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Foreword

On behalf of the Advisory Committee, I am delighted to welcome you to AusIMM's 2025 Critical Minerals Conference.

This conference has grown rapidly to become a unique industry-led forum to discuss challenges, solutions and the latest developments in the critical minerals sector. This year's event is taking place in a rapidly changing geopolitical environment. Constantly shifting trade relations and ongoing global conflict continue to impact the reliability of established supply chains, while adding further uncertainty to market forecasts.

In the shadow of these challenges, it is more important than ever that we collaborate and foster open dialogue between industry, academic and government agencies from around the world.

The Advisory Committee has put together an engaging program headlined by our outstanding keynote speakers and supported by 60 technical presentations covering processing, discovery and development, mineral economics, the circular economy and new technologies. The program is further strengthened by additional workshops, interactive panel discussions and plenty of networking opportunities.

I would like to thank our presenting authors for sharing their insights and our abstract reviewers for their time and diligence. We are also deeply grateful to our sponsors and exhibitors for their continued support.

Finally, I wish to acknowledge the Advisory Committee and AusIMM Management Team, whose dedication and expertise have been instrumental in bringing this event to life.

Yours faithfully,

Dr Helen Degeling

FAusIMM

Critical Minerals Conference Advisory Committee Chair

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Submissions

Development of a lithium zero-waste flow sheet – flotation based approach

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ABSTRACT

Lithium minerals, essential for energy storage technologies, are considered critical raw materials (CRM). They play a crucial role in enabling a carbon-free future through their utilisation in batteries and electric vehicles (EV). However, extracting lithium minerals (eg spodumene) from hard rock pegmatite ores requires overcoming significant challenges. Conventional flow sheets, which combine processes such as dense media, magnetic and flotation, enable effective metallurgical performance but do not target a waste production strategy. Consequently, this study addresses flow sheet development which combines explicitly metallurgical performance and waste management. In order to do so, a common thread has been identified through density among all the separation stages. In other words, a density-driven strategy, forming a zero-waste triangle based on mineralogy, flow sheet design, and waste management (that is to say, aiming at zero-waste).

Dense Media Separation (DMS) and flotation rely on density as the common separation driver. DMS exploits particle density to concentrate out valuable mineral (from reject gangue). In contrast, flotation operates at lower bulk density scales, where the formation and stability of bubble-particle aggregates govern separation. Understanding the phenomenological behaviour of DMS and flotation aggregates provides the foundation for a robust resource recovery strategy. This approach frames waste not merely as a by-product, but as an integral element of the flow sheet, one that must be managed strategically over time and considered within technical and economic constraints.

The current stage of the study focuses on flotation, beginning with mica removal to enhance selectivity and using bubble–particle aggregate density to guide spodumene recovery within a staged, zero-waste process. This research supports the development of an alternative and sustainable flow sheet for spodumene beneficiation at the Savannah mine (Portugal), as part of the EXCEED project funded by the European Union. Results from flotation testing will guide process scale-up and the refinement of density-based control strategies in hard rock lithium processing.

Automated characterisation and assessment for critical raw materials processing

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ABSTRACT

The transition to green energy relies on technologies demanding a wide range of critical raw materials (CRMs). In Europe, geopolitical conflicts have amplified the need for domestic sourcing. To support efficient extraction and diversification of the CRM sources as well as the reduction of mining and processing waste, a software tool is being developed in the Geological Survey of Finland as part of the REPower-CEST project funded by the European Union's Recovery and Resilience Facility. The tool provides automated analysis, visualisation, and reporting of the CRMs for energy transition in ore samples, mineral processing waste, or tailings samples. The general use case involves feeding automated mineralogy (AM) and chemical assay data to the software to facilitate answering questions related to the characteristics of the material under study and its potential applications. Most of the analytics offered by the software rely on processing Microsoft Access databases containing automated mineralogy analysis data of the material under study. These include information about the minerals, their properties and elemental compositions, with detailed characteristics of particles and grains. In addition, the software can import chemical assay data in Microsoft Excel format to perform data reconciliation between mineral composition data from bulk chemical assay and the elemental composition data from AM. The software combines the data sets with an embedded database of mineral properties and mineral processing information to produce a repeatable and systematic identification and visualisation of the potential utilisation of minerals. This comprehensive data integration enables characterisation of materials, assessment of applications and value, determination of processability, and evaluation of health and environmental risks. The software significantly accelerates sample analysis while reducing error-prone manual operations. The results can be used to produce estimates of the potential value of minerals and metals for the clean energy transition.

Obtaining rare earth element concentrates from Estonian phosphate rock via hydrochloric acid processing

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ABSTRACT

Sustainable recovery of rare earth elements (REEs) from alternative sources such as phosphate rock (PR) has recently gained more attention due to the growing demand for their use in clean energy technologies such as wind power, electric vehicles, and electrochemistry. This study focuses on the concentration of REEs from PR acid treatment solutions through neutralisation to induce REEs precipitation.

A PR from Ülgase deposit in Estonia containing 1063 ppm of REEs and 25.3 per cent of P_2O_5 was used for the precipitation tests. The solutions with a pH below 1.0 were obtained through a leaching process (leaching extent of REEs over 95 per cent) using HCl concentrations ranging from 0.8 M to 1 M.

To precipitate REEs, the pH of the solution was gradually increased, using an alkaline solution prepared from Ca-rich oil shale ash, a waste landfilled material. A precipitate containing up to 2.3 per cent of total REEs was obtained within the pH range of 2.5–3, enriched with lanthanum (0.12–0.31 per cent), cerium (0.31–1.41 per cent), neodymium (0.13–0.33 per cent), and yttrium (0.20–0.58 per cent). The recovery extent of REEs ranged from 81 to 88 per cent. The precipitate formed contained also 10.3–12.5 per cent phosphorus, 25.4–30 per cent calcium, 6.8–8 per cent iron, and 15.6–19.35 per cent fluorine due to co-precipitation.

The results of XPS analysis of the precipitate indicated that REE(3+)-compounds were present mostly in the form of REE-PO_4 and REE-F_3. The REE concentrate was subsequently treated with oxalic acid to form REE oxalates. This process enhanced the purity of REEs concentrate, enabling selective removal of 97.7–99.1 per cent of fluorine, 94–98 per cent of phosphorus and 94.5–99.5 per cent of iron.

The overall results demonstrated that REEs can be efficiently separated from PR through leaching with low–concentration hydrochloric acid, followed by concentration via precipitation and subsequent purification of the precipitate using oxalic acid.

Adding downstream value to Australian tungsten concentrates

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ABSTRACT

Tungsten is a very strong and inert metal that is of significant economic importance due to its use in tungsten carbide for the mining and automotive industries, and as tungsten alloys for defence and energy applications. The substitution of tungsten in such materials is difficult or impossible. As evidenced in recent times, geopolitical factors acutely impact the supply of tungsten and as a result, tungsten has been listed as a critical metal in Australia and all other western jurisdictions.

Australia has the second highest tungsten reserves worldwide (~13 per cent) and three operating mines producing tungsten concentrate, but despite this significant position in the upstream portion of the tungsten supply chain, we currently possess no value-adding, downstream processing capacity.

As part of the Australian Critical Minerals Research and Development Hub, a collaboration between ANSTO, Geoscience Australia and CSIRO, and funded by the Australian Government, a program to investigate Technology Metals Production Australia led by CSIRO is being undertaken.

As part of this wider program is a dedicated project investigating the downstream processing of Australian tungsten concentrates through to tungsten metal. ANSTO is investigating hydrometallurgical routes to produce saleable tungsten intermediate chemical concentrates and metallisation precursors.

The project commenced with a literature review which identified three hydrometallurgical routes used in industry to produce an intermediate tungsten product. An autoclave alkali leach was identified as the most used approach due to its applicability to a wide range of concentrates, but this processing technology is less than ideal with respect to water balance issues, reagent consumption, ability to handle various impurities etc.

The work to be presented will include a comparison of the industrial process routes, their relative pros and cons, the issues with their application to the processing of Australian concentrates, and the challenges and opportunities that lie ahead.

Defining regolith-hosted REE deposits using multivariate whole-rock geochemistry

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ABSTRACT

The rare earth elements (REEs) are critical metals for developing renewable technologies. Regolith-hosted deposits are emerging sources of REEs, though the economic viability of these ores depends on their hosting significant volumes of mineralised material which compensate for their low metal grades (<2000 ppm ∑REE). The clay-dominated nature of regolith-hosted REE deposits, which contributes to the difficulty of distinguishing transported cover units from *in situ* weathered units, makes their delineation through traditional methods like petrological analysis and core logging challenging. To expedite deposit-scale characterisation of the regolith-hosted Splinter Rock REE prospect, Western Australia, we applied principal component analysis and k-means clustering to >3000 whole-rock geochemical assays of its mineralised and barren regolith horizons.

K-means analysis successfully separated all samples into five stratigraphically continuous horizons (three barren and two mineralised). The horizons were interpreted as units of sedimentary cover and weathered granites, respectively. Once clustered, the mineralogical and metallurgical features of all samples were extrapolated from select drill cores defined by hyperspectral analysis. This facilitated the identification of several robust mineralogical, geochemical and metallurgical trends at the deposit scale:

- The highest REE grades exist in the granitic saprolite and saprock.
- Relative to the light REEs, the heavy REEs are enriched at the saprolite-saprock boundary and become depleted with increasing depth in the saprock.
- Optimal metallurgical conditions occur near the saprolite-saprock interface.
- Accumulation of the economically- and environmentally-important 'magnet' REEs occurs mainly in the saprock.
- MagREE enrichment can be linked to the development of negative Ce anomalies.

Principal component analysis also facilitated the establishment of tailored geochemical ratios for classifying future samples into their appropriate clusters/horizons, such that this study highlights the multivariate statistical analyses of geochemical data as an efficient method for outlining deposit-scale trends and zones of economic metal enrichment in regolith-hosted REE deposits.

Genesis and resource quality of contact-metamorphic flake graphite deposits – insights from the Leliyn Graphite Deposit, Northern Territory

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ABSTRACT

Flake graphite is a critical mineral for energy storage technologies, with flake size and structural order (crystallinity) governing its industrial value. This study showcases the value of integrating scanning electron microscope (SEM)-based automated mineral mapping, X-ray diffraction (XRD), and Raman spectroscopy at both bulk and grain scales to assess the origin and quality of flake graphite—from deposit to grain scale—in the contact metamorphic Leliyn Graphite Deposit in the Pine Creek Orogen, Northern Territory. Petrographic and mineralogical analyses of graphitic schists indicate that the flake graphite formed via high-temperature (≥600°C) contact metamorphism of organic-rich metasedimentary precursors, as evidenced by an alkali feldspar-rich composition and relict andalusite porphyroblasts. Subsequent retrograde hydrothermal alteration at temperatures down to ≤300–350°C produced muscovite and kaolinite. Mineral mapping reveals significant within-sample heterogeneity in flake size and morphology. Graphite occurs mainly as small flakes (<50–100 μm) in a schistose alkali feldspar–muscovite matrix and aligned along biotite-rich foliation. Larger flakes occur in less schistose domains, while irregular accumulations are associated with deformation fabrics and the altered andalusite porphyroblasts. Bulk XRD analysis indicates high crystallinity, with an average interlayer spacing of 3.357 Å and a crystallite stacking height of 70–130 nm—values suitable for advanced industrial applications. Bulk Raman data, which average across numerous crystallites within samples, yield a narrow defect density range, with corresponding in-plane crystallite sizes of ~80–150 nm and ~480–530°C graphitisation temperatures. Grain-scale analysis, however, revealed pronounced intra-sample defect heterogeneities, probably linked to retrograde alteration, with much broader lateral crystallite size (~20–400 nm) and temperature (~390–620°C) ranges. Thus, while the graphite's overall structural characteristics indicate industrial potential, the predominance of small flakes (<50–100 μm) and significant defect heterogeneities should be considered when assessing suitability for specific applications. Collectively, this study highlights the value of a multi-scale, multi-technique graphite characterisation workflow, which can be applied in early-stage exploration to assess key parameters controlling economic viability.

Multiscale mineralogy of clay-hosted REE deposits in Western Australia – practical applications for exploration, domaining and resource modelling

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ABSTRACT

Rare-Earth Elements (REE) are critical minerals due to their role in high-performance magnets for renewable energy, electric vehicles, and defence, as well as associated geopolitical risks. Clay-hosted REE deposits are particularly attractive for exploration as they can contain substantial tonnages and can be extracted using weak acid (pH>4). This study provides a multiscale mineralogical characterisation of two clay-hosted REE projects in south-west Western Australia: Splinter Rock and Balladonia, located ~80 km apart. These deposits are hosted within the Albany-Fraser Orogen and associated with granites, gneisses, and granitoids of the Recherche and Esperance Supersuites, including the REE-enriched Booanya Granite. The region is overlain by Eucla Basin sediments and palaeovalleys, with bedrock and saprock exposed in elevated areas. Regolith-hosted REE enrichment extends across an area of 12 000 km^2 and does not exhibit a stratigraphic control at a regional scale. Spectra-based mineralogy and geochemical analyses from drilling data were used to delineate boundaries between transported regolith, *in situ* saprolite and saprock. Detailed mineralogical investigations on selected drill holes included continuous infrared reflectance spectra collection using HyLogger-3 system to define analysis intervals for bulk and clay X-ray diffraction, scanning electron microscopy, and SEM-based automated mineralogy. Lithological boundaries between transported cover and *in situ* regolith were defined using bound water, and albedo IR reflectance spectra indices, while the saprolite and saprock contact can be identified by a sharp increase in potassium content. These results show that major lithological boundaries can be defined using both core scanning and handheld devices and provide a rapid workflow for resource domaining and sampling. The REE mineralogy is primarily hosted by secondary REE minerals, mainly monazite/rhabdophane, with local occurrences of bastnasite and allanite. The thickness of the REE mineralisation correlates with deposition sites of the Eucla basin palaeovalleys and can be used as a regional exploration tool.

Experimental insights into the mechanisms of florencite formation in rare earth element deposits

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ABSTRACT

The rare earth elements (REEs) are indispensable metals for manufacturing permanent magnets – key components in renewable energy technologies such as wind turbines and electric vehicles. However, the growing global demand for REEs, coupled with supply chain vulnerabilities, has raised the need for increasing REE production and diversifying REE resources. Many nations have thus classified the REEs as critical metals, and are incentivizing both the discovery of new REE deposits and the development of innovative approaches to REE recovery from less conventional sources.

Florencite ($REEsAl_3(PO_4)_2.6H_2O$) – a secondary REE phosphate mineral – has traditionally been perceived to have limited economic value in conventional REE deposits such as hydrothermal and igneous ores. However, florencite is now emerging as a potential resource in unconventional deposit types like coal seams, bauxite residues and regolith-hosted deposits, where its presence may permit economical REE recovery. Understanding the nature of florencite formation may therefore be crucial for facilitating REE exploration across various geological settings and ore systems, though despite this the mechanisms of florencite formation have been overlooked relative to other REE minerals.

Our work studies the impact of fluid composition (eg aqueous aluminium and cerium activities) on the formation of florencite through the hydrothermal conversion of apatite at 140–220°C. Results reveal the critical roles of temperature and fluid composition on the mechanisms of florencite formation, outlining temperature-dependent reaction pathways and the influence of Al/Ce ratios on florencite stabilisation relative to other phosphate minerals. These findings may be extrapolated to natural hydrothermal systems and supergene deposits, to offer exploration criteria for identifying:

1. Florencite-dominated zones over monazite or rhabdophane rich assemblages in conventional deposits.
2. Zones of economic florencite precipitation in unconventional deposits.

Li and RE hydro-met solid liquid separation processes and combinations

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ABSTRACT

Candle type pressure filters are used extensively for polishing and solids recovery duties particularly in lithium conversion to carbonate, hydroxide or via DLE but also in Rare Earth processing plants. They require specific operating considerations compared to the more commonly used pressure filters such as filter presses, media filters or continuous filters which will be discussed.

Those pressure candle filters operate across a wide range of feed solids from almost zero (SX feed or thickener overflow polishing) to about 15 per cent solids (RE recovery), with a limit defined by longer relative downtime and the need to refill the filter with unfiltered slurry after each discharge.

While they accept a wide range of feed solids their operation must assure that no overfilling occurs, requiring close attention to process control. The batch operation with constant feed flow/increasing filtration pressure followed by decreasing flow/constant pressure will be discussed, and how to optimise the overall filter capacity.

The versatility of those filters covering slurry and dry cake discharge, optional cake washing, (displacement or spray washing), cake blow-drying, using filter aids as pre-coat and/or body feed at a wide temperature range with plenty material of construction choices also requires a detailed understanding of possibilities and limitations.

