basaltic andesite to rhyolitic lavas and pyroclastic units dated at 425±0.7 Ma [2]. Temporally and spatially associated with the LPL is the alkali-calcic Kilmelford intrusive suite (KIS) dated at 425.8 ±1.7 Ma [4]. The shallow to subvolcanic intrusions of the KIS are the causative intrusions for Cu-Au-Mo porphyry and related mineralization styles that have been previously identified at the Lagalochan and Ardlochan prospects, [5], which lie <2 km from the southern margin of the LPL.

A suite of samples representing the variety of facies within the Kerrera Sandstone Formation were collected in September 2025 from field localities and drill core provided by Western Gold Exploration. The samples were collected at varying distances from the known mineralization where exposure allowed. The samples will be subjected to petrological analysis, whole rock geochemistry, mineral chemistry and X-ray diffraction analysis to establish whether if this permeable layer has been exposed to hydrothermal fluids associated with the Cu-Au-Mo mineralization of the district.

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The Li-bearing Kingsand Rhyolitic Formation: Insights into the extrusive equivalent of the Cornubian rare-metal mineral system

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Recent growth within the sustainable energy sector has seen an exponential increase in the consumption of lithium (Li). Global exploration efforts reflect this trend, with an increase of in-depth investigations into the behaviour of Li in the range of magmatic-volcanic-sedimentary settings seen. Closed basin Li-rich brines (salars) and Li-enriched pegmatites are the most widely exploited resources, but highly enriched peraluminous intrusive and volcano-sedimentary settings show promising potential as future targets. The link between Li and peraluminous magmatism is strong, but little is known about the characteristics of Li behaviour within these systems. In general, Li is incompatible, enriching in evolving melts, but also fluid mobile, and liable to remobilisation post-emplacement, adding significant complexity to deriving behavioural trends.

The Permian-age Kingsand Rhyolitic Formation (KRF) in Cornwall consists of three limited outcrops comprising a small subvolcanic intrusion and a pyroclastic extrusive unit, constrained by a major NW-SE structural corridor SE of the Permian-age Bodmin granite. This study has shown the formation to be anomalously high in Li, F and other fluorophile elements. These features therefore offer an unparalleled opportunity to investigate the potential for Li-F bearing supra-batholithic extrusive equivalents of the Cornubian Batholith.

Geochemical data in the forms of both whole-rock and specific mineral analysis has been employed to characterise the KRF, with the goal of determining (1) a petrogenetic model, (2) a potential melt source, and (3) the behaviour of Li before, during, and after eruption. Whole-rock data comprising ICP-OES, ICP-MS, CHNS, and XRD analyses can be compared to existing published data collected from the phases of the Cornubian batholith, with a view to investigating the potential of extended fractionation trends forming the KRF. Mineral chemistry determined using EPMA and LA-ICP-MS analyses can be used to trace the behaviour of Li-F within an evolving peraluminous system, looking at the effects of fractionation, eruption, and early kaolinization on the Li and F deportment.

The Mistress Pegmatite, Zimbabwe: Evidence for Extreme Fractionation and New Geochemical Proxies for Lithium Fertility

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The Mistress Pegmatite, located ~20 km north of Harare in the Zimbabwe Craton, specifically located at the southwestern edge of the Chinamora Igneous Complex [1], is a historically mined lepidolite-bearing lithium-caesium-tantalum (LCT) pegmatite that has received little geochemical study. Petrography, EPMA mineral chemistry, and whole-rock ICP-MS analyses from five representative zones were used to evaluate the pegmatite's degree of evolution, petrogenesis, and lithium fertility.

Micas span muscovite to lepidolite compositions, with decreasing K/Rb and K/Cs and increasing F, Rb, and Cs towards the most evolved domains. Albite-dominant feldspar and Mn-rich spessartine define late-stage fractionation [2] [3]. Whole-rock geochemistry shows extreme enrichment in Li, Rb, Cs, Ta, and Sn, severe depletion in Sr, Ba, and rare-earth elements, and Li contents up to ~1.1 wt% Li_2O.

To evaluate Li-fertility indicators, a new global open-source dataset of more than 200 bulk-rock analyses, comprising Li-fertile pegmatites, barren pegmatites and associated granites was compiled. This dataset developed a set of Li-independent trace-element proxies, most notably Rb/K, Ta/Nb, Cs/Zr and Nb/La which reliably discriminate fertile from barren pegmatites. The Mistress Pegmatite plots firmly within the fertile fields on Rb/K vs Ta/Nb and Cs/Zr vs Nb/La diagrams, confirming its highly evolved nature and significant lithium potential. This dataset is especially important considering many current exploration techniques, such as a handheld XRF cannot detect Li [4]. Importantly, trace-element patterns are consistent between the Mistress samples despite contrasting modal mineralogy, suggesting that non-Li-rich margins may retain geochemical fingerprints diagnostic of fertile cores.

These results position Mistress as one of the most extremely fractionated pegmatites recognised in southern Africa and demonstrate the broader utility of Li-free trace-element ratios as effective geochemical tools for identifying fertile pegmatites and targeting concealed lithium mineralisation.

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Tailings as Secondary Resource? Insights from a Legacy Cu Tailings in Benguet, Philippines

Gibaga, C.R.[1,2,3], Samaniego, J. [1], Gervasio, J.H.[1], Tanciongco, A.[2], Quierrez, R.N. [1], Jenkin, G. [2], Swift, R. [3], Chambers, J. [3], Crane, R. [4], Yan, Y. [4], Bautista, A VII[1], Peregrino, F.R.[1], Sabaria, L.G. [1], and Arcilla, C. [1]

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Mining operations worldwide generate vast quantities of tailings, a fine-grained residue produced after ore comminution and beneficiation. Historically, limited processing efficiencies left significant amounts of valuable metals unrecovered, making legacy tailings increasingly attractive as potential secondary sources of critical and economic metals. One example is a legacy Cu tailings deposit of Philex Padcal Mine, Benguet, Philippines, stored in Tailings Storage Facility 1 (TSF1), which operated from 1967 to 1981.

This study investigates the geochemical, mineralogical, and geophysical characteristics of tailings from Benches 4 and 5 of TSF1. A total of 69 surface samples and 38 depth samples were collected and analysed using portable X-ray fluorescence (pXRF), supported by ICP-MS, QEMSCAN, XRD, and petrographic techniques. Results show that Bench 5 contains notably higher Cu and Fe concentrations than Bench 4, with Cu reaching up to 0.28%—exceeding the 0.17% Cu grade currently processed by the mine. Concentrations of potentially toxic elements (e.g., As, Pb, Cd) are low throughout the sampled profiles. Mineralogical analysis identifies plagioclase, quartz, chlorite, biotite, hornblende, and magnetite as major constituents, while Cu is chiefly present in chalcopyrite occurring as angular in both unoxidized and oxidized forms.

Electrical resistivity tomography (ERT) arrays were also installed across and parallel to Dike 4. The geophysical inversion reveals two main tailings materials: a higher-resistivity unit and a lower-resistivity unit. Depth-sample results indicate that the higher-resistivity zones correspond to sandy tailings, whereas lower-resistivity zones correspond to muddy tailings, confirming a strong link between physical texture and geophysical response.

These results demonstrate that the legacy tailings at TSF1 retain economically meaningful copper grades with minimal contaminant penalties, and that geophysical methods such as ERT can effectively characterise their spatial distribution and material variability. Together, these findings suggest that affordable and environmentally responsible reprocessing could not only recover valuable metals but also support informed management strategies to reduce the long-term environmental footprint of historical mining operations.

Resource Potential or Environmental Liability? A Geochemical, Mineralogical, and Geophysical Assessment of Legacy Mine Wastes in Cornwall, UK

Gibaga, C.R.[1,2,3], Swift, R. [1], Jenkin, G. [2], Chambers, J. [1], Crane, R. [4], Marquis, E. [4], Horabin, C. [1], and Kuras, O. [1]

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Legacy mine wastes are the residual materials left behind after historical mineral extraction, and in Cornwall these deposits have accumulated over centuries of intensive mining. Although inefficient processing historically left appreciable quantities of valuable metals in the waste, aligning with current aspirations for a circular economy, many sites are also known to contain elevated concentrations of potentially toxic elements such as As and Pb. This duality highlights the need to evaluate legacy mine wastes not only as potential secondary metal resources but also as sources of environmental risk.

This study presents a preliminary geochemical, mineralogical, and geophysical assessment of representative mine wastes from two sites in Cornwall: Binner Downs, and Wheal Maid. Geoelectrical methods (e.g., electrical resistivity) were applied alongside laboratory analyses to characterise the spatial variability of the deposits and to assist in identifying different waste units. At Binner Downs, waste rock piles derived from 19th-century mining consist of sphalerite, galena, and chalcopyrite, with a representative sample containing 1.2% Cu and 1.5% Zn. A separate set of 38 surface samples analysed using pXRF yielded up to 0.23% Cu and 0.76% As, and resistivity imaging proved useful in distinguishing the original ground surface from the mine waste and in discriminating waste materials with different physical properties. Wheal Maid consists predominantly of grey tailings dominated by angular pyrite grains. Electrical resistivity results reveal a three-layer structure: an upper high-resistivity layer, an intermediate-resistivity layer, and a deeper low-resistivity layer. Depth sampling confirms that these correspond respectively to overburden brown sand, sandy grey tailings, and grey muddy tailings. Both pXRF depth analyses and ICP-MS results confirm elevated As concentrations ranging from 0.04–0.13%, and acid mine drainage is visible in the lower lagoon.

Together, these findings underscore the contrasting character of Cornwall's legacy mine wastes: they retain significant metal content, yet they also present persistent environmental challenges. Importantly, the integration of geophysics with geochemical and mineralogical data enhances understanding of subsurface variability, enabling non-intrusive mapping of waste distribution and material properties. This combined approach provides a robust framework for guiding future land management, remediation, and any targeted reprocessing of legacy mine wastes.

Investigating the timing of evolution of the Skaergaard hydrothermal system

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The Skaergaard Intrusion, East Greenland, is a globally significant natural laboratory for understanding magmatic differentiation and magmatic–hydrothermal processes in basaltic systems. Previous analysis of the $\delta^{18}O$ of plagioclase throughout the intrusion has demonstrated that a hydrothermal system was established in its upper parts [1], and that periodic roof collapse introduced hydrothermally altered blocks into the magma chamber [2]. These blocks, classified into three main groups (gabbroic troctolites, gabbroic anorthosites, and oxide gabbros), are abundant within the Lower and Middle Zones of the Layered Series, yet the temporal evolution and consequences of their alteration remain poorly constrained. In particular, the origin of unusually low-$\delta^{18}O$ late-stage ferrodiorite magmas, and the potential role of altered blocks in supplying ^{16}O-rich fluids to the differentiating reservoir, remain unresolved [3].

In this study we investigate the timing and extent of hydrothermal alteration within the roof zone of the intrusion, using a stratigraphically representative suite of 13 autolith samples derived from the roof zone, collected from across the Layered Series. The project aims to (1) determine whether cumulates beneath the roof underwent hydrothermal alteration shortly after crystallisation, (2) establish whether fallen blocks record the temporal evolution of the hydrothermal system, and (3) test whether dehydration of these blocks during foundering could have contributed to the development of low-$\delta^{18}O$ late-stage magmas using mass-balancing.

Plagioclase and clinopyroxene will be separated for $\delta^{18}O$ analysis, complemented by whole-rock XRD to characterise alteration mineral assemblages. Integration of isotope data with petrographic observations and known block source regions will constrain the spatial and temporal evolution of hydrothermal alteration in the roof zone. We anticipate that plagioclase will preserve progressive oxygen-isotope exchange with hydrothermal fluids, as it is more susceptible to oxygen diffusion than pyroxene, providing a sensitive record of alteration intensity over time. Petrography is expected to show replacement of mafic silicates by actinolite, biotite and chlorite, consistent with pervasive and fracture-controlled alteration phases described in earlier studies.

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Structural controls on mineralization at the Løkken claim areas, Norway

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The Løkken deposit in central Norway is one of the largest ophiolite-hosted, Cyprus-type VMS deposits in the world [1]. Historically, the Løkken mines contained around 17 million tonnes of ore with approximately 2.6% Cu, 1.8% Zn, and 0.2% Pb, and traces of gold and silver. Despite extensive mining and exploration through 1654 to 1987, the structural controls on mineralisation across the sites remain poorly constrained. It is inherent to the preservation of VMS deposits that they are strongly deformed and their structural geology is critical for delineating ore bodies [2-3]. Improved structural characterisation at Løkken is therefore essential for refining exploration models and identifying prospective drilling targets.

This study investigates the Åmot, Høydal and Dragset targets to evaluate how deformation and alteration has influenced the localisation, geometry and preservation of VMS mineralisation within the overturned Løkken ophiolite. This is conducted through detailed surface mapping around the three areas combined with structural logging of oriented core, as well as petrographic analysis of representative samples and integration of existing geophysical and geochemical datasets. Although analysis is ongoing, preliminary results from mapping and core logging show patterns that are consistent with established models [4-5]. These early results show a strong association between chlorite–quartz–sericite alteration and zones of deformation, with foliated chlorite-rich metavolcanics, recrystallised sulphides and sulphide-bearing quartz–chlorite veinlets consistently aligned with penetrative fabrics. Shear zones and brittle-ductile structures identified in core show orientations compatible with outcrop-scale folding, suggesting a district-scale structural framework that acted both as a pathway for hydrothermal fluids and a control on sulphide remobilisation.