Those considerations will be discussed based on typical lithium conversion applications such as impurity removal, Glauber salt and lithium carbonate filtration examples together with process options and combinations – how candle type filters work best in combination with centrifuges, thickeners or vacuum filters.

Wastewater treatment with LieNA® processed calcium silicate by-products

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ABSTRACT

Water contamination is a growing global issue, with pollutants from agricultural and industrial activities affecting freshwater sources. Common contaminants include metal and non-metal ions, hydrocarbons, dyes, and coliforms. Effective removal of these pollutants from wastewater is crucial before environmental release. This study explores the use of Calcium Silicate By-product (CSB), a metallurgical waste from the LieNA® process developed by Livium Corporation, as an adsorbent for removing contaminants such as Ni, Cu, As, Cd, Hg, and Pb from wastewater. The LieNA® process, which extracts lithium directly from α-spodumene without thermal conversion, generates approximately 40 per cent of its waste as CSB. Analysis using XRF, SEM, and TIMA shows that CSB has a small particle size (P_{80} 10 μm) and primarily consists of calcium, sodium, silicon, and oxygen, in the forms of natrite (74 per cent), oyelite (8.80 per cent), and the O-Na-Ca-Si system (10.20 per cent). Experiments conducted under various conditions demonstrate CSB's adsorption properties, after 24 hrs at 25°C, initial pH of 1.53, and 100 rev/min stirring speed. The removal efficiency (R_e) of contaminants is influenced by CSB dosage and adsorption duration. Results indicate that Re for Hg, Cd and Cu were 94 per cent, 93 per cent, and 93 per cent respectively, achieved with a 10 gL^{-1} dosage, while the R_e for As was 64 per cent at the same dosage. For Pb and Ni, R_e reached 96 per cent and 87 per cent, respectively, with a 20 gL^{-1} dosage. This study highlights the potential of CSB as an effective agent for the removal of specific toxic elements in aqueous solutions, proposes an innovative utilisation of a metallurgical wastes for contaminant removal from wastewater, potentially converting this material into a valuable byproduct for advanced wastewater treatment.

Critical minerals in all solid-state lithium-ion batteries – a path to sustainable and efficient energy storage

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ABSTRACT

The growing demand for sustainable energy solutions has underscored the importance of critical minerals in shaping the future of energy storage. It is essential to implement initiatives that diversify supply chains, invest in recycling technologies, create alternative materials, and improve mining methods. The all-solid-state lithium-ion battery (ASSLIBs) using critical minerals aims to address energy storage limitations, supply chain risks, environmental concerns, climate change, and energy security. Unlike conventional liquid electrolyte-based LIBs, which suffer from thermal instability, flammability, leakage, and limited electrochemical windows. ASSLIBs, however, eliminate these risks by utilising solid electrolytes (SEs), which exhibit better ionic conductivities, reduced safety hazards, and improved electrochemical performance. We aim to utilise critical minerals in ASSLIBs and provide recommendations and roadmaps to address key performance parameters such as ionic conductivity, energy density, and cycling stability. Numerous research efforts have been conducted to develop suitable solid-state electrolytes, and considerable progress has been made, particularly for garnet-type SEs. Nonetheless, the garnet-type SE still faces several critical challenges. The work focuses on the ionic conductivity of garnet electrolytes as well as the interfaces between electrodes and SEs and cathode active materials. A concise explanation of the garnet structure, the synthesis techniques for bulk, thin-film, and composite garnet SEs is presented. The goal of this study is to provide a basic understanding of the latest developments in the energy storage sector, which may help realise useful garnet-based ASSLBs. Furthermore, future advancements and alternative approaches to addressing these challenges will be discussed to enhance the understanding of garnet electrolytes cathode active materials utilising critical minerals and promote their practical application in solid-state batteries.

Jupiter rising – unearthing Australia's largest clay-hosted REE deposit

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ABSTRACT

The Jupiter clay-hosted rare earth element (REE) deposit is located 60 km west of Mount Magnet, Western Australia and is currently Australia's largest clay-hosted REE deposit with an Inferred Resource of 1.8 billion tonnes (Bt) at 1700 ppm total rare earth oxides (TREO) at a 1000 ppm cut-off. REE mineralisation is hosted by a clay saprolite zone developed over a 40 km^2 alkaline intrusion concealed by a thin layer of colluvial – alluvial sand and gravel. Microanalytical work shows REEs are mainly hosted by phosphate minerals gorceixite-goyazite-florencite, rhabdophane-monazite and xenotime, within regolith dominated by kaolinite with lesser quartz and iron (hydr)oxides, minor titanium oxides, manganese (hydr)oxides, baryte, and relict primary phases including feldspars, biotite, muscovite, amphiboles, chlorite, titanite, apatite, epidote and zircon increasing through the lower saprolite towards fresh basement.

Laterite geochemistry (Geological Survey of Western Australia (GSWA)) throughout the broader Jupiter region is La-Ce anomalous, the Jupiter deposit itself is a coincident magnetitic and gravity high within the regionally extensive Big Bell Suite and associated granitoids of the Murchison Domain. Two Enterprise Investment Scheme (EIS) co-funded Reverse Circulation holes were drilled to test the coincident gravity and magnetic feature in 2020, and followed up in 2023 by Air Core drilling with results including 42 m at 1619 ppm TREO from 5 m. Subsequent exploration and resource definition drilling shows extensive clay-hosted REE mineralisation across the entire Jupiter geophysical feature. The underlying basement comprises a complexly zoned, strongly REE anomalous alkali intrusive complex ranging from alkali gabbro through syenodiorite, syenite to quartz monzonite and granite. REE minerals in fresh basement include bastnaesite-parisite, monazite, titanite and allanite. Chondrite-normalised REE plots of the Jupiter Intrusive Complex do not readily correspond to currently known granitoids within the Murchison Domain.

This paper provides the first overview of the Jupiter deposit and its discovery, presenting the current geological interpretation, microanalytical and lithogeochemical data.

INTRODUCTION

Western Australia (WA) hosts significant deposits of critical minerals. These deposits are an integral part of Australia building their own supply of critical minerals such as lithium, cobalt, tungsten and rare earth elements. These resources present a significant opportunity for WA's mining and exploration sector to meet increasing demands for domestically sourced critical minerals. Some of these resources such as Australian clay-hosted rare earth element (REE) deposits are novel and unconventional, such that exploration and processing strategies around these styles are still being developed. The current understanding is that most of the Australian clay-hosted REE deposits have somewhat different REE mineralogy from the ionic adsorption clay-hosted REE deposits found in China that are currently commercially exploited, but the presence of secondary REE minerals in at least some of the Australian deposits that can be concentrated and leached offer a significant opportunity for economic exploitation. The Jupiter deposit is currently Australia's largest clay-hosted REE deposit and represents a potential opportunity for a long-term stable supply of rare earth elements within Australia.

PROJECT LOCATION AND HISTORY

The Jupiter clay-hosted REE deposit forms part of the Critica Limited owned Brothers project. The project is located approximately 550 km north-east of Perth and 60 km west of Mount Magnet in

Western Australia (Figure 1). Access to the project is from the Yalgoo-Mount Magnet Road via unsealed tracks through the Edah and Murrum pastoral stations.

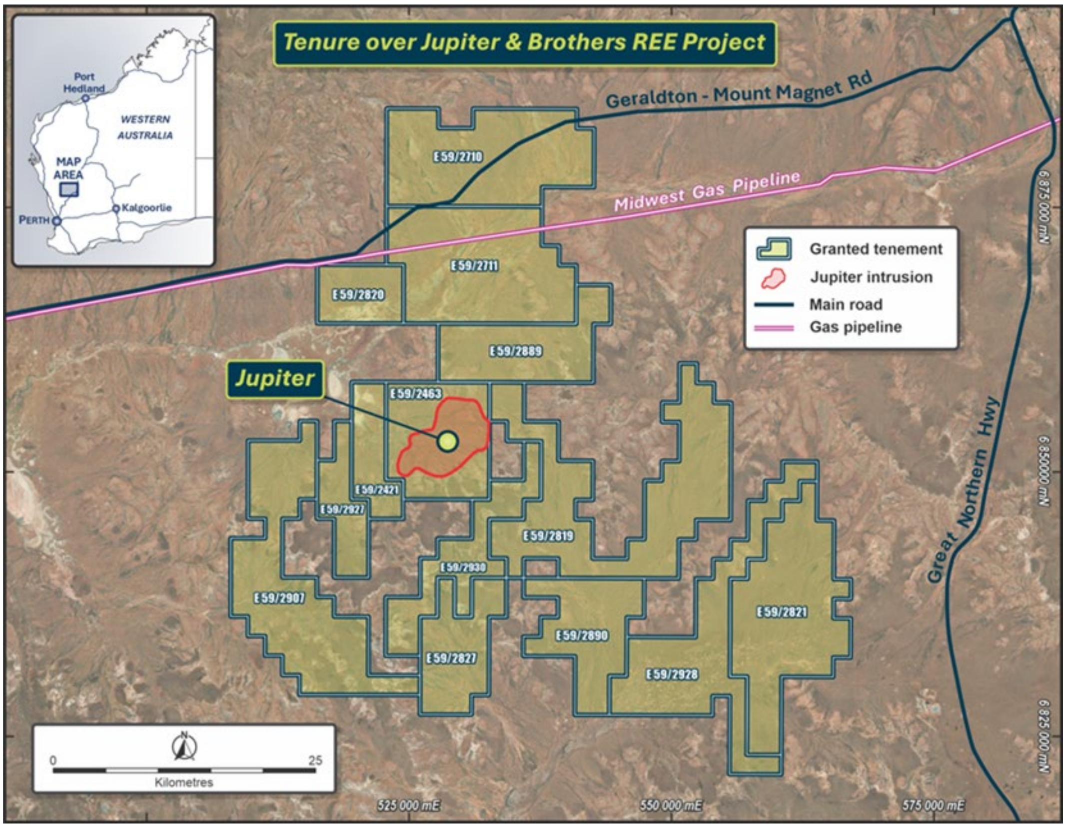

FIG 1 – Project location map, MGA94 Zone 50.

The Jupiter target was originally identified by geophysics with coincident aeromagnetic and gravity anomalies coupled with anomalous rare earth element results from GSWA laterite geochemistry and two co-funded EIS drill holes (Ross, 2020) drawing Critica geologists into the area. First pass Air Core (AC) drilling of the Jupiter target was completed in June 2023 with every drill hole reporting significant rare earth mineralisation within clay and saprolite zones. The grades and thicknesses were considered high compared to other known Australian clay-hosted rare earth deposits at the time. Following the discovery, aeromagnetic and gravity surveys were conducted (Figure 2) along with several Reverse Circulation (RC) and AC drilling campaigns which delineated an area of 40 km^2 of high-grade, clay-hosted rare earth mineralisation. The mineralisation comprised of consistent, broad zones up to 80 m thick with grades above 1000 ppm TREO (TREO includes La_2O_3, CeO_2, Pr_6O_{11}, Nd_2O_3, Sm_2O_3, Eu_2O_3, Gd_2O_3, Tb_4O_7, Dy_2O_3, Ho_2O_3, Er_2O_3, Tm_2O_3, Yb_2O_3, Lu_2O_3, and Y_2O_3).

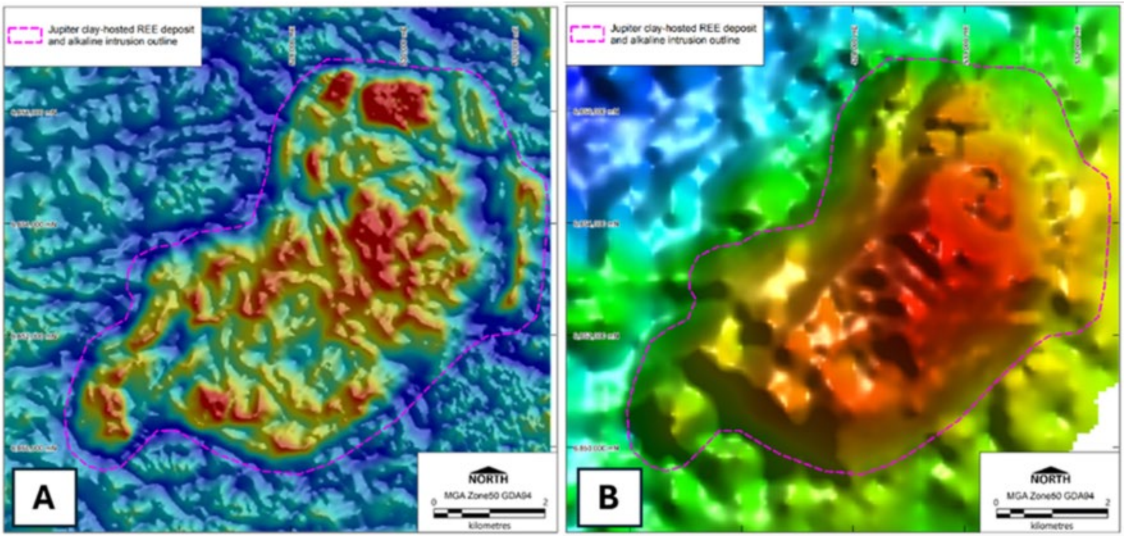

FIG 2 – (a) Unmanned Aerial Vehicle (UAV) magnetic survey: Total Magnetic Intensity (TMI) image; (b) gravity survey: Bouger gravity image.

In 2024, resource definition drilling was completed with 625 holes for 37 663 m used to calculate an inferred maiden resource for the Jupiter deposit. In February 2025 an inferred resource of 1.8 billion tonnes (Bt) at 1700 ppm total rare earth oxides (TREO) at a 1000 ppm cut-off was announced (Critica Limited, 2025a) making Jupiter the largest and highest-grade clay-hosted rare earth deposit in Australia (Figure 3). Metallurgical test work for the deposit is ongoing with the current established pathway to extraction of rare earth minerals from their clay host at Jupiter involving magnetic separation of iron-oxide gangue minerals and the flotation of REE-phosphates at room temperature. To date, this has resulted in an 830 per cent up-grade in REEs and 95 per cent mass reduction, producing a beneficiated REE product with a grade of 1.33 per cent TREO (Critica Limited, 2025b). The next phase of test work involves producing a mixed rare earth carbonate (MREC) from the beneficiated product.

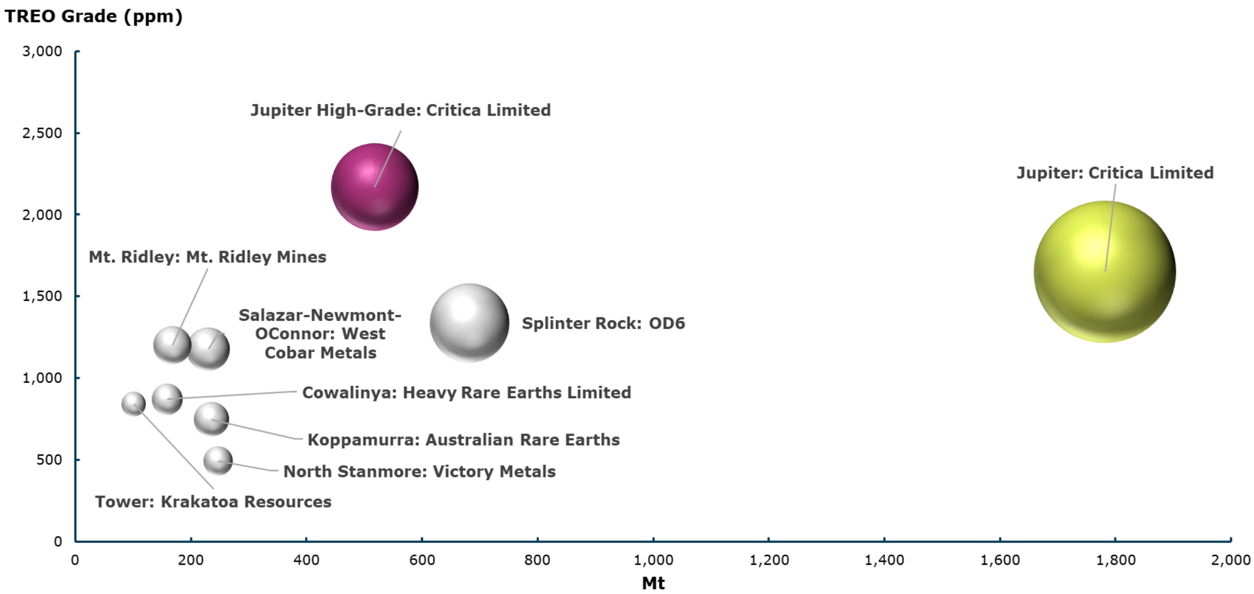

FIG 3 – Grade and tonnage of Australian clay hosted REE deposits.

GEOLOGY

The Jupiter deposit is located within the Archaean Murchison Domain of the Youanmi Terrane, Yilgarn Craton. The Murchison Domain comprises narrow belts of supracrustal greenstones, the large layered mafic–ultramafic Meeline and Boodanoo suite intrusive complexes in the east, and voluminous granitic rocks emplaced between c 2.7 Ga and 2.6 Ga (Watkins and Hickman, 1990).

The extensive granitic rocks are divided into the Cullculli Suite (tonalite-trondhjemite-granodiorite), Big Belle Suite (tonalite-monzongranite), Tuckanarra Suite (granodiorite-monzogranite), Jungar (K-feldspar-porphyritic monzogranites) and the Bald Rock Supersuite (monzogranite and fluorite bearing alkaline granite) (Mathison *et al,* 1991).

Geology of the Jupiter Deposit

The Archaean basement throughout the Jupiter area is generally deeply weathered and extensively covered by Cenozoic alluvial and colluvial sands and gravel, laterite and lateritic gravels on breakaways and uplands. The Jupiter REE deposit and associated intrusion itself is completely concealed by alluvial and colluvial sand and hardpan within an area previously interpreted to be underlain by Big Bell Suite granitoids (Ivanic *et al,* 2013). Regolith development is up to 100 m thick across the entire extent of the Jupiter geophysical anomaly that is extensively mineralised >1000 ppm TREO (Figure 4).

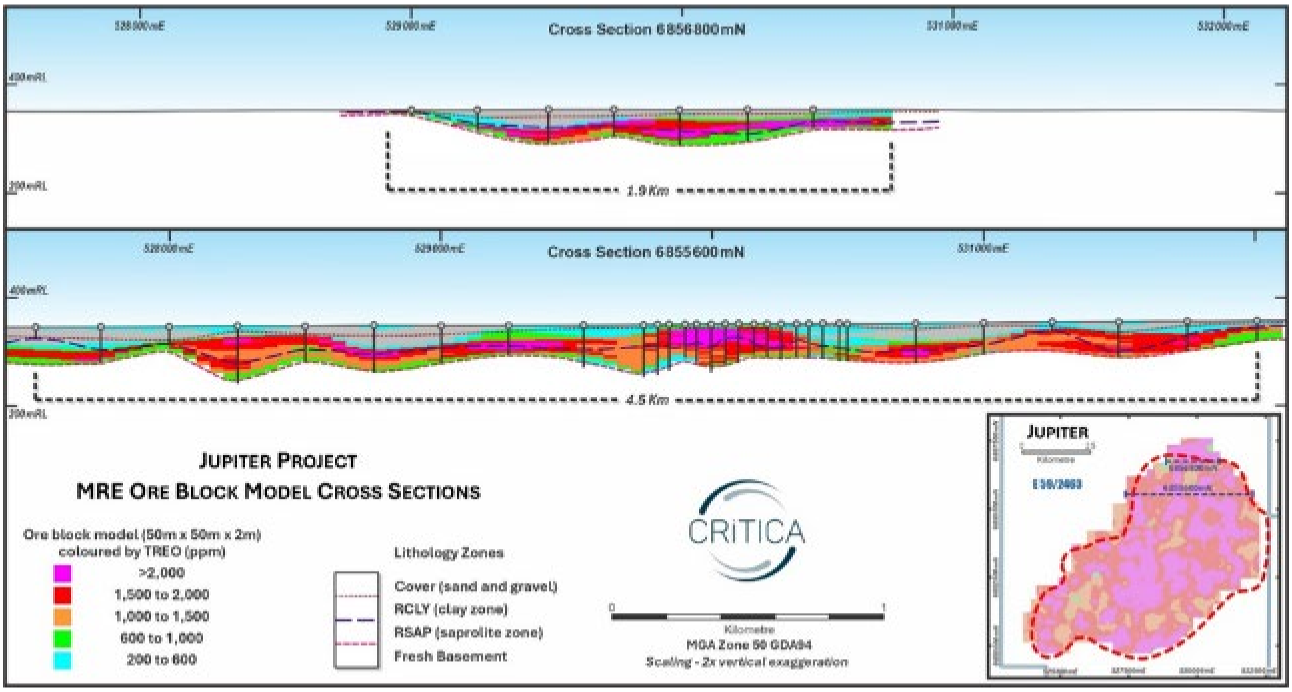

FIG 4 – Cross-sections through the Jupiter deposit (looking north).

The Jupiter regolith comprises of three main zones (Figure 5):

1. **Transported overburden:** 1–35 m thick. Alluvial and colluvial sands and gravel, extensively cemented and commonly laminated microcrystalline silica and lesser iron oxides. Gravel clasts comprise of largely deeply weathered granitoids, and vein or pegmatite quartz, while the sand comprises iron-oxide stained rounded to sub angular quartz. A well washed quartz sand or grit is present in many areas at the base of the transported cover.
2. **Upper saprolitic clay:** Up to 60 m thick. Kaolinitic clay with a variable content of sand-sized relict quartz reflecting protolith (which ranges from quartz-free syenite to granite). Colour ranges from white to dark ferruginous red brown, through to white or pink in the middle part of the upper saprolite (bleached) to yellow and brown in the lower part. An element of protolith control is also apparent with white and yellow kaolinite typically better developed over monzonite and granite protoliths with <20 per cent ferromagnesium mineral content, and red brown clays developed over monzonite, syenite and alkali gabbro with >20 per cent ferromagnesium mineral content.
3. **Lower saprolite:** Up to 40 m thick. Saprolitic clay with feldspar content increasing downhole, and depending on the protolith an increase of magnetite, biotite, amphibole, epidote and chlorite downhole towards fresh basement. Hyperspectral logging shows declining kaolinite

and increasing nontronite and relict primary phases towards base of the saprolite. Relict igneous minerals and texture is increasingly evident through the lower saprolite.

FIG 5 – Example of Jupiter clay-hosted mineralisation. Regolith development over Syenite (BRAC160).

The underlying basement, referred to here as the Jupiter Intrusive Complex, comprises a composite, zoned, strongly REE anomalous mainly alkali intrusive complex ranging from alkali gabbro through syenodiorite, syenite and quartz monzonite (Figure 6). Diamond drilling into the underlying fresh rock shows that the Jupiter Intrusive Complex has intruded the surrounding granite of the Big Bell Suite (Figure 6). Extensive weathering of the Jupiter Intrusive Complex means that the unit does not outcrop and has gone unidentified until the discovery of the Jupiter REE deposit. Geological logging coupled with extensive bottom of hole lithogeochemical sampling of all percussion and diamond drilling show the main lithologies of the Jupiter Intrusive Complex to be alkali gabbro, quartz monzonite, syenodiorite and lesser syenite (Figure 6). Granite derived from the Big Bell Suite is locally intersected and coincides with magnetic lows (Figure 2a).

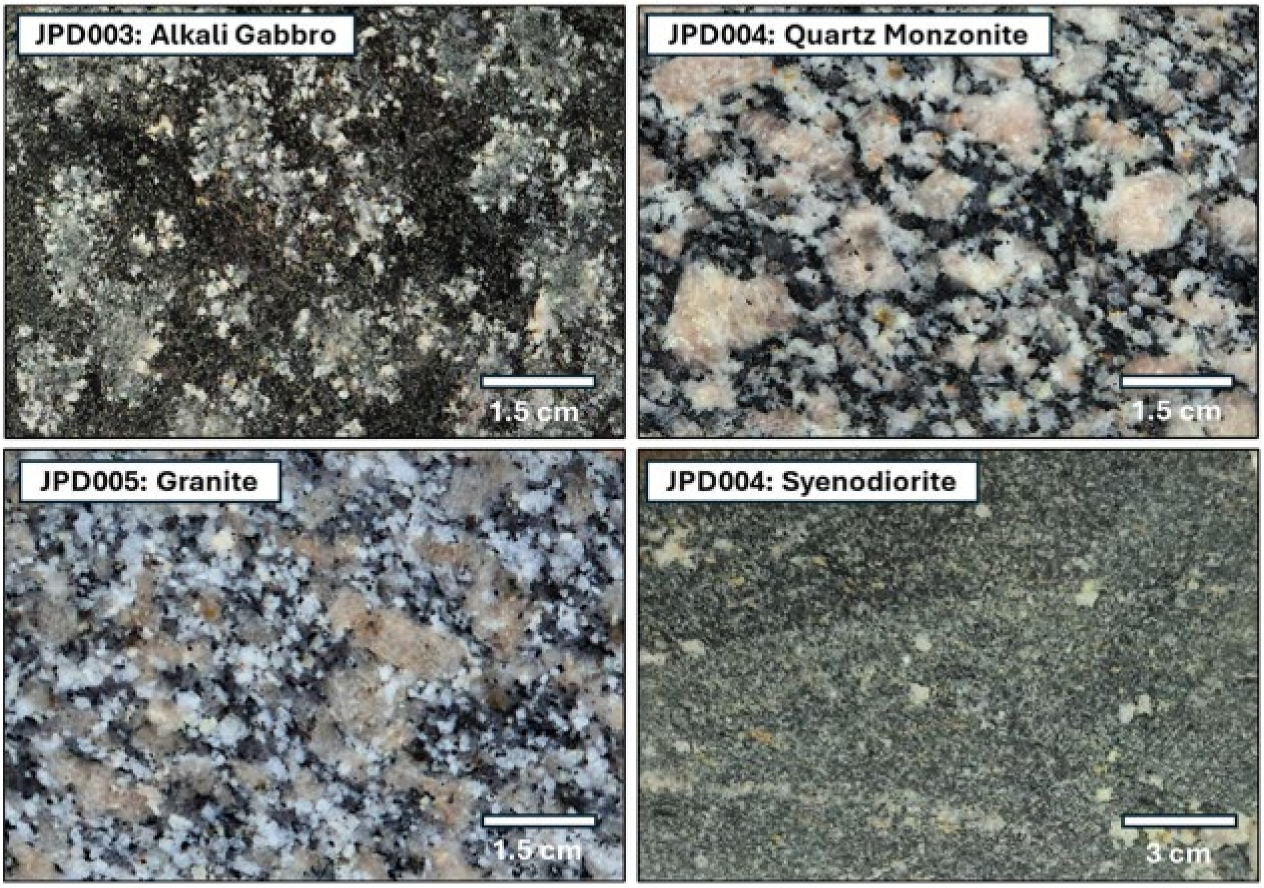

FIG 6 – Photographs of Jupiter fresh rock lithologies. Alkali Gabbro (JPD003:63 m), Quartz Monzonite (JPD004:96.6 m) and Syenodiorite (JPD004:99.1 m) of the Jupiter Intrusive Complex and Granite (JPD005:127 m) of the Big Bell Suite.

MINERALISATION

Clay-hosted REE and gangue mineralogy is typically very fine grained and requires microanalytic techniques to resolve. Currently, mineralised regolith samples from Jupiter have been analysed by TIMA (Tescan Integrated Mineral Analyser) to establish mineralogy (via a mineralogical library) and key grain size and liberation characteristics. Selected Jupiter TIMA samples were further analysed by LA-ICPMS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) and EPMA (Electron Probe Micro Analysis) to verify and determine the compositions of the TIMA identified REE phases and gangue minerals.

This microanalytical work shows the REE-phosphates Florencite-Gorceixite-Goyazite, Rhabdophane-Monazite and Xenotime to be the dominant REE phases in the Jupiter regolith. Florencite $(REE)Al_3(PO_4)_2(OH)_5(OH)_6$ – Gorceixite $(Ba,REE)Al_3(PO_4)(PO_3OH)(OH)_6$ – Goyazite $(Sr,REE)Al_3(PO_4)_2(OH)_5(OH)_6$ are hydrated phosphates with solid solution between barium, strontium and REE end members. Rhabdophane $REE(PO_4)(H_2O)$ is a hydrated form of monazite $REE(PO_4)$, and it is likely that hydrated forms of the identified Xenotime $(Y,HREE)PO_4$ will also be present. Dominant gangue minerals are quartz, magnetite, hematite, feldspar, kaolinite, epidote, biotite, muscovite, illite, chlorite, baryte, rutile, titanite, ilmenite, Mn-oxides, zircon and apatite (Figure 7).

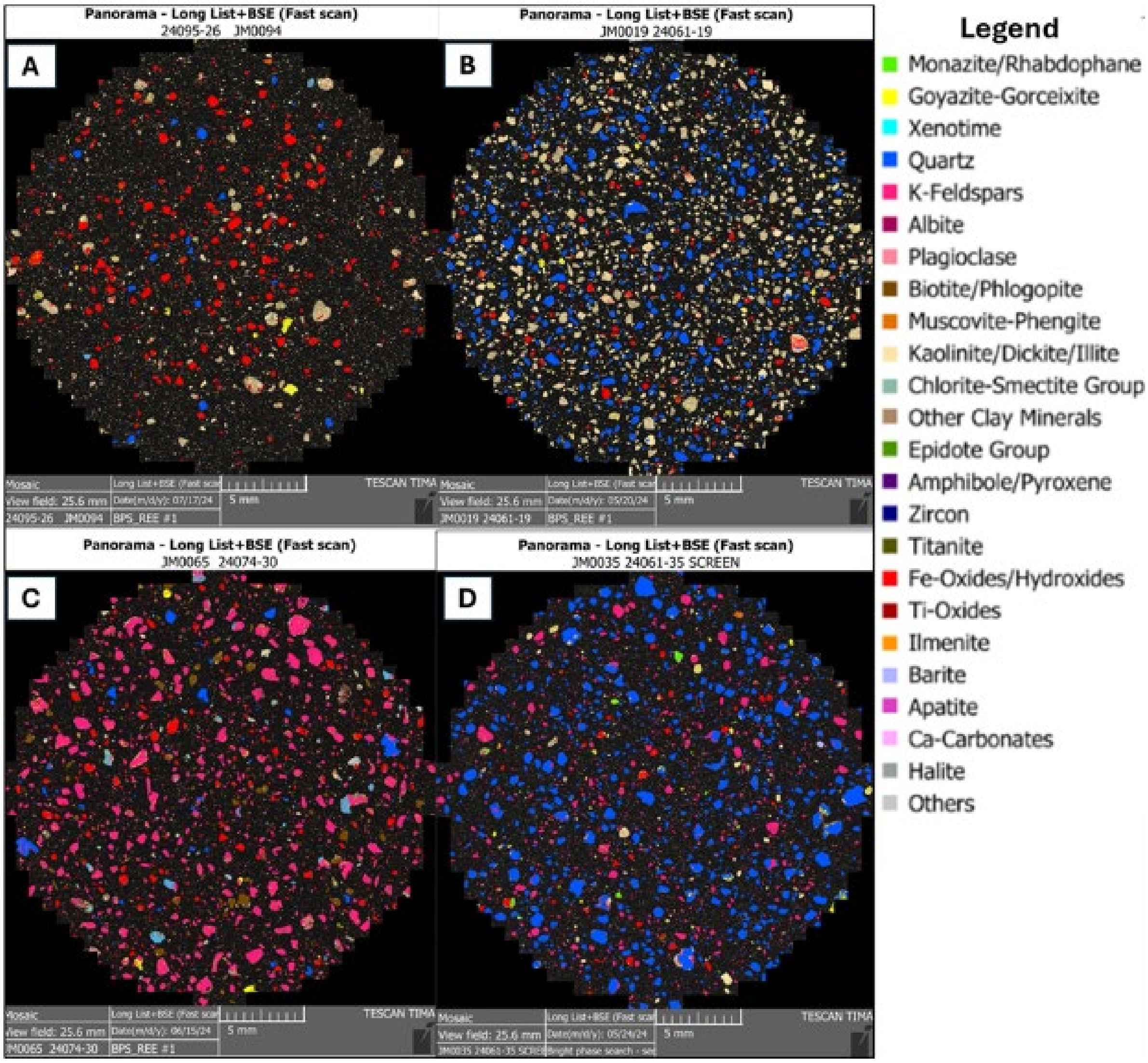

FIG 7 – TIMA images of examples of Jupiter clay-hosted mineralisation: (a) BRAC159: 28–32 m. Upper Saprolitic clay with kaolinite and Fe-Oxide gangue minerals. (b) BRAC047: 38–40 m. Upper Saprolitic clay with kaolinite, quartz and Fe-oxide gangue. (c) BRAC264: 60–64 m. Lower Saprolite with K-Feldspar and Fe-Oxide gangue minerals. (d) BRRC019: 36–38 m. Lower Saprolite with quartz and K-feldspar gangue minerals.