Early interpretations support a model in which Caledonian folding and shearing played a major role in concentrating and redistributing mineralisation within the synformal architecture of the Løkken ophiolite. Ongoing microstructural analysis will refine the relative timing of alteration, sulphide deposition and deformation. Integrating these datasets into a 3D structural model will improve understanding of VMS system architecture at Løkken and support more predictive exploration targeting across the district.

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Mineral prospectivity of the mafic–ultramafic Caledonide intrusions of Northeast Scotland

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Critical raw materials (CRMs) such as nickel (Ni) and cobalt (Co) are integral components of low carbon technologies, vital for the energy transition [1]. To achieve the stated UK policy aim of Net Zero by 2050, it is vital that prospective areas are thoroughly investigated. The Caledonian mafic-ultramafic intrusive suite of Northeast Scotland is recognised as potentially prospective for CRMs [1]. This suite encompasses ~10 intrusions emplaced into the Dalradian Supergroup of the Grampian Highlands during arc-continent collision and pre-syn peak regional metamorphism (*c.*470 Ma) associated with the Grampian Orogeny (*c.*488 – 461 Ma) [2]. Active exploration is ongoing at the Arthrath (by Aberdeen Minerals Ltd) and Huntly-Knock (by Peak Nickel Ltd) intrusions, known to contain magmatic Ni-Cu-Co sulphide mineralisation [3]. The Belhelvie intrusion is also recognised as prospective [3].

It is broadly accepted that the suite was emplaced ~470 Myr ago [4]. However, existing age data is dispersed over 30+ Myrs around ~470 Ma [4], reflective of inconsistent and potentially imprecise dating methods (e.g., Rb-Sr, K-Ar). Several intrusions of potential economic interest have little or no age data (e.g., Arthrath). At an intrusion scale, existing data cannot determine if mineralised units were emplaced contemporaneously or as distinct temporal magmatic events. Regionally, existing data cannot determine if the suite was emplaced coevally, potentially as one layered intrusion, subsequently faulted into its surficial distribution, or if intrusions were emplaced as temporally and genetically discrete bodies through crustal weaknesses, each undergoing distinct crystallisation histories [5]. The suite contains abundant xenoliths of Dalradian metasediments [5] and the sulphur (S) / selenium (Se) geochemical data for the mineralised units in Arthrath and Knock reflect crustal contaminated magma [6]. It is unclear how crustal contamination corresponds to mineralisation within intrusions or if there is systematic variation in the extent of crustal contamination between or within the magmatic system(s). Understanding the temporal magmatic framework and extent of crustal contamination is necessary to address uncertainties around mineralisation controls at both an intrusion and regional scale.

This study follows an approach of extensive regional sampling, core logging, detailed petrography and whole-rock geochemistry to constrain the magmatic evolution and mineralisation potential of the intrusive suite. High precision U-Pb zircon geochronology will address specific uncertainties around intra- and inter-pluton temporal variability and temporal controls on mineralisation. Lu-Hf zircon isotope analyses will assess the extent of crustal contamination within and between mineralised intrusions and those with no known mineralisation, thus addressing uncertainties around crustal contamination as a control for mineralisation. This work will directly contribute to the developing exploration model at Artharth and could inform regional targeting efforts across other mafic-ultramafic intrusions in Northeast Scotland.

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Mobilisation of Cobalt and Associated Ore Metals during Sulphide Deformation and Recrystallisation at Rajapalot, Finland

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Many ore deposits have undergone post-formation deformation and recrystallisation, processes that can significantly alter original mineralogy and metal distribution [e.g. 1, 2]. In orogenic mineral deposits, early sulphide phases are particularly susceptible to these processes. Despite the potential implications for ore genesis and mineral processing, the effects of deformation and metamorphism on sulphide bearing ore metals remain only partially understood – especially in polyphase orogenic gold deposits.

Rajapalot is a Paleoproterozoic Au-Co deposit in Northern Finland, owned and explored by Mawson Finland Ltd.. The ore mineralisation is polyphase with cobalt minerals forming from pre-peak to late orogenic stages [1], a timing consistent with that of other orogenic gold deposits in Finland [e.g. 3]. A structural control on the cobalt mineralisation at Rajapalot is interpreted to result from syn-tectonic solution transfer, with enrichment localised in fold hinges [4]. Early pyrite (FeS_2) and cobaltite (CoAsS) at Rajapalot exhibit signatures of crystal plastic deformation including crystal lattice bending, subgrain formation, and recrystallisation and complex chemical zonation, providing an ideal case study to investigate links between microstructure and metal mobility.

Based on a paragenetic study and EDS mapping of chemical zonation in sulphides [5], targets in cobaltite and pyrite were selected for further in-depth analyses. Electron Backscatter Diffraction (EBSD) was used to quantitatively asses grain crystallographic orientations, location of grain and subgrain boundaries and degree of nature of intracrystalline plastic deformation. LA-ICP-MS mapping was employed to quantify element distributions at the subgrain to grain-scale in areas of microstructural interest.

Results show partial recrystallisation of cobaltite and pyrite (in clusters of > 1 mm) with contrasting microstructures. Large grains of pyrite and cobaltite containing inclusions exhibit subgrains and high intracrystalline strain, whereas small grains have straight polygonal grain boundaries and no internal strain. Primary oscillatory zonation, reflecting varying Co:Fe and S:As ratios, is preserved in domains/grains of pyrite and cobaltite that have not been subject to recrystallisation processes.

Preliminary LA-ICP-MS analyses indicate three domains of distinct elemental signatures: 1) deformed older cores/grains; 2) recrystallised grains/zones; and 3) networks of defects. These three domains indicate at least two stages of element mobility across the deformation history of pyrite and cobaltite at Rajapalot. Coupled analysis of EBSD and LA-ICP-MS maps will determine if these defects represent fractures or subgrain boundaries, and clarify which events mobilised specific key elements.

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An initial assessment of gold and sulfide mineralisation in the Glen Garry area of the Central Highlands, Scotland

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Regional stream sediment surveys and follow up exploration in the 1980's identified widespread alluvial gold in the central Scottish Highlands [1,2]. More recent work focussing on compositional characterization of alluvial gold at localities where the source is unknown has shown that magmatic hydrothermal systems are locally important, whilst the genetic origins of other occurrences remain unclear [2]. Newly discovered occurrences of alluvial gold in the River Garry drainage are notable as scoping compositional studies have revealed both inclusion signatures comprising minerals stable at high *f* Te and the presence of particles comprising an Au-Pd alloy. In addition, alluvial native silver is commonly present. The compositional profile of the gold resembles that associated with alkalic porphyry systems and associated epithermal occurrences. [3,4].

Follow up fieldwork in the area has revealed large numbers of roughly N-S striking potassium feldspar-quartz-pyrite veins, hosted in Dalradian metasedimentary rocks. These veins vary in width from a few mm to several cm, and have been identified in all south flowing tributaries including and between Edendon water and Allt a Chireachainn, together with outcrops in the upper River Garry itself. Their occurrence outwith this area of approximately 20km^2 remains unproven. The apparent spatial coincidence of alluvial gold with a distinctive signature, and these veins raises the possibility of a genetic link, and the potential for a previously unrecognised major magmatic, metal-bearing hydrothermal system.

Here we describe the ongoing early characterization of both particulate gold and vein occurrences, using petrography, cathodoluminescence, scanning electron microscope and electron microprobe analysis.

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Dzhezkazgan and associated sediment-hosted stratiform copper (SSC) deposits of the Chu-Sarysu basin, central Kazakhstan

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Sandstone-hosted copper (sandstone Cu) deposits, often also called sediment-hosted stratiform copper (SSC) deposits, occur within a 200 km reach of the northern Chu-Sarysu basin of central Kazakhstan (Dzhezkazgan and Zhaman-Aibat deposits, and the Zhilandy group of deposits).

The deposits consist of Cu sulfide minerals as intergranular cement and grain replacement in 10 ore-bearing members of sandstone and conglomerate within a 600-1000 m thick Pennsylvanian fluvial red bed sequence. Copper metal content of the deposits ranges from 22 Mt (Dzhezkazgan) to 0.13 Mt (Karashoshak in the Zhilandy group), with average grades of 0.85-1.7% Cu and significant values for silver (Ag) and rhenium (Re).

Broader zones of iron reduction (bleaching) of sandstones and conglomerates of the red bed sequence extend over 10 km beyond each of the deposits along east-northeast-trending anticlines, which began to form in Pennsylvanian time. The bleached zones and organic residues within them are remnants of former petroleum fluid accumulations trapped by these anticlines.

Deposit sites along these F1 anticlines are localized at and adjacent to the intersections of nearly orthogonal north-northwest-trending F2 synclines. These structural lows served to guide the flow of dense ore brines across the petroleum-bearing anticlines, resulting in ore sulfide precipitation where the two fluids interacted. The ore brine was sourced either from the overlying Early Permian lacustrine evaporitic basin, whose depocenter occurs between the major deposits, or from underlying Upper Devonian marine evaporites.

Sulfur isotopes indicate biologic reduction of sulfate but do not resolve whether the sulfate was contributed from the brine or from the petroleum fluids.

New Re-Os age dates of Cu sulfides from the Dzhezkazgan deposit indicate mineralization took place between 299-309 Ma near the Pennsylvanian-Permian age boundary.

At the Dzhezkazgan and some Zhilandy deposits, F2 fold deformation continued after ore deposition. Copper ore bodies in Lower Permian shale near to the Zhaman-Aibat deposit indicate at least some of the mineralization there is younger than at Dzhezkazgan, consistent with the Re-Os age and with differences in their ore Pb isotopes.

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Machine-Learning Approaches to Predict Undetectable pXRF Elements: a Case Study of Na Prediction from the Northern Bushveld Complex, South Africa

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The use of Portable X-Ray Fluorescence (pXRF) equipment in mineral exploration provides, cheap, rapid, real-time geochemical analysis of soil and rock samples [1], enabling swift on-site decision-making. Despite these advantages, pXRF has limitations; particularly its inability to detect light elements (atomic numbers below Mg) and its shallow penetration depth. [2], This limits the capability to accurately predict Na-bearing minerals when calculating a mineral balance using norms or other approaches. In the Northern Limb of the Bushveld Complex, Na is an essential component of the plagioclase–orthopyroxene–clinopyroxene dominated Platreef Ni-Cu-PGE ore system at Mogalakwena mine. This study explores the use of tree-based Machine-Learning (ML) algorithms to predict Na concentrations using pXRF analyses on diamond drill core. Four tree-based models were applied: one bagging method (Random Forest, RF) and three boosting methods (Gradient Boosting; Extreme Gradient Boosting; and Adaptive Boosting). The pXRF dataset consisted of 18 elements and four elemental ratios (Sr/Cr, Sr/Ti, Sr/Al, and Sr/Y). Three boreholes representative of the Zwartfontein mining area, with accompanying 10-cm resolution pXRF analyses and 1-m resolution 72 element assay data, were selected as the training dataset. For training, Na_2O concentrations were "borrowed" from the assay data and inserting them into the pXRF dataset [3]. Both datasets were composited to 1-m intervals to preserve underlying stratigraphic relationships. Missing values were replaced with element-specific detection limits. The test dataset consisted of 2 more Zwartfontein area boreholes and 6 from exploration along strike north and south of Mogalakwena mine. Preliminary results are shown in Figure 1. The Gradient Boosting model performed best with predicted Na concentrations matching the observed Na and picking out the most important trends and breaks, demonstrating the value of ML techniques in predicting undetectable elements like Na. The model performed better on other Zwartfontein boreholes compared to those farther away, illustrating the impact of out-of-distribution (OOD) prediction, and the importance of selecting training data that represent the same geological domain as the target prediction area.

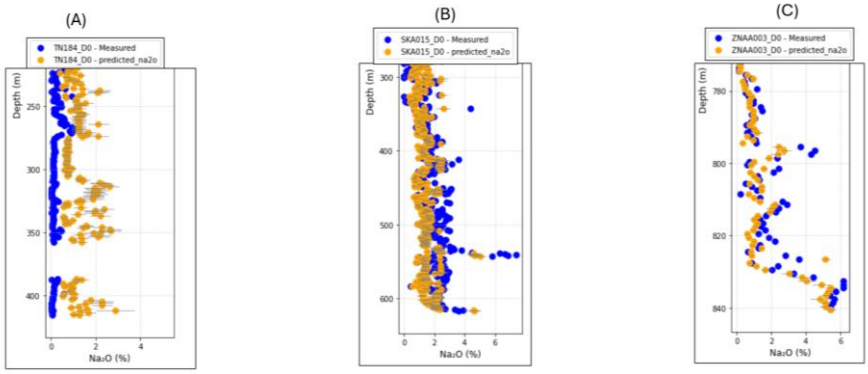

Figure 1. (A) Borehole TN184_DO, representing the poorest prediction performance; (B) Borehole SKA015_DO, representing average prediction performance; (C) Borehole ZNAA003_DO, representing the best prediction performance, with measured values shown in blue and predicted values shown in orange.