GEOCHEMISTRY

The drill samples (diamond and air core) were analysed at ALS Perth, WA. Samples were oven-dried, crushed and pulverised to P_{95} passing 75 µm, then assayed for a broad suite of minor and trace elements, including the REEs, by lithium borate fusion followed by acid digestion with an Inductively Couple Plasma – Atomic Emission Spectroscopy (ICP-AES) finish (ME-MS81) and four-acid digest on pulps with ICP-AES finish (ME-ICP61). Major elements were analysed by X-ray florescence (XRF) on fused discs with loss on ignition at 1000°C (ME-XRF26).

Diamond drilling of the fresh rock basement of the Jupiter deposit has identified several lithologies that have not been previously observed or identified within the Murchison domain. Geochemical analyses of the diamond drill core and published data from the Murchison Domain (Ivanic *et al,* 2013) are shown on a R1-R2 Plutonic Chemical Variation Diagram in Figure 8 and the TAS Plutonic diagram in Figure 9. The diagrams show the Jupiter Intrusive Complex plotting across the alkali gabbro, syenodiorite, syenite and quartz monzonite domains. Data from the Murchison Domain granitoids predominantly plot in the granodiorite, granite and alkali granite fields. Samples from the Big Bell Suite, including those intersected on the periphery of Jupiter also plot in the granodiorite, granite and alkali granite fields, confirming previous observations that the Jupiter Intrusive Complex is not part of the Big Bell Suite. Furthermore, REE primitive mantle plots of the dominant granitoid suites of the Murchison Domain and Jupiter Intrusive Complex are plotted in Figure 10. The plot shows significantly higher REE endowment of the Jupiter Intrusive Complex compared to other suites within the Murchison Domain.

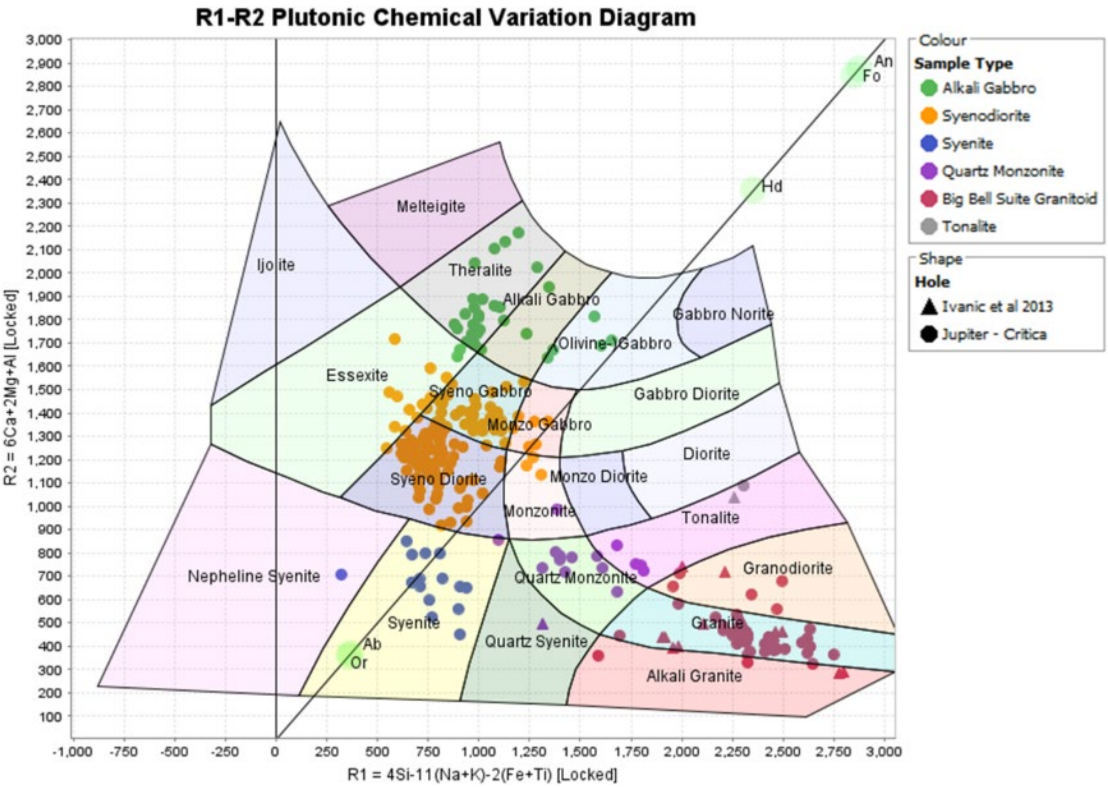

FIG 8 – R1-R2 Plutonic Chemical Variation Diagram (De La Roche *et al,* 1980) for the dominant suites of the Murchison Domain (Ivanic *et al,* 2013) and Jupiter Intrusive Complex.

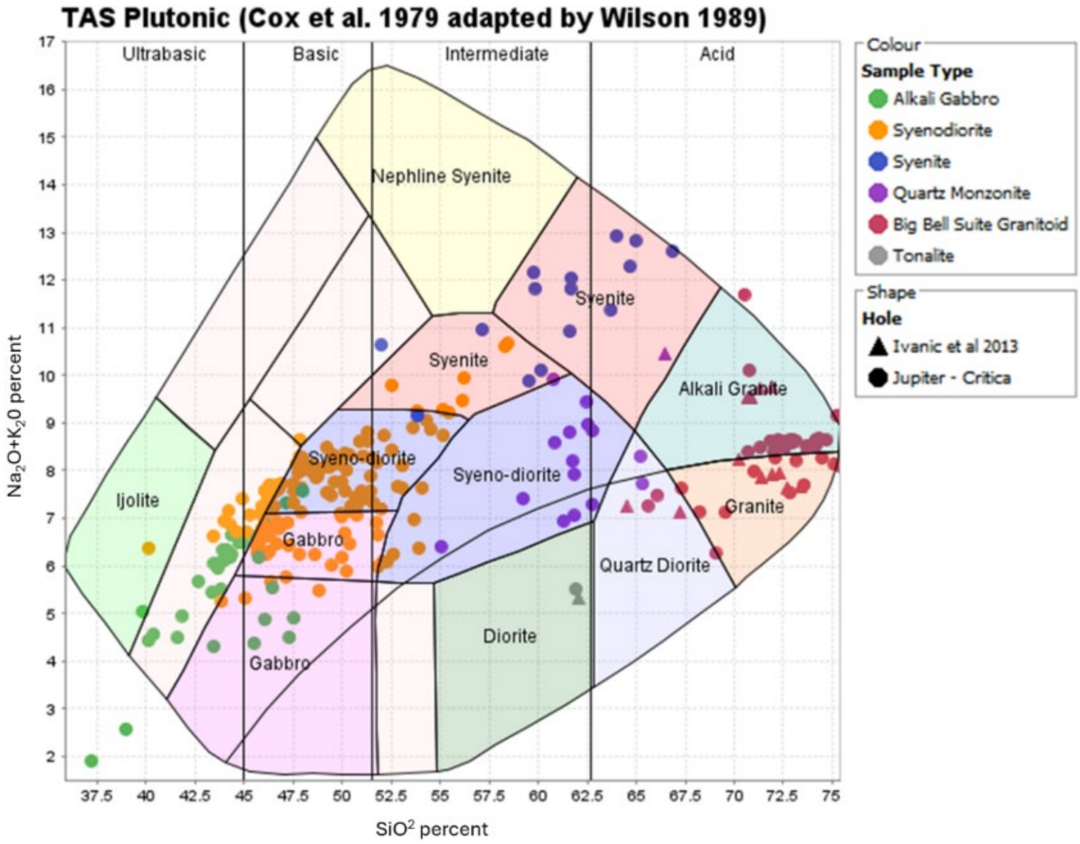

FIG 9 – TAS Plutonic Diagram (Cox, Bell and Pankhurst, 1979; adapted by Wilson, 1989) for the dominant suites of the Murchison Domain (Ivanic *et al,* 2013) and Jupiter Intrusive Complex.

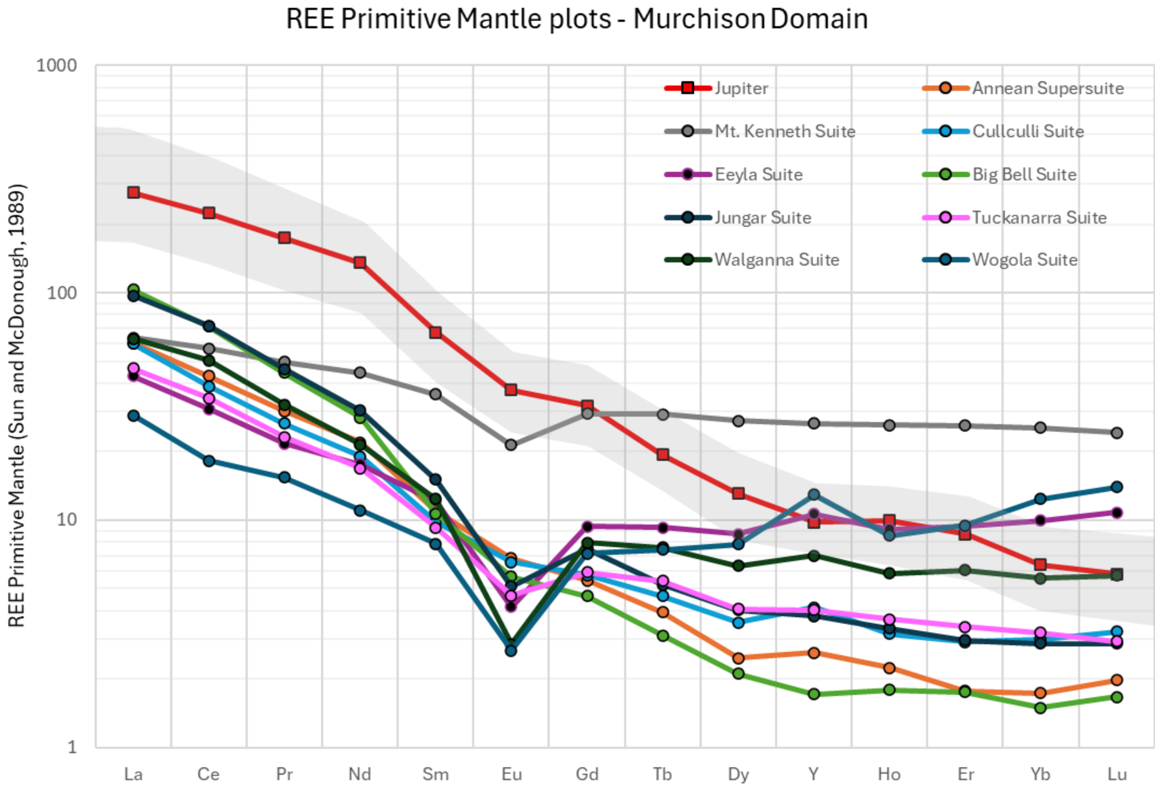

FIG 10 – REE Primitive Mantle normalised plots (Sun and McDonough, 1989) for the Jupiter Intrusive Complex and granitic suites of the Northern Murchison Domain (Ivanic *et al,* 2013).

CONCLUSIONS

The Jupiter target was originally identified by geophysics with coincident aeromagnetic and gravity anomalies coupled with anomalous rare earth element results from GSWA laterite geochemistry and two co-funded EIS drill holes drawing Critica geologists into the area. Subsequent exploration and drilling delineated a 40 km^2 footprint of thick (up to 100 m) clay-hosted rare earth mineralisation. In 2025, Jupiter became the largest clay-hosted REE deposit in Australia with an Inferred Resource of 1.8 Bts at 1700 ppm TREO at a cut-off grade of 1000 ppm TREO.

The underlying basement comprises a strongly REE anomalous composite intrusion ranging from alkali gabbro through syenodiorite, syenite to quartz monzonite and granite here referred to the Jupiter Intrusive Complex. These rock types are not typical of and were largely previously unknown within the Murchison Domain. Geochemical analyses of the Jupiter Intrusive Complex compared to the currently known suites of the Murchison Domain show Jupiter has, at this stage, a unique trend to silica-undersaturated alkali gabbro and syenite members and is significantly more endowed in rare earth elements than other granitoids of the Murchison Domain.

The presence of a previously unidentified REE endowed alkaline complex within the Murchison Domain highlights significant exploration opportunity for large, concealed, clay-hosted and fresh rock REE deposits within Western Australia. These deposits represent an opportunity to provide a long-term stable local supply of rock rare earth elements within Australia.

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Prospectivity analysis of critical mineral systems in Western Australia and the Mineral Systems Atlas

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ABSTRACT

Western Australia's *Battery and Critical Minerals Strategy 2024–2030* government-led strategy highlights the states potential for producing and processing minerals and elements essential to modern technologies and the global energy transition. However, exploration for these critical minerals remains challenging. To address this, the Geological Survey of Western Australia has developed the Mineral Systems Atlas (MSA), an online platform that compiles and disseminates spatial data to support exploration. The MSA enables the Critical Mineral Systems team to generate critical mineral prospectivity maps, which reduce search areas and enhances exploration efficiency.

The approach of prospectivity analysis for critical minerals uses a mineral system-based, data-rich, knowledge-driven approach to create predictor maps reflecting evidence of geological processes linked to mineralisation. Each predictor map is rasterised at 1 km cell resolution, with each cell being assigned a relative prospectivity value calibrated using a data set of harmonised assay results from exploration drill holes. Fuzzy logic is employed to combine predictor maps into a final prospectivity map. The results of these maps are tested against known critical mineral resources in Western Australia.

While this methodology has several limitations, including sampling bias, data density variability, and reliance on input data quality, the resulting maps show a strong correlation with known mineral deposits and highlight areas for further exploration, while considerably reducing the search area of the State. The predictor maps and final prospectivity map are published on the MSA allowing users to recreate the map or combine this approach with their own data sets.

Critical Minerals Group Lindfield Project case study – geology, exploration and vanadium resources

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ABSTRACT

Critical Minerals Group is an actively progressing development of the Lindfield Vanadium Project in Northwest Queensland. Located approximately 70 km north of the township of Julia Creek, the Project is covered by exploration permit EPM 27872. The Flinders Highway and Mount Isa Rail System, to the south of the project provides access (600 km to the east) to the Qld critical minerals processing hub at the Port city of Townsville.

Geologically, the Project is situated on the Euroka Ridge, a regional feature that separates the Carpentaria and Eromanga Basins. The Euroka Ridge is a major Proterozoic basement-high feature trending north-east between tectonic blocks of the Mt Isa Inlier Eastern Fold belt to the Georgetown Inlier. The Project mineralised material is stratigraphically hosted in the Toolebuc Formation.

Exploration drilling within across the Project area spans from the 1960s up to 2023. Within the Project, the geological database contained 95 exploration holes including 54 holes drilled by previous or surrounding explorers, 24 holes drilled and previously reported by CMG, and 17 exploration holes drilled by CMG in 2023. Drill hole grade sampling across the Project area spans from 1974 up to 2023. Associated to the Project and surrounding area the geological database contained 4951 samples across 415 exploration drill holes.

The Lindfield Vanadium Project mineral resources were estimated in accordance with the JORC Code (2012), as of 26 April 2024. The total estimated resources within the Lindfield Project is 713 million metric t (Mt) of vanadium mineral resource at 0.32 per cent V_2O_5 (wt%), 3.4 per cent Al_2O_3 (wt per cent), 130 ppm Mo.

CMG recently completed the Project Scoping Study. CMG is well progressed with the Lindfield Vanadium Projects PFS work, and looks forward to completing and publicly reporting the project updates prior to the upcoming Critical Minerals Conference.

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Nature as an asset – accounting for nature in the closure process

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ABSTRACT

Mining companies face a significant closure liability burden, with the total asset retirement obligations for the 24 largest mining companies reaching the equivalent of 42 per cent of the mining industry's long-term debt. Meanwhile, our natural environment underpins half the global economy, yet it remains undervalued and unaccounted for. As ecosystems collapse, so too does the economic stability they uphold. Capital markets are waking up to this reality, bringing nature onto the balance sheet not just to recognise risk, but to account for critical value. For mining operations approaching closure, the question is no longer if we must account for natural assets, but how?

Natural assets such as forests, rivers, soils and species, have traditionally been treated through a broadbrush approach to 'rehabilitation', overlooked in their value potential relative to technical assets and infrastructure. But what if we reimagined them as strategic assets, fundamental to post-mining value accretion? What if progressive, sustainable land transfer and stakeholder trust depended not only on technical remediation, but on nature's renewal? Forward-thinking companies are reframing natural assets as strategic value drivers in closure, not liabilities.

Acting for a nature-positive future can unlock capital, secure community trust, and leave an enduring legacy beyond extraction. To lead, companies must map, value, and integrate natural systems into closure planning. This means understanding the natural assets on and around site, understanding the flows of value they provide, and identifying opportunities for nature-centric opportunities in closure.