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Zircon geochemistry of volcanic rocks related to low-sulphidation epithermal gold mineralisation: a case study from the Hishikari deposit, Japan

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Low-sulphidation (LS) epithermal deposits form at the shallow periphery of magmatic-hydrothermal systems, where meteoric fluid is conventionally thought to dominate over magmatic fluid due to the typically dilute nature of the hydrothermal fluid. Magmas have been considered to be involved solely as a heat source, with metals being scavenged from basement rocks [1]. However, there is increasing evidence that the metals within these deposits are derived from magmatic fluids [2,3], calling for a better understanding of the geochemical characteristics of igneous rocks associated with these systems.

The Hishikari LS epithermal gold deposit in southern Kyushu, Japan, ranks among the world's highest-grade gold deposits, averaging ~40 g/t and locally exceeding 1000 g/t, with total reserves estimated at over 250 t Au [4]. The Hishikari Volcanic Rocks (HVR) have been dated at 2.4-0.5 Ma (using whole rock K-Ar dating [5]) and are located within 10 km of the deposit. The HVR are split into two groups – the northern Kurosonsan Group (2.4 – 0.9 Ma) and the southern Shishimano Group (1.6-0.5 Ma), with each exhibiting a similar evolution from early andesites to later rhyodacites [5]. Quartz-adularia-gold veins of the Hishikari deposit (1.11-0.73 Ma [4]) are hosted in the basement Cretaceous accretionary complex and the lowermost andesite of the Shishimano Group. Pb and Sr isotopic studies on vein quartz-adularia indicate sourcing of these components from both supracrustal rocks and the HVR, even in veins hosted entirely within sedimentary units [2]. These spatial, temporal and isotopic lines of evidence suggest that the HVR record the evolution of magmas that potentially contributed metals to the deposit.

In this study, zircons were separated from six lava samples of the HVR, with one andesite and two dacites from each stratigraphic group. Cathodoluminescence images were obtained using scanning electron microscopy (SEM) and zircons were analysed using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to determine $^{206}Pb/^{238}U$ ages and trace element compositions. The determined ages of 1.55 Ma to 0.72 Ma are consistent with previous dating. Trace element geochemistry indicates a significant shift in both oxidation state and temperature before the onset of mineralisation. These findings support a magmatic contribution to the Hishikari LS epithermal system and strengthen the case for magmatic involvement in LS epithermal deposits globally.

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Back to Programme

Nitrogen Behavior in continental rift magmas: a case study of the Gardar Province, SW Greenland

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The Mesoproterozoic Gardar Province of South Greenland is the largest rare earth element (REE)belt in Europe. As a mantle-derived magmatic system, previous studies indicate that the parental melts were sourced from a lithospheric mantle domain enriched in REE. However, the processes responsible for generating these enriched mantle sources, whether it is related to subduction driven metasomatism or to mantle plume activity remain an active research focus. Recent studies suggest that the Gardar mantle source was modified by Ketilidian subduction related metasomatism ~500 Ma prior to rifting. The sulfur isotope data further reveals pronounced temporal and spatial heterogeneity across different intrusive complexes. The nitrogen isotopes are unaffected by partial melting processes and are the key tracer of volatile transfer between Earth's surface and mantle. Nitrogen isotopes offer new insight to identify the mantle source.

To understand the behaviour of nitrogen in these alkaline systems, we targeted a varierty of minerals for alkali feldspar, plagioclase, biotite, astrophyllite, and syenite whole rocks from major Gardar intrusions, to identify which phases host nitrogen. Samples were analysed using Elemental Analyzer-Isotope Ratio Mass Spectrometry (EA-IRMS) and sealed-tube combustion line, coupled to a continuous flow isotope ratio mass spectrometer (IRMS).

Preliminary results show extremely low nitrogen concentrations across the system, increase systematically from early crystallizing feldspars (0.7 to 5.8 ppm) to late-stage hydrous minerals such as astrophyllite confirming highly incompatible behaviour of N during alkaline magmatic differentiation. Most minerals display negative $\delta^{15}N$ values (-5‰ to 0‰), broadly overall with upper mantle values (-5 ± 3‰) but lower than the plume mantle (+3 ± 2 ‰). The distribution closely resembles $\delta^{15}N$ patterns in the modern continental rift in East Africa. These data indicate that the Gardar magmas were derived from a metasomatized and enriched subcontinental lithospheric mantle, with additional contributions from a mantle plume.

Ultramafic-hosted massive sulphide mineralisation at an oceanic detachment fault, Mid-Atlantic Ridge 13°30'N

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It is now recognised that seafloor spreading at many of the world's slow- and ultraslow-spreading mid-ocean ridges is accommodated by oceanic detachment faulting rather than generation of a 'textbook' layer-cake basaltic ocean crust. The architecture of ocean lithosphere formed at detachment-dominated mid-ocean ridges is heterogeneous, characterised by reduced or absent magmatism and by the exposure of (now serpentinised) mantle peridotites at or near the seafloor at 'oceanic core complexes', which represent the exhumed footwalls of the detachment faults. Such structures also appear to be the loci of significant ultramafic-hosted massive sulphide mineralisation at or near the seafloor. The processes by which such mineralisation occurs – the controls, extent and composition – are poorly constrained; however they appear to contrast significantly with basalt-hosted seafloor massive sulphide mineralisation such as the TAG deposit, not least in apparently being much greater in size.

We here present some initial results from the 'ULTRA' project, our ongoing study of mineralisation associated with the 13°30'N oceanic detachment fault on the Mid-Atlantic Ridge: the so-called 'Semenov' ultramafic-hosted massive sulphide deposit. Previous studies by Russian authors have shown that the deposit is the most extensive and potentially largest yet known at a mid-ocean ridge – they estimate up to 40 million tons (10x TAG), and enriched in Au, Ag, Cu, Ni, Co & Pt – but these claims are poorly verified and the mineralisation mechanisms are not well understood.

Under the aegis of the ULTRA project we have conducted two expeditions to the 13°30'N area (RRS *James Cook* cruises JC224 & JC254), during which we acquired a wide selection of near-bottom geophysical data, and collected rock, mineral and fluid samples using remotely-operated rock vehicles and seabed drills. We will here present new data and preliminary constraints on mineralisation mechanisms, emphasising how close interplay between the tectonic, magmatic and hydrothermal processes is required to generate such ultramafic-hosted massive sulphide deposits.