Recognising, enhancing, and transferring nature's value in mine closure demands a shift in thinking. The choice before us is stark: treat nature as an externality and be left behind, or treat nature as an asset class which, if sustained, can unlock capital, reduce liability, and leave a positive legacy that endures long after operations cease.

Lessons learned from graphite projects with beneficiation and purification

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ABSTRACT

The typical graphite found in nature has a low value however its value can be greatly enhanced if suitable as anodes in lithium-ion batteries. This paper has studied the methods of producing marketable graphite from a number of graphite ores. Graphite is a versatile material with diverse applications, including pencils, lubricants, batteries, and industrial processes. Its unique properties, like high thermal and electrical conductivity, make it suitable for various uses, from nuclear reactors to electrical motors. It is found in metamorphic rocks as disseminated crystal flakes, in veins and fractures. QEMSCAN is not applicable for graphite making liberation analysis difficult. Graphite is soft and can slime so grinding is often done in rod mills. It is naturally floatable requiring kerosene as a collector and sometimes sodium silicate as a dispersant. Achieving a high rougher recovery and thereafter uses multiple stages of regrinding and cleaning to achieve a typical 95 per cent total fixed carbon in concentrate (FC). Purification is required to achieve 99 per cent FC and can be difficult to achieve. Graphite spheroidisation is then required to make the graphite suitable as anode material for lithium batteries. A number of graphite projects are discussed and differences in mineralogy and difficulties in achieving a product that meets market specification.

Comparative analysis of narrower lamella spacing on performance of the reflux classifier – pilot and full scale results

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ABSTRACT

This technical paper presents a comprehensive analysis of a pilot trial and full-scale sampling conducted at a manganese beneficiation plant. This development in manganese beneficiation allows for improved recovery of manganese, an element essential for steel production and battery manufacture. The trial aimed to compare the performance and efficiency of two pilot-scale REFLUX Classifiers (RC300's) in recovering manganese sand (~P100 1180 µm). The existing Beneficiation Plant consists of five parallel full scale REFLUX Classifiers (RC2000s), each with lamella plates installed at 6 mm spacing. Operating data suggested the efficiency of separation is reduced for finer feed particles passing 300 µm, owing to the broad feed particle size distribution. Narrower spacing results in increased shear induced lift force between the lamella plates for enhanced gangue rejection as well as increased effective settling area for improved recovery of fine heavy particles (Galvin *et al,* 2020).

The pilot trials aimed to compare the difference in performance between 3 mm and 6 mm lamella plate spacing by taking feed directly from the beneficiation plant feed and operating two RC300's in parallel with each other. One RC300 was installed with 6 mm spaced lamella plates and the other was installed with 3 mm spaced lamella plates. Each RC300 was operated with the same operational set points, and the product and rejects streams sampled to determine the differences in separation efficiency. The successful trial indicated that between a 4.7 to 8.8 per cent manganese recovery improvement could be expected by switching to the 3 mm spaced plates. An average absolute recovery improvement of 9 per cent was measured at full scale.

This paper discusses the pilot plant experiment set-up, test work methodology, data collection, analysis, and statistical assessments use to compare the performance of 3 mm and 6 mm lamella spacing to make a recommendation about the viability of retrofitting the existing RC2000s with 3 mm spaced plates as well as full scale results following the full retrofit.

INTRODUCTION

The REFLUX Classifier (RC™) is a mineral separation unit operation. It effectively separates fine particles based on differences in density or particle size. The RC integrates a conventional fluidised bed separator with a system of parallel inclined plates, forming lamella channels. The design of the lamella chamber and the introduction of a fluidising medium contribute to the efficiency and accuracy of the mineral separation process.

South32's GEMCO 'PC02' plant operates 5-off reflux classifiers in parallel to recover manganese from the manganese concentrator sand tails, both online from the primary concentrator and from historical sand tailings dams.

The reflux classifiers at GEMCO were originally supplied in 2016 with 6 mm spacings in the lamella chambers, however test work completed by the University of Newcastle (2022) suggested that an additional recovery benefit of ~10 per cent Manganese could be obtained by changing to 3 mm plates. Whilst the lab-scale test work showed promising results with respect to manganese recovery, the test work did not replicate the product grades required in the production plant, so a decision was made to pursue an in-plant, side-by-side trial of two reflux classifier pilot units where the performance of the 3 mm and 6 mm plates could be directly compared.

The main objective of the trial was to assess the potential benefits of using 3 mm spacings on manganese recovery. The study also compared the performance of both pilot scale units to the performance of the production plant, to ensure the results would be scalable to a production environment.

The full-scale commissioning trial was performed on the real-time feed from the sand tailings dam after changing all five RC's with 3 mm lamella plates. The study compared the recovery uplift with 3 mm lamella spacing GEMCO RC units. In addition, the study on the particle size analysis was performed to understand the recovery uplift.

Pilot plant – 3 mm versus 6 mm lamella plate testing

Pilot plant experimental set-up

The reflux classification trial was conducted using two pilot-scale (RC300) classifiers in parallel, using feed material sourced directly from the pump discharge of one of the production-scale reflux classifiers (see Figures 1 and 2). The classifiers were operated with identical operating conditions, including feed rate (5.3 m^3/h), fluidisation water flow (2.6 m^3/h), and bed density (1.9–2.2 SG as dictated by feed grade to achieve the final concentrate grade ~40 per cent Mn).

Samples were collected from a common feed bypass line, product lines and tailings lines. All of which were continuously discharging into the underflow hoppers during each test. After filling the units and establishing stable bed density, samples were collected during each test (~1 hr per test) by manually 'cutting' each of the flowing pipes with a bucket at ~ 6 min intervals. As far as practicable, this was the most cost-effective way to obtain reasonably representative samples without installing automatic sample cutters on the pilot units.

If there was an upset condition in the production plant during the test, the test was abandoned.

FIG 1 – Pilot RC300 units – 3 mm and 6 mm units side by side.

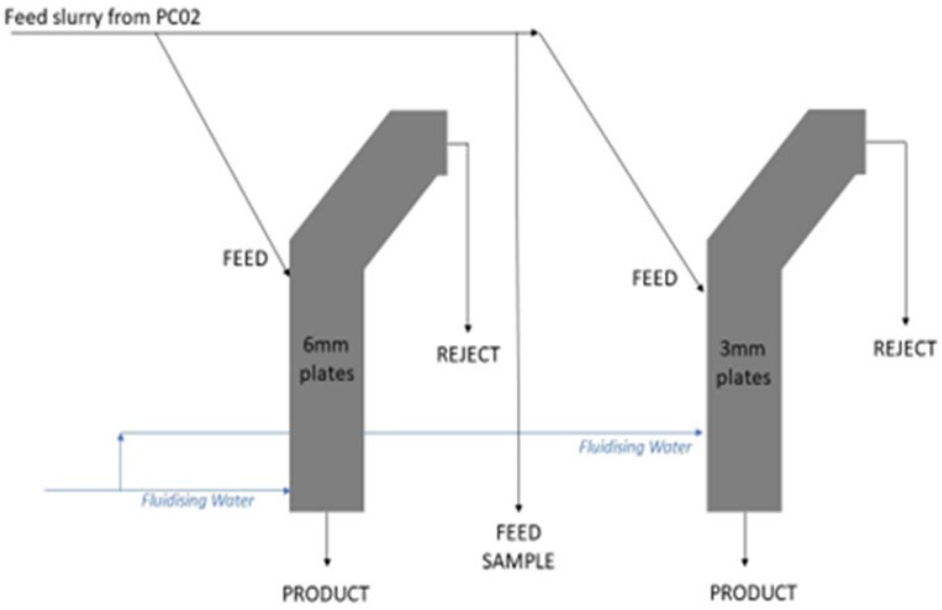

FIG 2 – Pilot plant set-up.

Challenges in pilot plant control

The feed and fluidisation water were controlled by manual ball valves, and the bed density was controlled via PID loop controller with local PLC. As there was no automatic control of the feed and fluidisation water, there was some unavoidable variation in these flows (especially the feed) over the duration of each test. This is not considered 'optimal' operation as performance is related to volumetric flow-through the classifier. Every effort was taken to ensure the feed rate was as stable and as close to the required set point as possible.

Performance comparison

The analysis of the trial results revealed notable differences in the performance of the two classifiers. Classifier A, with 3 mm lamella spacings, demonstrated a higher separation efficiency and improved manganese recovery compared to Classifier B, with 6 mm lamella spacings – results reported in Table 1.

TABLE 1

Average results for 3 mm and 6 mm lamella spacings (paired test only, n = 28).

Average	3 mm	6 mm	Sig (Y/N)
Feed grade (%Mn)	18.95		N/A
Product grade (%Mn)	39.7	38.3	Y
Rejects grade (Mn %)	13.1	14.2	Y
Recovery (%)	46.1	39.8	Y

The results were assessed both in terms of final rejects grades and recovery (as calculated by the two-product formula) and assessed for significance using a paired t-test (95 per cent confidence).

The results show a net difference in recovery of 7 per cent, however the results also showed that each test achieved slightly different product grades, with the 6 mm plates achieving a below specification product grade.

As previously discussed, the feed flow control to the pilot units was challenging, so the minor difference in product grade was not concerning. If the pilot plants had better product grade feedback (ie run continuously for long periods) and could more reliably achieve the required 40 per cent product grade, it is expected that the rejects grade from both tests would be marginally higher with an even larger performance difference.

Comparison with production performance

The secondary reason for undergoing pilot test results, was to have confidence that the pilot results would be replicable in full scale (hence the 6 mm and 3 mm side by side comparison).The results show that after adjusting for the difference in product grade, the 6 mm pilot plant achieved marginally poorer recovery performance compared to the production scale plant, while the 3 mm plates achieved better performance than the production plant (Figure 3). An ANCOVA assessment showed that these differences were statistically significant (Figure 4), with the 3 mm plates achieving an average adjusted recovery of 53.1 per cent at 21.3 per cent Mn Feed, versus 6 mm production at 48.4 per cent and 6 mm pilot at 44.3 per cent.

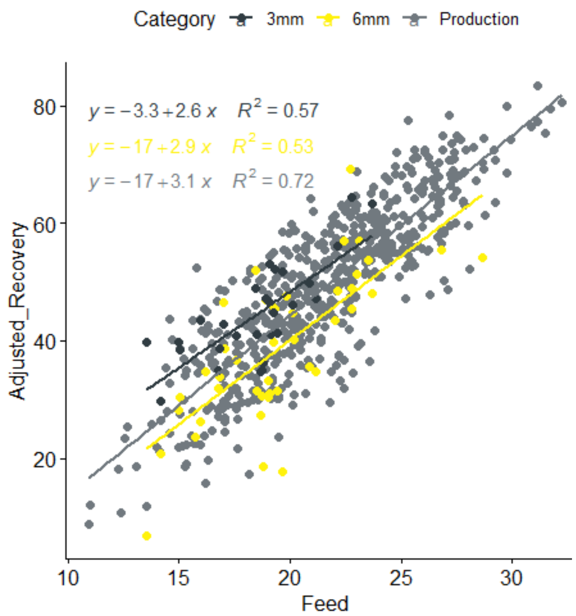

FIG 3 – 3 mm, 6 mm pilots compared to 6 mm production.

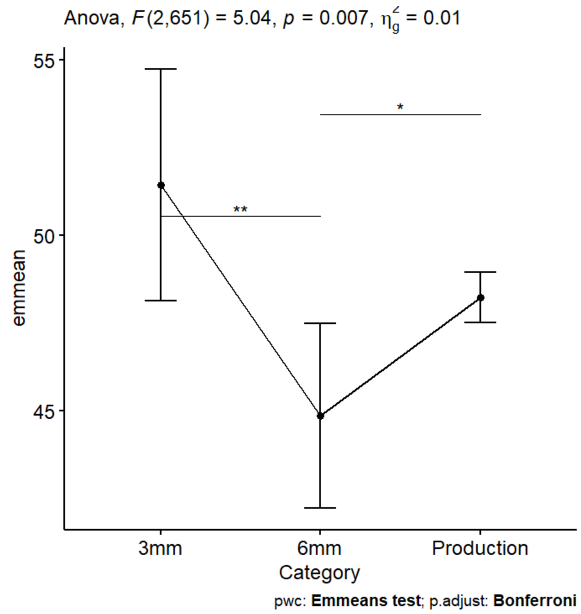

FIG 4 – ANCOVA results comparing both pilots and production data.

Technical discussion of results

The results achieved in the pilot trials are consistent with the technical understanding of the effect of decreasing the lamella spacings:

- Improved Particle Stratification: Narrower spacings allow for increased velocity gradients and therefore stronger shear induced lift force for lifting and transporting gangue to the overflow. As a result, the coarser and denser particles settle more quickly and are effectively separated from finer and less dense particles.
- Enhanced Separation Efficiency: Narrower spacings provide more lamella channels within a given area, increasing the total surface area available for particle settling. The additional surface area allows for greater interaction between particles and the inclined plates, facilitating more efficient separation. This increased separation efficiency leads to higher recovery rates and improved overall performance of the reflux classifier.

Whilst the 6 mm pilot plant was not able to perfectly replicate the 6 mm production scale results, it was accepted that the variability of the manually controlled feed rate to both pilot plants could have contributed to a slight degradation of performance. Full scale RC units have been recorded outperforming pilot scale units elsewhere.

The minor differences in product grade were attributed to short-term tests with no grade feedback, so the bed set points could not be 'dialled in' as they would under production conditions. After adjusting the results for the difference in product grade, the 3 mm plates showed an 8.8 per cent recovery improvement over the 6 mm plates.

The 6 mm pilot results were acceptably close to the production performance, and the difference between the two side by side pilots (which both had the same control challenges) was significant enough to progress to a full-scale installation.

3 mm lamella plate full scale commissioning trial

The PC02 plant commissioning trial was performed on the tailings dam feed. The average dam feed grade was 22 per cent Mn. The site installation is pictured in Figure 5.

FIG 5 – RC2000 Full scale units at GEMCO.

The main objectives of the 3 mm lamella plate commissioning trial were:

- Evaluate plant performance post installation of 3 mm lamella plate under high clay feed condition and test the reliability of plant equipment and functionality of control systems following the extended outage post tropical cyclone Meghan.
- Determine the overall Mn recovery and compare with the historical recovery using 6 mm plate spacing.
- Determine the recovery of finer fractions (-300+212 μm and -212+150 μm) and compare with historical.

Sampling

- The main sampling streams were dam feed (SA101), plant feed (combined feed stream of tailings dam feed and online feed from concentrator) (SA501), reject (SA502), product to Bin601(SA601) and product to emergency stockpile. All the streams are equipped with auto samplers except product to emergency stockpile. The sampling frequency was 2hrs for each stream. Sampler cutter frequency was set to 10 mins.
- All the samples were analysed using the XRF unit in GEMCO lab.
- Shift composites for each stream were prepared by combining subsample of each individual sample. Size by assay analysis was conducted on shift composite to calculate Mn recovery from each size fraction.

Challenges in the commissioning trials

- The feed rate was impacted due to the high clay content. Additionally, feed rate was also affected by ROM stockpile compaction from heavy vehicle traffic. Frequent maintenance on the frontend loader and longer travel distance between feed bin and ROM stockpile affected feed rate when the feed bin ran empty. This is not considered optimal operation as plant performance is dependent on the volumetric flow-through the classifier.
- The frequent but short plant downtime periods due to the feed preparation screen (SC501) blocked chute affected the plant performance and made it difficult to achieve a steady state run at times. Above average clay concentration in the dam feed was the cause of these blockages.
- Every effort was taken to stabilise feed rate as close to the set point as possible. Moreover, the plant operator was inspecting and hosing the SC501 more frequently to minimise blockages to maintain steady plant operation.

Methodology to compare 3 mm and 6 mm Lamella plate performance

The feed size distribution on which RX's fitted with 6 mm lamella plate operated in the past (including during the pilot trials) is different than 3 mm lamella plate full-scale commissioning trial feed.

Comparative plant data (Jan 2022–May 2023) for the 6 mm lamella plate feed contained 65 per cent ore above 300 μm compared to 48 per cent for 3 mm lamella plate commissioning period. In addition, 9 per cent of total feed with the 6 mm lamella plate reported below 150 μm compared to 27 per cent of total feed during commissioning trial. This is a significant increase and indicative of the higher concentration of ultrafine material in feed during commissioning.

A finer feed particle size distribution increases the difficulty of the separation; hence it would be expected that without changing the lamella spacing, performance would decrease with the new feed size distribution.