Structural controls on porphyry copper formation at Copper Cities, Arizona, USA

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Global demand for copper is rising quickly due to its critical role in building the electrical technologies driving the green energy transition [1]. Porphyry copper deposits (PCDs) supply a large proportion of global Cu, but with demand due to outstrip supply within the next 5 years, the need to find more is becoming acutely apparent [2,3]. While the arc-scale tectonic framework for PCD formation is generally accepted to be subduction zone settings along convergent margins [4], the regional to local tectonic controls remain poorly constrained. For example, within the Laramide Porphyry Province, USA, which lies along the southern margin of the Colorado Plateau, it is unclear what controls the variation in PCD size, grade, and abundance [5]. This margin-parallel variation suggests that pre- to syn-Laramide fault architecture could be important in controlling the ascent of magmatic-hydrothermal systems and concentrating fertile copper-bearing fluids at a deposit scale [6].

This study investigates the structural controls on porphyry copper mineralisation in the Copper Cities deposit, which forms part of the Laramide Porphyry Province in Arizona. Copper Cities is intriguing because it has a relatively low hypogene copper grade of ~0.30% Cu [7], which stands in stark contrast to the nearby high-grade Resolution deposit (~1.54% Cu), despite both having formed in the same tectonic regime. This contrast provides an opportunity to evaluate how local variations in structural evolution influence mineralisation. Structural measurements of faults and veins within the Copper Cities site were collected from surface outcrops and from drill core, focusing on orientations and kinematic indicators where present. Drill holes crossing faults at depth were specifically targeted, and often revealed ductile deformation fabrics, revealing sense-of-shear indicators. From the vein-bearing samples, 165 veins have been characterised, noting cross-cutting features and ore minerals present, namely chalcopyrite, pyrite and molybdenite. Cross-cutting relationships have been used to define a vein paragenesis, revealing multiple generations of mineralising fluids that can be correlated with vein orientations to infer structural controls on fluid pathways and mineralisation.

Preliminary results suggest that the mineralised veins are sub-parallel to a series of WSW-ENE trending fault structures, such as the Sleeping Beauty Fault, which lie approximately orthogonal to the Colorado Plateau margin. These orientations mirror pre-Laramide basement structures in the region [8], suggesting long-lived lithospheric scale structures may have influenced mineralisation. The metal-bearing fluids will be characterised by fluid inclusion surveys, preliminary results of which have shown an association between intermediate density, CO_2-bearing fluids and sulphide mineralisation. Ductile shear fabrics in the vein-parallel fault structures will also be characterised to constrain fault kinematics and the relative timing of deformation and mineralisation.

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The NERC Ion Microprobe Facility: SIMS analyses to support mineral deposits research

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The NERC Ion Microprobe Facility (IMF) at the University of Edinburgh supports academic and commercial services in Secondary Ion Mass Spectrometry (SIMS) for chemical and isotopic analyses of small volumes of solid material. SIMS can achieve detection limits down to parts per billion for many elements, including those relevant to mineral deposits research.

The Facility hosts two state-of-the-art ion microprobes. The compact Cameca IMS 7f-Geo was commissioned in 2019 and is particularly well suited for the analysis of volatile and light elements, as well as trace element concentrations in both silicate and non-silicate materials. The large-geometry Cameca IMS-1300 HR3 was delivered in November 2025 and is expected to be fully operational by April 2026. It features high secondary ion transmission, high mass resolving power and multicollection capabilities. It is ideally suited to measure high-precision stable isotope ratios (e.g., H, Li, B, C, N, O, S, Si, Mg), K-Ca and U-Pb geochronology, and to analysis of elements that require extremely high mass resolution such as heavy halogens (Cl, Br, I) and transition metals. Both instruments are supported by comprehensive sample preparation facilities, experienced technical staff, and a wide range of well-characterised standard materials.

Recent examples of projects related to minerals and mineral deposits research include:

- Nathwani et al. [1] measured volatiles (H, C, F, Cl) in apatite inclusions in zircon grains from the Quellaveco porphyry copper deposit, Peru. They discovered that the magmatic system sourcing the Cu porphyry mineralization remained fluid-saturated, while the pre-mineralization batholith remained fluid-undersaturated.
- Cangelosi et al. [2] measured oxygen isotopes in calcite and quartz from the Dasighou carbonatite deposit, China. They discovered two styles of rare earth element mineralization, according to the degree of hydrothermal reworking.
- O'Driscoll et al. [3] measured sulfur isotopes in sulfides from the platinum group element (PGE)-mineralized Rum layered intrusion, Scotland. They constrained magmatic and crustal sources of sulfur, and discovered strong spatial patterns of PGE mineralization associated with sulfide mineral breakdown.

The IMF is keen to engage with new and prospective SIMS users from the mineral deposits research community. We invite any interested researchers to contact the facility staff to discuss the needs of your project.

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A Century of Copper Metallurgical Slag Production: Global Trends and Implications in UK Copper Slags

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Global copper consumption continues to rise, with refined usage increasing fourfold in the past fifty years [1] and driving corresponding increases in mine, smelter, and refinery wastes. Among these, copper smelting produces large volumes of waste slag that can retain significant amounts of residual metals including Cu (0.5-3.7 wt.%) [2], Ni, Co, and critical metals. Although copper smelting spans over a millennium of history [3], the overall quantity of slag produced worldwide and its resource potential remain poorly quantified, even as demand for copper and critical metals accelerates.

This study estimates global copper slag production from 1928 to 2021 using a proxy approach utilising

annual smelter output and technology-specific slag-to-copper ratios. Results show a steady increase in production from about 4.27Mt in 1928 to 34.44Mt in 2021. The United States leads cumulative production (>220Mt), followed by China, Chile, Japan, and the USSR and Russia at about 128Mt. Over the century, production dynamics has shifted from the decline of U.S. smelting to the rapid rise of China's copper sector from the 1960s onwards (>74-fold increase from 1960s to 2020s). This upward transition is also reflected in slag composition: legacy slags typically contain higher residual Cu (10-20 wt.%) due to less efficient reverberatory furnaces [4], whereas modern slags are lower in residual metals but of larger volumes, produced by advanced technologies such as flash and ISASMELT smelting [5].

Within this global context, the United Kingdom presents a unique case of nineteenth-century copper slags that have been largely understudied for their economic or critical-metal potential. To address this gap, a preliminary study on mineralogical and geochemical characterisation of legacy Cornwall slags reveals significant residual copper as sulfides and critical metals occurring as minor Cu±Sn±Bi alloys indicating enrichment in critical metals in potentially recoverable phases. These results highlight the value of utilising robust methods to identify viable secondary resources and strengthen potential critical-metal supplies. Ongoing work focuses on detailed mineralogical characterisation, metal deportment, and leaching behaviour to assess their re-processibility.

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The Paragenesis of the Gold Mineralisation at Nanoq, Southeast Greenland

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Newly discovered orogenic-style gold mineralisation at Amaroq's Nanoq site in Southeast Greenland sits within the Nanortalik Gold Belt that spans southern Greenland. The mineralisation is hosted in quartz veins within a volcano-sedimentary sequence which has been deformed, most notably, by the Ketilidian Orogeny. Mineralisation is hosted within two prominent, NE-SW trending shears. Additionally, proximal saddle-reef type veining has also been identified within the layered sequence, presenting a compelling, multi-faceted gold exploration target.

Due to Nanoq being in the early stages of exploration there are many gaps in knowledge surrounding the site. Mineralising fluid sources, pathways, and depositional mechanisms are all, thus far, unconstrained.

Initial results show that the purple-rust stained quartz veins contain sulphides including pyrite and chalcopyrite. Two of the smaller veins contain garnets and malachite, with one being coated in elemental sulphur.

The mineralogy of the deposit will be determined through petrological analysis using the ZEISS scanning electron microscope (SEM), laser ablation, and reflected light microscopy. This analysis aims to highlight textural and mineralogical differences in the main vein and minor vein structures which, in turn, indicate which processes played a role in the formation of Nanoq. Leading from this, depositional mechanisms and fluid sources will be determined by fluid inclusion analysis and optical petrology.

The petrology of the Nyungu Central Deposit, Northwestern Zambia: What is the lithogeochemical stratigraphy?

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Sediment-hosted stratiform copper deposits in the Central African Copperbelt (CACB), are some of the highest known grade and tonnage Cu deposits in the world, accounting for 23% of world copper production [1]. Of this production, the DRC and Zambia, both make up the CACB, dominate, accounting for 50% [2]. The Katangan Supergroup of the CACB is known to host many of these major SSC deposits; orebodies at Lumwana, Kansanshi and Sentinel [3].

The Katangan Supergroup formed in a series of marine rifts during the breakup of Rodinia in the Neoproterozoic [4]. During the Pan-African event of the Gondwana amalgamation, these sediments were metamorphosed to amphibolite facies [5] and now form much of the Lufillian arc. In the domes region of northern Zambia, uplifted basement rises form inliers within the Katangan metasediments. These “domes” are often flanked by notable SSC deposits; e.g. Lumwana on the northeastern flank of the Mwombezhi dome and Sentinel on the northeastern flank of the Kabompo dome.

The Nyungu Central deposit is part of Prospect Resources Mumbezhi project, located between Lumwana and Sentinel, on the western flank of the Mwombezhi dome. It has not been subject to any previous petrological study or analysis, and as such field relations and field observations are relied on when logging on site. A petrologically evidenced lithogeochemical stratigraphy of the deposit will provide more concrete resource defining and can be applied to further exploration. The relationship of fold structures to the mineralisation is also, at current, unknown. This petrological study has potential to provide insight to this by relating morphology of lithologies and alterations to bulk geochemical assays to infer structure both downhole and along strike.

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What is the Relationship of Kyanite with the Cu-Sulphide Mineralisation at Mumbezhi, Zambia?

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The Central African Copperbelt (CAC) is the world's largest sediment-hosted stratiform Cu deposit. containing 140 Mt Cu and 6 Mt cobalt [1]. Mineralisation is hosted within units of the Katangan Supergroup; a basinal sequence made up of basal redbeds overlain by siliciclastics, carbonates and evaporites, with mineralisation located at varying stratigraphic positions across the CAC. The sequence was deformed during the Lufilian orogeny as part of the Pan African Orogenic event around 550-520 Ma. In the 'Domes' region of the CAC, in northern Zambia, major deposits such as Sentinel and Lumwana are located close to the lower, sheared contact of the Katangan rocks with the underlying basement. Prospect Resources' Mumbezhi project is located between Lumwana and Sentinel in the Kalumbila region of Zambia, and geologically sits on the western margin of the Mwombeshi dome.

The Cu-sulphide mineralisation at Mumbezhi is found in association with kyanite. Kyanite is an aluminosilicate metamorphic mineral that forms at high pressures and is often used to determine metamorphic facies along with its polymorphs: andalusite and sillimanite [2]. However, it has recently been recognised that in the CAC that some kyanite is hydrothermal/metasomatic in origin, being found in veins and replacement textures, often with associated Cu and Co sulfides [3]. Several textural styles of kyanite have been identified in this study from cores at Mumbezhi; some of which are intimately associated with chalcopyrite.

It is unknown whether the kyanite at Mumbezhi is metamorphic or hydrothermal, and therefore its relationship with the Cu-sulphide mineralisation is unknown, leaving a knowledge gap for the research that will take place in this project. Petrological and mineral chemistry studies on the kyanite styles are underway, which aim to determine constraints on the fluid history that has led to Cu (and kyanite) mineralisation, and whether kyanite can be used as an effective vector for Cu mineralisation in the area.

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Before we can look at the minerals: non-geological considerations for the investigation of metalliferous mine wastes in SW England

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Commercialisation of combined remediation and recovery of critical metals has been seen as a potential circular opportunity by UK government to address the environmental challenges related to historic mine waste in the environment. Many mines and mine waste accumulations are stored in manners inconsistent with modern contaminant containment and geotechnical stability, and were abandoned prior to the establishment of legislative frameworks necessitating remediation activities. With critical minerals becoming an increasingly visible topic both nationally and globally, the potential of these residues to contain such minerals has been viewed as a possible mechanism for offsetting the cost of remediation. However, prior to the deployment of any ground-based study, there are multiple features, designations and legislative frameworks relating to historic mine waste sites that must be considered. In addition, the nature and purpose of the study may inform the permissions and permits required.

Previous studies, such as Crane et al. [1], have identified such designation as challenges. Building upon such studies, this contribution provides a deep dive into several key archaeological, ecological, and environmental designations and legislative frameworks relevant to historic mine wastes, and highlight the potential impacts of these on the ability for these sites to be investigated by private entities for combined remediation-recovery purposes. Highlights from this deep dive include 1) the requirement for extensive (near-feasibility) level of investigations would likely be required prior to undertaking sampling that would normally be required prior to a decision on whether a project should be taken to feasibility study; and 2) potentially conflicting requirements for historical preservation and environmental stabilisation of such sites.

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Matrix supported clasts and associated structures and textures: Examples from quartz veins in the Central Wales Pb-Zn Mineral District

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Quartz veins with matrix supported clasts (MSC) have been reported and briefly described from the Central Wales District [1-4]. Mason [3] recognised a distinctive 'close-grained' quartz texture. To support the clasts, the quartz was interpreted as having been deposited from rapidly cooled fluids [1-4]. Sulphides can be a component of the matrix [2]. Blocks from mine tips at, and near, the Bryn-y-rafr Mine provide additional information about the range of internal structure and texture in these veins and some aspects of the quartz matrix evolution. Host rocks are Ordovician and Silurian turbidite sequences showing Acadian deformation and anchizone to epizone metamorphism. The blocks studied all belong to the early A1 assemblage of Mason [3], having cloudy white quartz, some evidence of deformation and cut by much later A2 assemblages. Acadian 'Alpine type' quartz veins [3, 4] and fibre textured quartz veins [poster] also cut A1. The A1 mineralization is inferred to be late Acadian.