Based on the historical sizing data, individual fraction's Mn recovery for 6 mm lamella plate was calculated. The fractional recovery of 6 mm lamella plate was directly compared with fractional recovery of 3 mm lamella plate to find out the recovery uplift and the size fraction where the improvement was achieved. Due to the similar feed %Mn distribution between -300+212 μm and -212+150 μm fractions, the direct recovery comparison between 3 mm and 6 mm plates became possible. Table 2 shows the feed size distribution for 3 mm and 6 mm lamella plate feed.

TABLE 2

Feed size distribution comparison.

Screen sizes (μm)	**Feed %Mn distribution**	
	6 mm (historical)	**3 mm commissioning trial**
+300	65%	48%
-300+212	15%	14%
-212+150	11%	11%
-150	7%	8%
-106	2%	19%

Results and discussion

The size by assay analysis of the trial results revealed significant improvement in the Mn recovery using RX with 3 mm lamella spacings compared to 6 mm lamella spacings. The most notable improvement in the finer fractions (-300+212 μm and -212+150 μm) recoveries have been observed with 3 mm lamella spacing over 6 mm spacing. Moreover, it is confirmed after careful analysis that neither plate size can recover Mn below 150 μm, due to the very wide feed particle size distribution.

Table 3 shows the fraction recovery improvement using 3 mm lamella spacings in comparison with 6 mm lamella spacing.

TABLE 3

Size fraction's recovery comparison, 3 mm versus 6 mm lamella plate.

Screen sizes	**Recovery**		**Recovery improvement**
	6 mm	**3 mm**	
+300 μm	66%	74%	8%
-300+212 μm	26%	44%	19%
-212+150 μm	6%	24%	18%

Table 4 shows the overall recovery has been calculated from the fractional recovery which shows 9 per cent improvement in the Mn recovery.

TABLE 4

Commissioning trial Mn recovery comparison, 3 mm versus 6 mm.

	Screen sizes	%Mn distribution Feed	Recovery of individual size fractions	Overall recovery contribution by size fraction	Overall recovery
6 mm plate estimated recovery on trial feed	+300	48%	66%	31%	36%
	-300+212	14%	26%	4%	
	-212+150	11%	6%	1%	
	-150	8%	1%	0%	
	-106	19%	0%	0%	
3 mm plate recovery (from the trial sizing data)	+300	48%	74%	35%	45%
	-300+212	14%	44%	6%	
	-212+150	11%	24%	3%	
	-150+106	8%	7%	1%	
	-106	19%	0%	0%	

CONCLUSION

Based on the results, it is concluded that 3 mm lamella spacings in the production-scale plant shows 9 per cent absolute improvement in the Mn recovery compared to 6 mm spacing – correlating to a 25 per cent relative improvement. In addition, the commissioning trial results aligned with the initial results obtained from the lab test work at University of Newcastle (claimed 9 per cent recovery improvement) and pilot plant test work (claimed 8.8 per cent recovery improvement). In addition, commissioning trial proves that the narrower spacing provides improved particle stratification and facilitates superior separation efficiency, resulting in higher overall recovery. After several months of operations, no blockages of the lamella plates were experienced.

ACKNOWLEDGEMENTS

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Quantifying spodumene and classifying pegmatite using core photography – how, why, and its use in resource estimation

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ABSTRACT

In recent years, there has been particular interest in the raw materials required for lithium-ion batteries: nickel, cobalt, manganese, graphite, and lithium. Demand for these raw materials is expected to grow markedly in the coming decades, providing a potential economic opportunity for those developing countries with appropriate resources. While there is an obvious need for geologists, mineralogists, metallurgists, economists, and environmental experts to work together to identify and develop the best resources of all these raw materials, Artificial Intelligence (AI) is playing an increasingly important role in rapidly boosting the capability of the geologist, ultimately aiming to efficiently develop orebody knowledge.

Machine Learning (ML) is a branch of AI that aims to build models to iteratively learn from data, finding insights and structure without being explicitly programmed on where and how to look. This paper describes two types of ML models – segmentation and classification – built to quantify spodumene crystals and classify pegmatite texture using good quality, high-resolution core photography, from diamond drilling on the Goulamina pegmatite lithium deposit.

The segmentation model identifies individual spodumene crystals, visible in diamond core photos, providing quantitative information on the size, shape, area and colour – all key to understanding the mineralogy. The classification model defines the pegmatite as coarse-, medium- and fine-grained pegmatite. Both the combined quantification of spodumene crystals, and pegmatite texture classification, provided foundational data sets not previously manually logged by geologists on-site. Indeed, once these models were trained on known examples, they were rapidly applied across diamond core photography taken across the entire deposit.

We discuss why and how these models were trained, how the results have improved knowledge of the orebody, and their potential use in resource estimation.

INTRODUCTION

While global lithium demand forecasts vary, most indicate strong and sustained growth, driven largely by rechargeable battery use in electric vehicles and energy storage systems. This increasing demand has placed greater importance on the efficient exploration and characterisation of lithium-bearing deposits.

Unlike the brine-based reserves of South America, high-grade lithium resources, such as those in the Goulamina deposit in Mali, are extracted through hard rock mining, primarily as spodumene. This context underscores the value of applying advanced tools, such as ML models and core photography analysis, to better understand orebody characteristics and support resource estimation in hard rock lithium projects.

WHAT IS SEMANTIC SEGMENTATION IN GEOSCIENCE?

Semantic segmentation is a computer vision technique used to classify and localise objects within an image by assigning each pixel to a defined category using a segmentation mask. Unlike instance segmentation, which identifies individual objects, semantic segmentation focuses on pixel-level classification of image classes.

In geoscience, this technique can be applied to high-resolution core photography, typically captured with a standard DSLR camera, to automatically identify geological features such as veins or minerals. For lithium deposits, where crystal boundaries are clearly visible, machine learning models can extract detailed quantitative information including grain count, shape, colour, area, and axis ratio relative to the core. This paper presents an example of mineral segmentation applied to spodumene ($LiAlSi_2O_6$), a lithium-bearing pyroxene commonly found in pegmatites.

FROM CORE PHOTO TO ANALYTICS-READY IMAGERY

In order to extract quantitative insights from core imagery, including semantic segmentation, Datarock requires preparatory steps to ensure imagery is fit for purpose. The Datarock Core software includes Data Manager, Processing and Depth Registration steps to create analytics ready imagery for any additional products and processing. Depth Registration is essential for accurately assigning depths to core images (Figure 1). This allows for precise identification of geological structures and facilitates reliable comparison and calibration with other downhole data sets, such as assays.

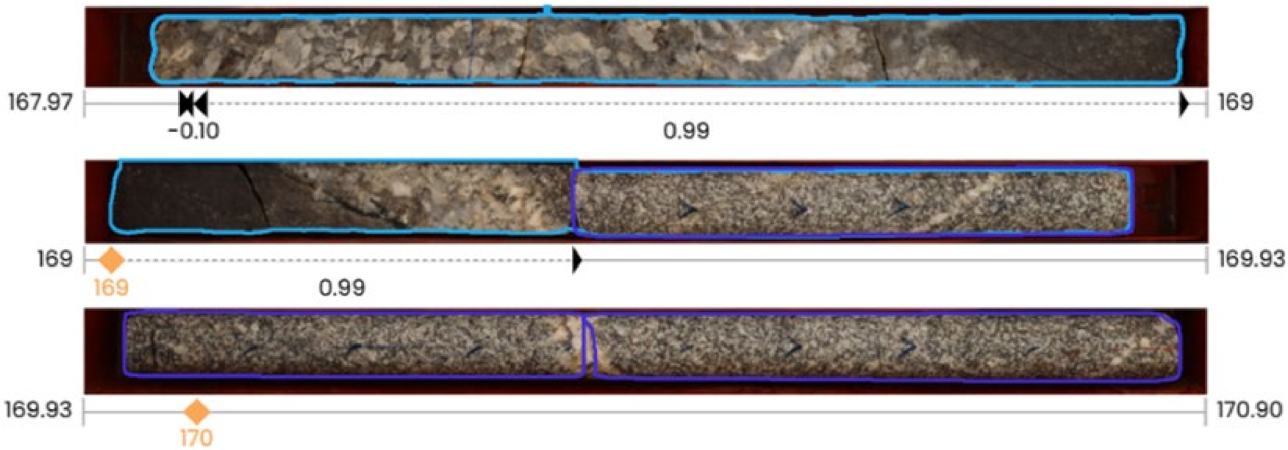

FIG 1 – Examples of depth-registered rows and their assigned depths.

The drill core that was photographed on-site was uploaded to the Datarock Core software and preprocessing and depth registration models run – the core tray gets cropped, empty row spaces and core blocks are recognised, and coherent and incoherent rock measured and depth registered with a depth stamp every 1 m interval. A total of ~7000 m of core imagery was processed in 45 mins, at a speed of 150 m per min.

HOW TO TUNE A SEGMENTATION MODEL

Geological features are able to be segmented from core photos through a process called labelling. Essentially, features of interest are manually labelled in third-party software using polygons to teach a machine learning model what is of interest (Figure 2). The best results are obtained when internal geologists work closely with customer geologists to manage a process where images are selected to be labelled to represent feature variability across the entire deposit. Training and test data are separately labelled to evaluate model performance across the test data set for each iteration of the model.

From a raw core photo… to manually labelled spodumene crystal polygons.

(a)

(b)

FIG 2 – (a) Raw core photo; (b) raw core photo showing manually labelled spodumene crystal polygons.

Usually, several iterations of labelling, training and evaluation are undertaken to address any encountered false positives and negatives in the model outputs. Occasionally, similar looking gangue minerals, alteration, and image glare or dry patches on core can cause model confusion which can be addressed by providing examples of these to the model to teach it to ignore unwanted features. Model predictions were also tested across multiple drill holes to ensure masks are performing as expected.

To date, most customer segmentation models have focused on vein detection in core imagery. This ranges from any vein visible (semantic segmentation) to multiple individual vein types (instance segmentation). Quartz, sulfide, asbestiform minerals, and different vein textural styles have all been delineated in the past.

At the Goulamina deposit, a proof of concept was devised to experiment detecting individual spodumene crystals within the core imagery intervals provided. The customer communicated that albite and quartz gangue material closely resembled spodumene and some spodumene exhibited diffuse boundaries which were identified as areas of potential model confusion. Version one of the training and test data focused on labelling large spodumene crystals with defined boundaries (not diffuse hydrothermal alteration), clear striation, characteristic 'pale pistachio' colouration, and containing visible pitting in crystals to initiate the process with minimum confusion.

Version 1 training results (Figure 3) showed generally good detection of spodumene and differentiation from other minerals. There was an understandable tendency to lump clusters of spodumene instances as one crystal, especially where diffuse boundaries between crystals were apparent. The image below shows ground truth (manually labelled image) and the model predicted result on the test data (the training model does not see test images).

FIG 3 – Version 1 of the training results showed good detection of spodumene and differentiation from other minerals.

Version 2 training addressed false positives by refining spodumene labels and adding non-target minerals for negative reinforcement. Increased image resolution and training epochs improved crystal boundary detection, and post-processing filters were applied to separate intergrown grains.

At this point, experimentation with machine learning tools and parameters were integrated to further refine crystal detection. These refinements included:

- Training stage:
  - Increased row width resolution to 2128 pixels (3-step increase from default for veining) to highlight finer details in imagery. Low resolution results in lumping lots of fine crystals.
  - Increased number of epochs to 100 to increase the amount of times the model is trained over the same imagery. With increased resolution applied, more iterations of grain training is needed for finer segmentation to prevent lumping.
  - Applied 'erosion' to crystal masks to further define edges of individual grains where possible and reduce the clustering effect of finer or intergrown crystals (Figure 4).

(a)

(b)

FIG 4 – Images showing before and after crystal erosion was applied: (a) before crystal erosion applied (polygon clustering); (b) after crystal erosion applied (separates polygon clustering).

- Post-processing modifications applied:
  - Optimise bleb filtering to retain small crystal predictions.
  - Optimise gap filling and instance merging (could contribute to lumping).
- Inference modifications applied:
  - Class splitting (spodumene (small), horizontal, vertical) to allow for a measurement proxy to the bottom of the core row to be taken.
  - Extra statistics – RGB values, average roundness, average size, crystal area bins were extracted specifically for the customer.

Ultimately, not all predictions of spodumene were resolved, but an upside was that smaller spodumene grains were detected using the same texture and colour patterns (Figure 5).

(a)

(b)

(c)

FIG 5 – (a) Clustering effect for finer intergrown spodumene unable to be fully resolved; (b) Clustering occurred on predictions with diffuse edges. More examples of altered and etched spodumene were trained into the model with good detection; (c) Upside-smaller unlabelled material detected based on texture and colour recognition beyond what was labelled.

NEW OUTPUTS FOR THE SEMANTIC MODEL

Additional statistics were developed that had not previously been generated. They included:

- spodumene grain average size
- spodumene grain average roundness/shape
- spodumene area breakdown per interval (ie all grains, <5 cm^2, <10 cm^2 etc)
- class splitting – spodumene (small), spodumene_horizontal, spodumene_vertical
- colour (RGB) values of spodumene.

Each statistic is discussed further here.

Spodumene grain average size and count were requested to better understand the distribution of spodumene grain size across the deposit and better account for recovery issues associated with grinding size. Figure 6 shows a clear correlation between lithium assays and average spodumene grain size (cm^2) and grain count.

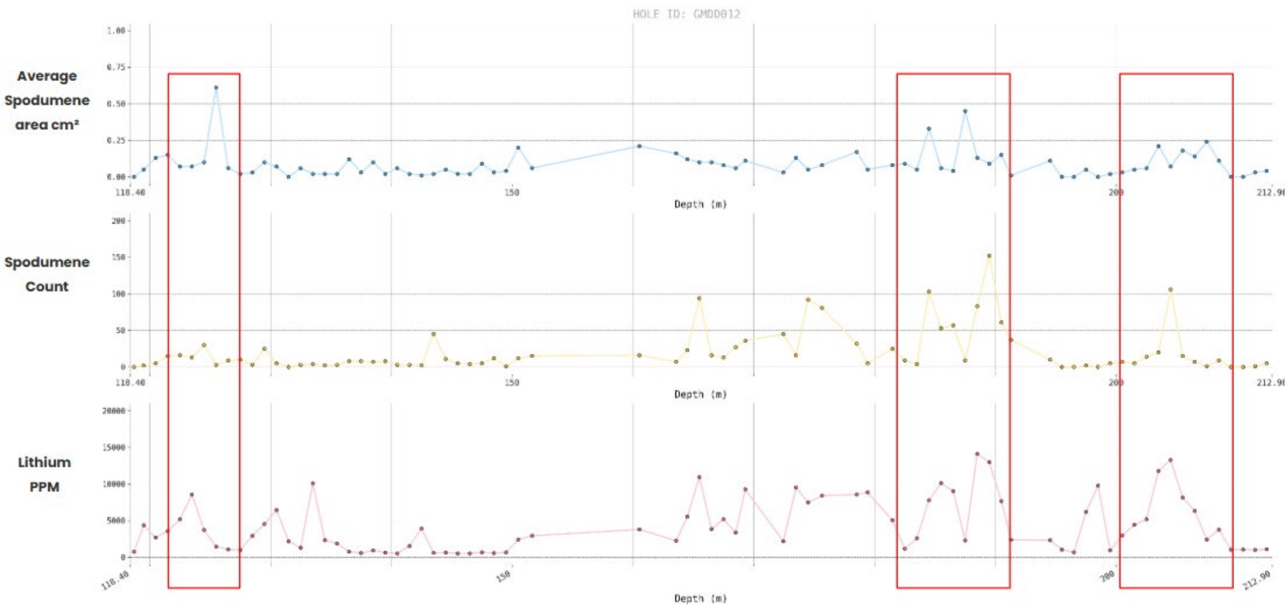

FIG 6 – Comparison of average spodumene grain area (cm^2), spodumene grain count and Lithium mg/kg (ppm) for drill hole.

Spodumene grain average roundness/shape (axis ratio calculation) was requested to better understand characteristics of spodumene grains that may affect lithium grade. When plotted, no significant orientation preference for Spodumene crystals were observed.

Spodumene grain area bins were requested to help identify populations of spodumene grain sizes within pegmatite sills to help further define grade domains.

Class splitting was used to test whether there was a preferred spodumene grain orientation. This was hypothesised as a preferred cooling event or zonation. All grains that were too small or round were reclassified as 'spodumene' and an angle was not calculated. Only elongate grains were measured as 'spodumene_horizontal' or 'spodumene_vertical' relative to the core axis.

Colour (RGB) values were calculated on each detected grain to identify if spodumene colouration was affected by alteration zonation or any other key associations to lithium grade. Downhole plots for three RGB channels per grain are shown below per core row instance (Figure 7). Inconsistent core photography colours were deemed to skew colour interpretation.

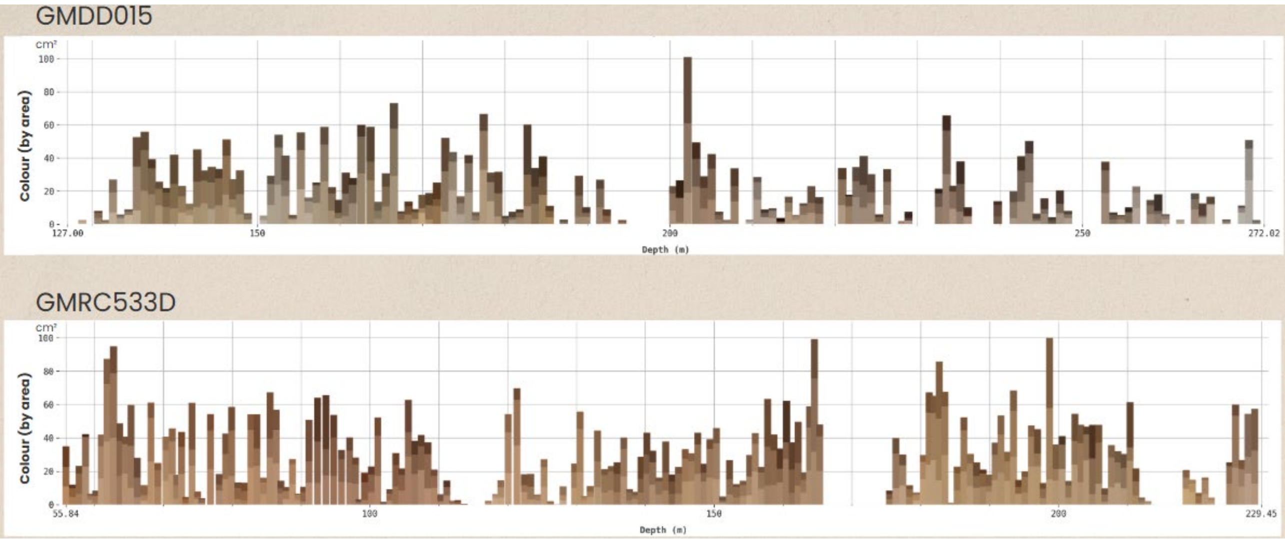

FIG 7 – RGB representation of spodumene grains for two drill holes.

CONCLUSIONS

The application of machine learning (ML) models, specifically segmentation and classification techniques, to high-resolution core photography has demonstrated significant potential to enhance geological interpretation in lithium pegmatite deposits. By identifying and quantifying spodumene grains, we were able to generate high-resolution, interval-based data sets that were previously unavailable through traditional manual logging methods.

The segmentation model enabled precise extraction of spodumene grain size, shape, orientation, colour, and spatial distribution. The iterative process of model development, including labelling refinements, resolution enhancements, and integration of post-processing techniques such as crystal erosion and bleb filtering, led to improved accuracy and generalisation across the data set. New statistical output including spodumene grain roundness, area bins and RGB colour profiles, provided deeper insight into mineralogical variation and potential geometallurgical controls on lithium grade.

Ultimately, the ability to derive meaningful, quantifiable features from core imagery using ML not only accelerates the development of orebody knowledge but also provides a scalable foundation for integrating these insights into broader geological and resource models. The approach outlined here demonstrates a clear value proposition for AI-driven geoscience workflows and sets the stage for further innovation in the analysis of complex mineral systems.

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Frankenstein's and fairy tales – accelerating discovery to delivery

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ABSTRACT

Resource project delivery is increasingly balancing the divergence between what is *technically feasible* and what is *possible or permissible*. This is a material challenge for the conversion of discoveries into production assets as projects are taking longer to develop, are more contested, and are increasing in complexity (Bonakdarpour, Hoffman and Rajan*,* 2024; Valenta *et al,* 2019).

Contemporary case studies and literature highlight the risks to discovery, planning, and execution, particularly in the identification and management of non-technical risks that could undermine even the most technically sound projects. For instance, a mining project might face strong community opposition or regulatory barriers, with enabling infrastructure increasingly delayed due to land access issues or environmental concerns. Ensuring realistic feasibility by integrating real-world constraints into project studies—and grounding performance expectations in practical human, environmental, and legal factors—is an increasing challenge (Lèbre, 2024).

To unlock critical minerals projects, proponents must build stakeholder confidence. Investors, governments, and communities are more likely to support projects that demonstrate due diligence and awareness of potential challenges. Environmental, Social, and Governance (ESG) compliance is essential and now central to investment and regulatory decisions; overlooking ESG considerations can lead to reputational damage or outright project denial.

Recognising key project delivery factors early allows for adaptive strategies, enabling project teams to incorporate flexibility in timelines, budgets, and even core designs to better align with evolving real-world conditions. A systems-based approach is essential for understanding the multiple interconnected factors that contribute to development risk. Trust and transparency are critical, as mining projects increasingly face delays or abandonment due to direct, indirect, or cumulative risks stemming from Modifying Factors (JORC, 2024b). These Modifying Factors include—but are not limited to—mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governance (ESG), and regulatory factors (JORC, 2024a, Exposure Draft).

Synthesising and decoding this diverse, interconnected, and interdependent project information is a prerequisite for managing the risks of so-called *'Frankenstein'* or *'Fairy Tale'* project delivery and disclosures. *Frankenstein Projects* arise from uncontrolled multi-factor risks created by the interactions and interdependencies between Modifying Factors. Conversely, *Fairy Tale* project assessments that fail to use available data to make reasonable and realistic evaluations.

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Critical minerals from mine waste – aiming for a zero waste mine

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ABSTRACT

Estimates of waste volumes produced from mining activity exceed 13 billion tonnes (Bt) annually (Valenta *et al,* 2023). In this case, we refer to mine waste as that produced from mining and processing activities and subsequently stored in a waste storage facility such as a tailings dam, integrated waste landform or similar. We do not include other forms of waste from the mining industry, such as wastewater, truck tyres, and other forms of industrial or municipal waste equivalent. The vast majority of this is in the form of tailings and other waste rock products, such as waste dumps and spent leach heaps.

Furthermore, most mining operations extract one to two commodities of value, representing only a small portion of the material disturbed as part of the operation. However as clean energy technology uptake increases, so does our requirement for a large range of minerals and metals that were not historically of interest, many of which are designated 'critical'.

The opportunity exists to make better use of mine waste to augment and diversify global critical mineral supply, reduce or remove large volumes of waste from mining operations and thereby improve environmental outcomes for mine sites during and beyond mine closure.

In this desktop study, our goal is to demonstrate the viability of creating a valuable product from every component of a mine's waste rock material. Using the waste composition of a typical Queensland sedimentary-hosted Cu-Pb-Zn deposit as a starting point, a high level flow sheet for zero waste outcomes was designed. Critical metals targeted include HPA, As, Co, Mg, Mn and Si. Many of these are common elemental components of typical rock forming minerals, and are not themselves rare. Additional 'strategic' metals that were targeted include Cu and Zn. The goal for all remaining metals, minerals and other products was to propose outcomes that maximise value and minimise harm.

By adding a suite of critical and other minerals and metals to traditional commodity production, mine operations are able to diversify their portfolio and may be somewhat protected from the vagaries of individual commodity markets.

On demonstration of the technical and commercial viability of the zero-waste mine, the next step for this project is to develop a site-based pilot study, with real-world inputs and outcomes.

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Texture and compositional zoning in pegmatitic mineral assemblages from Pilgangoora deposits – Pilbara Region, Western Australia

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ABSTRACT

The global transition towards a clean energy future fundamentally relies on a secure and sustainable supply of critical minerals, including lithium (Li). As a key component of energy storage technologies, Li plays an essential role in the development of low-carbon systems. Therefore, advancing our understanding of the petrogenesis and emplacement mechanisms of Li-bearing pegmatites, in relation to their host rocks, is crucial to guiding future Li exploration.

This study aims to move beyond traditional whole-rock compositional approaches by integrating various techniques spanning the macro- (eg hyperspectral analysis) to the microscopic scales (eg automated mineralogy). We focus on pegmatite-hosted rocks from the Pilgangoora Li-deposit (Pilbara Region, Western Australia), using a 1 km drill core data set provided by the Geological Survey of Western Australia. This deposit represents a key example of mineralised pegmatites in Australia that displays significant petrographic and structural variations with depth.

For this purpose, Hylogger3™ hyperspectral reflectance data (VNIR-SWIR-TIR – visible near-infrared; shortwave-infrared; thermal infrared) were used to map pegmatites, their host rocks, and the respective contacts across the entire core, focusing on the relative abundance of spodumene, mica, silica, plagioclase, and pyroxene minerals. Based on hyperspectral data, 112 representative samples were selected for modal analysis using Scanning Electron Microscopy TESCAN Integrated Mineral Analyzer (SEM-TIMA). Detailed petrographical and textural analyses revealed compositional zonings (eg normal, reverse, patchy) in several pathfinder minerals, including spodumene, mica, apatite, and Ta-Nb oxides. HyLogger data were calibrated against SEM-TIMA results using partial least square regression to obtain semi-quantitative mineralogy estimates at 1 cm spatial resolution along the drill core. Preliminary results deliver an error of prediction (Root Mean Square Error (RMSE)) of 8–14 per cent for major mineral phases, including quartz, albite and spodumene.

This work highlights that characterising phase size, shape, zoning, and intergrowths between pegmatite and host rocks provides a powerful strategy for reconstructing P-T emplacement conditions and distinguishing between non-prospective and prospective pegmatite occurrences.

ESG due diligence in a volatile market – aligning global standards with business objectives and lender expectations

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ABSTRACT

As the global energy transition accelerates, critical minerals such as lithium, nickel, rare earth elements, and cobalt are under intense scrutiny—not only for their strategic importance, but also for the environmental and social risks associated with their extraction. In this context, rigorous environmental, social and governance (ESG) due diligence has become essential for securing financing, de-risking projects, and maintaining stakeholder confidence. However, these minerals are subject to considerable market fluctuations, raising concerns regarding the cost of transparency measures.

This presentation draws on experience from SLR Consulting's Global Mineral Advisory team in conducting ESG due diligence across a portfolio of critical minerals projects. Using internationally recognised standards—including the Equator Principles, IFC Performance Standards, and the Initiative for Responsible Mining Assurance (IRMA)—we explore how ESG risk frameworks are applied to projects underpinning the energy transition.

Importantly, these standards are not just about compliance—they provide a structure for communicating risk mitigation strategies to lenders and investors who are increasingly integrating ESG criteria into decision-making. While ESG expectations remain strong in Europe—driven by regulation and investor pressure—the United States has shown signs of retreat, creating a fragmented global environment. Despite this, project developers cannot afford to ignore ESG, as access to capital, offtake agreements, and social license increasingly depend on transparent, credible ESG performance.

This presentation will provide practical insights on integrating ESG into critical minerals project evaluations in a way that does not compete with business objectives. Through real-world examples, we will demonstrate how aligning due diligence processes with financial and operational strategies can unlock value, enhance resilience, and meet the evolving expectations of both markets and stakeholders in a rapidly changing global landscape.

The importance of proved material in industrial mineral ore reserves – a case study of the Epanko Graphite Project, Tanzania

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ABSTRACT

Several of the minerals featured on critical minerals lists published by Australia, the European Commission and the United States of America happen to be what the JORC Code regards as Industrial Minerals. Industrial Minerals are those whose variable physical specifications dictate their potential uses and thus their value. With graphite, much of the value lies with its flake size and carbon grade, which helps establish its suitability for different applications. For example, as a refractory (large flake) or battery anode (fine flake) material, with high purity carbon required for optimal performance and lifespan of the anode of lithium-ion batteries. The importance of physical specifications in Industrial Minerals can determine whether a deposit is economically viable or not, hence the requirement to consider these factors, along with other Modifying Factors whilst classifying an Ore Reserve.

Given the reliance on an Ore Reserve when determining the economics of a project, the authors of this paper consider that for Industrial Minerals a minimum portion of Ore Reserves must be Proved and as such, defined within the JORC Code. Thus, better informing companies and individuals involved in Industrial Mineral project evaluation. This becomes of greater significance when considering the elevated level of importance that Modifying Factors are anticipated to have in the forthcoming update to the JORC Code.

This paper takes the Epanko Graphite Project in Tanzania as a case study, where currently 82 per cent of its total Ore Reserve is classified as Proved, partially dictated by the strong understanding of the metallurgy, physical properties and marketability of the Ore and product, which has been established over the past 12 years.

Analysis was completed on 19 major, publicly listed graphite deposits, of which 15 had declared an Ore Reserve. Results of which demonstrate significant variation amongst peers. At 82 per cent Proved, Epanko is the only deposit globally with a Proved proportion of Ore Reserve greater than 75 per cent, and one of only two greater than 50 per cent. Of the 15 deposits with Ore Reserves, five contained 0 per cent Proved, and therefore all material classified as Probable, with one of these deposits already in production.

INTRODUCTION

The recent increased awareness of which minerals are critical for sovereign capability and continued economic advancement has resulted in attention being drawn to previously unloved minerals. Historically, it has been the classic metallic, non-industrial minerals to receive the majority of attention from explorers, miners and investors; gold, copper, nickel and iron, with fossil fuels at the centre of the energy mix. As the world evolves with regards to geopolitics as well as industrial and environmental ambitions, minerals that previously held a low priority, for example lithium and natural flake graphite (graphite), have been thrust into the limelight. Several of the minerals featured on critical minerals lists published by Australia, the European Commission and the United States of America happen to be what the JORC Code regards as Industrial Minerals.

Industrial Minerals are those whose variable physical specification dictates its potential uses and thus its value. Taking graphite as an example, where the flake size impacts whether it is suitable as a refractory (large flake) or battery anode (fine flake) material, each of which carry a different valuation. Additionally, carbon purity, and the level and type of impurities dramatically effects the performance and lifespan of graphite battery anodes. Therefore, customers are willing to pay a premium for graphite with a higher carbon grade. The physical specifications of Industrial Minerals can define whether a deposit is economically viable, hence the requirement to consider these, along with other Modifying Factors whilst classifying an Ore Reserve.

Given the reliance on an Ore Reserve when determining the economics of a Project, the authors of this paper consider that, for Industrial Minerals, a minimum portion of Ore Reserves must be Proved and such as, defined within the JORC Code. Thus, better informing companies involved in Industrial Mineral project evaluation.

This paper takes the Epanko Graphite Project (Epanko or the Project) as a case study, where 82 per cent of the total contained graphite in the Ore Reserve is classified as Proved, partially dictated by the strong understanding of the metallurgical, physical properties and marketability of the Ore and its products.

PROJECT LOCATION AND ACCESSIBILITY

Epanko is located 6 km south-west of the town of Mahenge, in the Ulanga district of the Morogoro region of Tanzania. The country's commercial hub and largest city; Dar es Salaam, is approximately 350 km north-east of the Project area. The city of Dar es Salaam is strategically positioned on the Tanzanian coast of the Indian Ocean, and home to East Africa's second busiest port, a key link in the logistical chain for the Project. The city is connected to the Project area with a tarmac road running from Dar es Salaam, to within 65 km of the Project, after which, a well-maintained unsealed road takes over.

PROJECT HISTORY

Epanko is held under the Duma TanzGraphite joint venture, of which Australian publicly listed company; EcoGraf Limited (EcoGraf) owns 84 per cent and the Government of Tanzania 16 per cent, following the April 2023 signing of a framework agreement between the two parties.

Graphite was first recorded at Epanko by the German colonial government in 1914, with trenching completed by a Czech mineral exploration company in 1959. The Epanko mineral licenses were secured by EcoGraf (previously Kibaran Nickel) in 2011, via local subsidiary Tanzgraphite (TZ) Limited, with initial exploration commencing in 2012. Over the following 12 years, including a Project hiatus between 2017 and 2022, the deposit was taken to its current pre-development stage (total drilled 19 391.4 m), with a Mineral Resource of 290.8 Mt at 7.2 per cent Total Graphitic Carbon (TGC) (Table 1), the largest development ready graphite Mineral Resource in Africa (EcoGraf, 2024a) and Ore Reserve of 14.3 Mt at 8.8 per cent TGC (Table 2) (EcoGraf, 2024b).

TABLE 1

March 2024 Mineral Resource Estimate for the Epanko Deposit >5.5 per cent TGC (EcoGraf, 2024a).

JORC classification	Tonnage (Mt)	Grade (%TGC)	Contained graphite (kt)
Measured	32.3	7.8	2500
Indicated	55.7	7.5	4200
Measured + Indicated	88.0	7.6	6710
Inferred	202.8	7.2	14 310
Total	290.8	7.2	21 010

TABLE 2

July 2024 Ore Reserve Statement for the Epanko Deposit (EcoGraf, 2024b).