Blocks show a continuous range from: 1 clast supported breccias, 2 quartz with abundant MSC, 3 quartz with rare, small MSC. MSC are recognised using Jébrack's [5] criteria: no point contacts, quartz >50%. The matrix in quartz with abundant MSC shows elongate quartz crystals with an overall radial pattern forming jackets around clasts. Jackets are up to 10mm thick. Radial growths from adjacent centres abut at distinct sutures. Small vugs occur between 3 or more jackets. A few radial quartz growths have very fine-grained dark rings separated by bands of radial quartz crystals. Two examples of spirals of fine, dark material were also seen. These possibly record some mixing events in the matrix. Quartz with rare MSC shows small (2-3 mm across) radial clusters of quartz crystals that abut against each when seen in thin section. Nucleation points are dispersed through the quartz and rarely seen. Very small vugs are present at the ends of radiating crystals. Crystals are difficult to see in hand specimen and often appear to be randomly oriented. The rare clasts have small quartz crystals normal to surfaces. Vein walls all have quartz crystals similar in size to those in the bulk matrix, suggesting that they grew at the same time. Quartz crystals in general enclose small, pale rods and locally have a mottled appearance, features thought to represent traces of the early stages of silica evolution.

Quartz with MSC can be uniform or show domains with varying clast content and clast size. Uniform veins with MSC record single emplacement events without prior growth of crystalline wall linings. Domain boundaries can be wall parallel, oblique to walls or irregular. Clast poor layers are seen along some walls and there are some examples where the vein fill is asymmetrical with differing clast domains on opposite walls. Boundaries can be sharp but are diffuse where only marked by changes in clast size or orientation. Clasts of earlier quartz with MSC can have sharp or diffuse boundaries. Some relatively large clasts may span domain boundaries. These and the diffuse boundaries may record limited lithification of the early matrix and erosion at domain boundaries. Sharp boundaries record fracture of lithified material. There is a history of vein opening, vein fill and matrix lithification.

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Supervised Machine Learning Classification of ASTER Satellite Imagery for Lithological Mapping

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Lithological mapping represents the geometry and distribution of rock formations at the Earth's surface[1]. Traditional field mapping can be labour intensive, costly, spatially limited and with potential for sampling bias[2,3]. Spectral remote sensing (RS) is a key tool to complement fieldwork that allows for broad area coverage with uniformly collected data with no logistical costs or disturbance to the environment and local populous.

Multispectral and hyperspectral satellite, airborne, and drone data can be used to identify rock formation variation, the presence of alteration and geological structures via spectral responses in the electromagnetic spectrum[4,5], particularly in arid regions with good exposure. With a wide range of imagery providers and highly variable temporal, spectral and spatial resolution data sets, RS poses a multi-source and multi-resolution challenge with no clear consensus in the literature on the best approach and methodology[5]. The integration of RS with GIS, data science, and machine learning (ML) is one way to address these high dimensionality challenges and create automated, robust and reproducible models for rapid large-area coverage[1,6].

This study applies three supervised ML classifiers; 1. Spectral Angle Mapper (SAM), 2. Maximum Likelihood Classification (MLC), and 3. Support Vector Machine (SVM), to ASTER imagery for lithological mapping in central-western Namibia. The 14-band ASTER dataset, across the visible and near infrared, short wave infrared and thermal infrared (VNIR, SWIR, TIR) bands, was resampled to 15 m resolution and classified using 5,000 training and 2,000 validation Region of Interest (ROI) samples. The ROIs were derived from a reprocessed 1:250,000-scale Geological Survey of Namibia (GSN) map[7] compiled between 1968 and 1978, prior to the launch of modern satellite data offerings.

Geometric quality assessment of the geological map identified minor georeferencing and interpretative uncertainties, with local shifts up to 400 m, especially along historical map boundaries. These were considered during ROI generation but had minimal impact on overall interpretive validity. In many cases these errors were automatically corrected through the ML classification.

Accuracy assessments yielded overall accuracies of 73.9% (Kappa = 0.66) for SVM, 46.5% (Kappa = 0.39) for MLC, and 34.4% (Kappa = 0.26) for SAM. SVM most closely matched the existing geological map, while MLC provided complementary discrimination among schist, quartzite, carbonate, and ultramafic units. SAM produced noisier outputs influenced by illumination and topography, which could potentially be improved through advanced preprocessing. The results demonstrate SVM's robustness for lithological discrimination, while MLC effectively identifies subtle compositional variations overlooked by SVM and highlights areas for interpretation of previously unrecognised geological relationships.

The study demonstrates the potential of ML-driven RS to validate and refine legacy geological data, especially in similar semi-arid environments such as Namibia. ASTER's generous spectral offering across the VNIR, SWIR, and TIR spectrums and open-source data access positions the imagery as a cornerstone for geological assessments. This method can be used to generate updated interpretations that build upon the preexisting body of knowledge and supports ongoing field data collection or wider geological assessments where rapid, low impact analysis is critical.

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The Geological Controls and Mineral Parageneses of the Gunheath Lithium Deposit, St Austell, Cornwall

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The peraluminous granites of the early Permian Cornubian Batholith have been divided into five categories based on mineral assemblage, geochemistry and texture, with the rare-metal topaz granites (known as G5) hosting significant lithium concentrations principally within micas [1]. The Gunheath Project represents one of the four significant locations in SW England where the G5 granites occur near the surface of the Cornubian Batholith [2,3]. However, mica composition and paragenesis are influenced by regional-scale complexity [4].

By integrating whole-rock geochemical data, trace-element mapping and 3D deposit modelling, this research aims to quantitatively characterise variation in lithium and tin grades within the Gunheath deposit as a product of repeated cycles of magmatic fractionation (typically leading to Li enrichment) and magmatic-hydrothermal alteration (typically leading to Li depletion) associated with incremental assembly from multiple magma batches. Substantial volumes of magmatic-hydrothermal fluids, exsolved from each G5 batch and adjacent G4 tourmaline granite, may have scavenged Li from the primary magmatic micas and subsequently precipitated Li-rich overgrowths or new mica at higher levels in the system [4]. Timescales of deposit assembly will be established using high-precision U-Pb and Rb-Sr geochronology.

Understanding the relative contributions of magmatic and magmatic-hydrothermal processes on mica-hosted lithium grade at deposit scale, and the associated variability in Li-mica species, will inform how minerals are processed, which will affect commercial viability. An accurate paragenetic model could establish transferable criteria for other mica-hosted lithium projects.

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