JORC classification	Proved			Probable			Total		
	Tonnes (Mt)	Grade (%TGC)	Cont. (kt)	Tonnes (Mt)	Grade (%TGC)	Cont. (kt)	Tonnes (Mt)	Grade (%TGC)	Cont. (kt)
Oxide	8.9	9.0	805	0.2	8.4	15	9.1	9.0	820
Transitional	1.0	8.0	79	0.8	8.3	65	1.8	8.1	144
Fresh	1.8	8.3	149	1.6	8.6	140	3.4	8.4	289
Total	11.7	8.8	1033	2.6	8.5	220	14.3	8.8	1253

GEOLOGY

The Project lies within the vast Neoproterozoic Mozambique belt, which forms part of a composite Proterozoic Mountain building period stretching from the Arabian-Nubian shield to the East Antarctica through East Africa and Southern Mozambique (Jacobs *et al,* 1998). The closure of the Mozambican Ocean during the Neoproterozoic and Cambrian periods resulted in the formation of this north–south trending orogenic belt (Shackleton, 1996). The belt in Tanzania is divided into two parallel sections, the Eastern Granulites and Western Granulites based on protoliths dating (Fritz *et al,* 2009; Leger *et al,* 2015). The two domains are separated by flat thrusts and sedimentary basins of young age.

Epanko is located within the Mahenge Mountains, in the western margin of the Eastern Granulite domain. The Eastern Granulite terrane contains anorthosites dating from 900 to 700 million years ago, as well as a metasedimentary sequence. This sequence includes the Epanko graphite deposit and several marble layers. However, part of the mountains have the same affinity of those of the Western domain where amphibolite orthogneisses, amphibolites and paragneisses dominate (Johnson *et al,* 2003). Both domains are bounded by major tectonic contacts and based on metamorphic ages, the peak metamorphism in the Eastern and Western domains occurred at 640 Ma and 560 Ma respectively (Möller, Mezger and Schenk, 2000; Leger *et al,* 2015; Apen *et al,* 2020).

The Epanko deposit is comprised of metasedimentary units, with the graphite Mineral Resource attributed to a graphite-quartz schist, where graphite concentration ranges between 3 to 30 per cent. The surrounding waste rock units include quartz-feldspar schist, quartz-garnet gneiss, dolomitic marble, amphibolite and metamorphosed granitoids.

NATURAL GRAPHITE OCCURRENCE

Graphite is a crystalline, grey to black, opaque, very soft allotrope of carbon. Considered as the most stable form of carbon under standard conditions (Puronaho, 2018), graphite occurs naturally exhibiting both metallic and non-metallic properties making it useful for diverse industrial applications.

Industrially, natural graphite is used in refractories, electrodes, batteries, brake linings, and steelmaking (Shaw, 2013). These vast applications are attributed to graphite's properties of being a good conductor of heat and electricity. Furthermore, graphite is valued industrially for its self-lubricating and dry lubricating properties. Many of these end uses, including refractory, expandable graphite and lubricants, require the large flake graphite in order to achieve the required physical properties of the products. Globally, fine flake graphite is more prevalent, with the scarcity of large flake being one factor that results in it carrying a higher price, as well as the high technicality and cost involved large flake production.

Geologically, natural graphite occurrences can be categorised into; flake graphite usually disseminated in gneiss or schist (in the case of Epanko), vein or lump graphite in magmatic rocks (Puronaho, 2018) and lastly, amorphous graphite formed by metamorphism of carbon rich sediments (Simandl, Paradis and Akam, 2015).

Metamorphic rocks are the common host of graphite where organic materials in sedimentary rocks are heated and compressed to produce graphite. This process is believed to be responsible for the disseminated graphite mineralisation seen at Epanko. Alternatively, precipitation of carbon from hydrothermal fluids is thought to be the formation mechanism of vein hosted graphite, as seen in Sri Lanka (Simandl, Paradis and Akam, 2015).

At present China dominates the mining and production of both natural flake graphite and Spherical Graphite (SpG). Global demand for natural graphite is expected to increase by 2030, driven by the rapid expansion of lithium-ion batteries used in electric vehicles and energy storage systems in North America, Europe and Asia. As electrification accelerates across the transport and energy sectors, lithium batteries are becoming central to this transition, placing increasing strategic importance on developing new technologies and supply channels. Forecasts show that approximately 2.5 Mt of natural graphite is required for battery demand which will represent 81 per cent of the market. Graphite will play a pivotal role in supporting global decarbonisation objectives and the scaling of clean energy technologies (EcoGraf, 2024c).

MINERAL RESOURCE AND ORE RESERVE

The Epanko Graphite Project boasts the largest development-ready graphite Mineral Resource in Africa, totalling 290.8 Mt (Mt) at 7.2 per cent TGC, containing 21 010 t (kt) of graphite (EcoGraf, 2024a). The Resource is classified under the JORC Code 2012, with 88 Mt at 7.6 per cent TGC considered Measured and Indicated, providing a high degree of confidence. A significant Inferred Mineral Resource of 202.8 Mt at 7.2 per cent TGC also exists, demonstrating the potential for future upgrades and expansion of the Project's defined Resources.

Epanko has a total Ore Reserve of 14.3 Mt at 8.8 per cent TGC, of which 11.7 Mt in Proved and 2.6 Mt Probable. The Project's Ore Reserve supports Epanko's 18 year Life-of-mine (LOM) Bankable Feasibility Study which included extensive metallurgical testing and flow sheet design, mining optimisation, environmental and social considerations, and detailed infrastructure and process plant engineering. This comprehensive approach supports reliable capital and operating cost estimates and enhances confidence in financial projections. Epanko's Ore Reserves are based solely on Measured and Indicated Mineral Resources, excluding Inferred Resources, which are treated as waste.

The combination of the extensive multi-disciplinary studies for Epanko, along with the confidence provided by the Project's European and Asian offtake partners, helps support the classification of the Epanko Ore Reserve, with a market leading 82 per cent of contained graphite as Proved.

THE IMPORTANCE OF PROVED ORE RESERVES FOR INDUSTRIAL MINERALS

The conversion of Mineral Resource to Ore Reserve and subsequent classification takes into account both the geological knowledge and confidence, as well as consideration of various Modifying Factors (Figure 1). Modifying Factors are defined by the JORC Code as considerations used to convert Mineral Resources to Ore Reserves. These include, but are not restricted to, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors.

Due to Industrial Mineral deposits economic viability being as much related to the products physical specification as it is the deposit's size and grade, the importance of several of the Modifying Factors is further elevated when compared to non-Industrial Minerals.

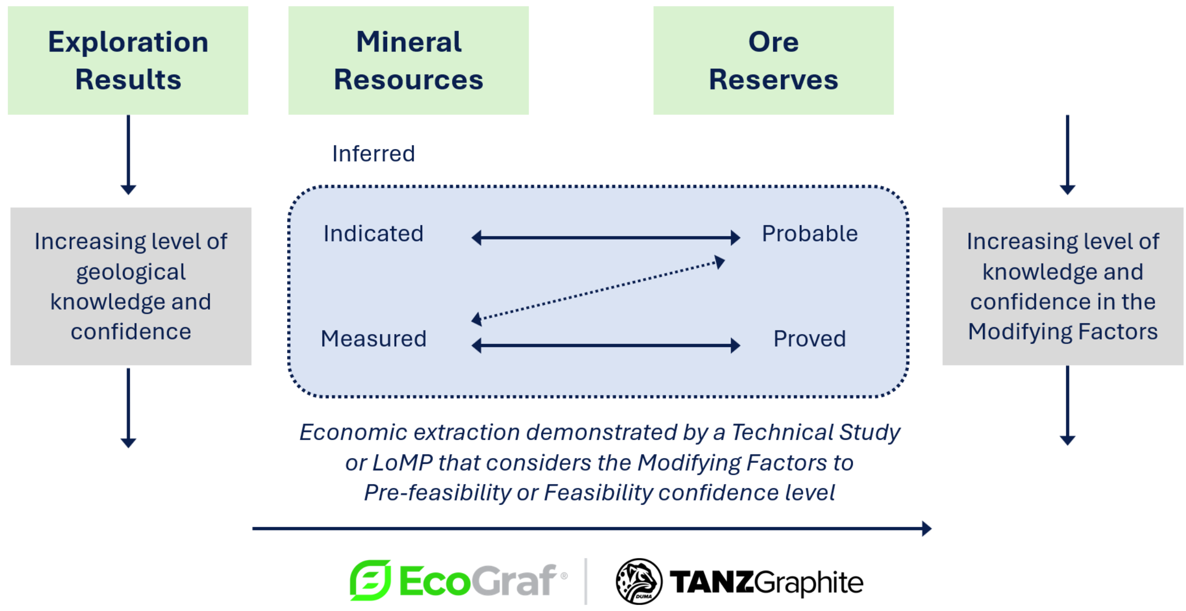

FIG 1 – General relationship between Exploration Results, Modifying Factors, Mineral Resources and Ore Reserves (modified from JORC, 2024).

It is this point surrounding the extra importance of Modifying Factors, when it comes to Industrial Minerals that is the support for the argument that all Industrial Mineral Ore Reserves should have a minimum portion classified as Proved, in order for an Ore Reserve to be declared. This becomes of greater significance when considering the elevated level of importance that Modifying Factors are anticipated to have in the forthcoming update to the JORC Code.

Without in-depth consideration of Modifying Factors for Industrial Minerals, with particular focus on metallurgy and marketing, an Industrial Mineral deposit's economic viability can vary greatly.

Ore Reserves are a fundamental input in evaluating the economic viability of a mining project. Consequently, defining a minimum portion of Proved Ore Reserves, rather than predominantly Probable Ore Reserves, strengthens the reliability of project economics and reduces risk.

Unlike precious metals, base metals and bulk commodities, the value of Industrial Minerals is highly sensitive to:

- physical and chemical characteristics
- end-user requirements
- market-specific specifications
- downstream processing capabilities.

Projects can show apparently favourable resource quantities but fail commercially if their product does not meet market needs.

The JORC Code requires that Modifying Factors, such as metallurgical recoveries, product specifications, marketing, and pricing, are reasonably well-defined and justifiable when converting a Resource to an Ore Reserve. In Industrial Minerals, these factors carry elevated importance because they directly affect saleability and pricing.

The Project's chosen route for development financing has been through Germany's KfW IPEX-Bank, with a German Government loan guarantee. This high-quality financing approach has necessitated the highest level of technical, environmental, social and financial due diligence to meet the strict requirement of a bank of KfW IPEX-Bank's stature. A positive result of this has been the elevated quality and quantity of work put into the various disciplines for the Project, which are also those considered to be Modifying Factors by the JORC Code. This, when coupled with the geological confidence that the Measured Mineral Resource provides, has allowed for the market leading classification of 82 per cent of the Ore Reserve as Proved, ensuring the Project financier has the highest level of confidence prior to execution.

Analysis was completed on 19 major, publicly listed graphite deposits, of which 15 had declared an Ore Reserve. At 82 per cent, Epanko is the only deposit globally with a Proved proportion of Ore Reserve greater than 75 per cent, and one of only two greater than 50 per cent. Of the 15 deposits with Ore Reserves, five contained 0 per cent Proved, hence not visible on Figure 2 (including projects in Australia, Sweden, Mozambique and Tanzania), with all material classified as Probable. One of these deposits with 0 per cent Proved Ore Reserves is already in production (Figure 3). The graphite industry has experienced multiple mine closures in recent years which has elevated the importance of sufficient due diligence in the sector to ensure that necessary supply is established to facilitate the desired commodity independence from China.

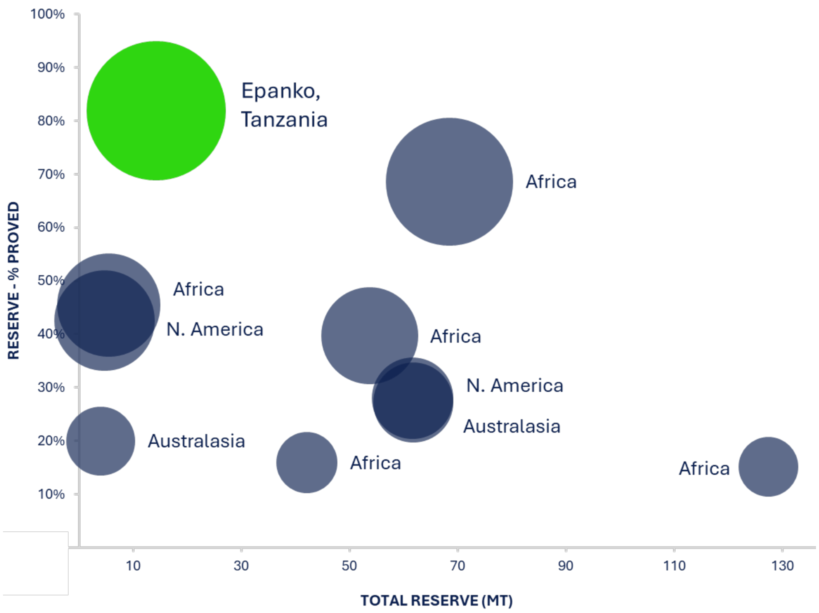

FIG 2 – Proportion of proved material in the ore reserves for major global graphite deposits (host region labelled).

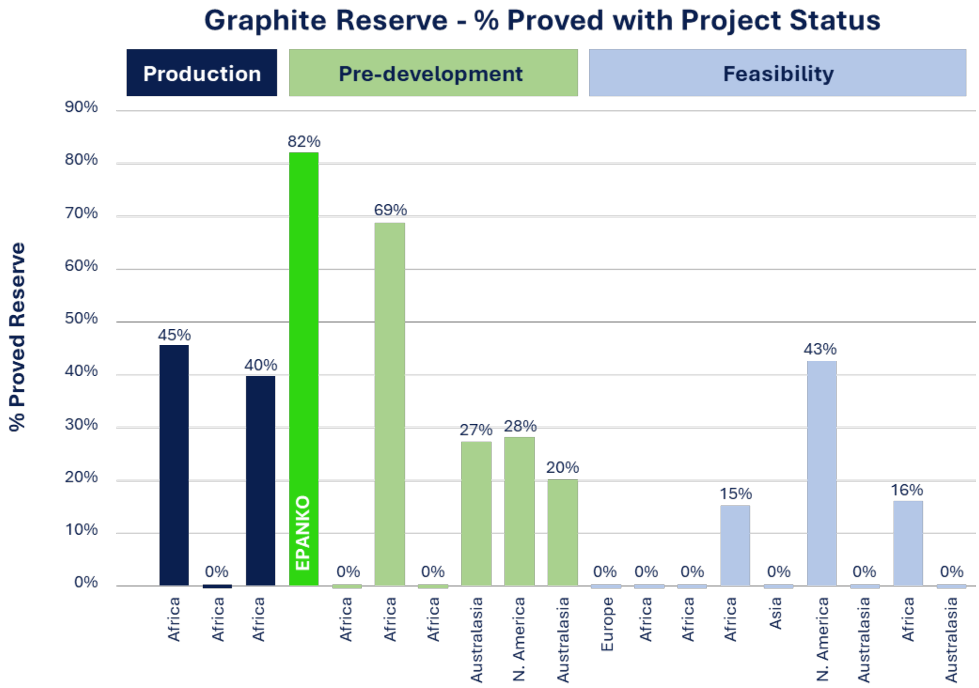

FIG 3 – Graphite ore reserves – % proved with project status and project location.

The risks of the lack of sufficient Proved material in an Ore Reserve have been recently realised at operating graphite mines in North America, Africa, Europe and Asia Pacific regions, where insufficient understanding of a project's deposit, processes and end users resulted in product which did not meet the customers stringent requirements for flake size and carbon grade.

The graphite sector has seen mine closures across multiple jurisdictions where variations in aspects relating to Modifying Factors have resulted in unviable operations. Examples include greater than expected impurities in the Ore and resultant graphite product, carbon grades of the product being below standard, insufficient high-value large flake material, poor segregation of the varying flake sizes and challenges with meeting production capacity.

Prior to development, a greater understanding of these project's Modifying Factors, including the metallurgical process that delivers the final flake distribution and carbon grade, and its sale and marketing, would have provided the opportunity to better factor these considerations into the operations design and capacity. The lack of sufficient Proved material, can result in an operationally flawed project, highlighting the criticality and real-world importance of this discussion, elevating the need for changes in regulations.

CONCLUSION

As the recognition of the importance of Modifying Factors grows, so too does the importance of the percentage of Proved within Ore Reserves, no matter what the mineral. At this stage, the focus is on Industrial Minerals, given the added importance that Modifying Factors hold in their economic viability, when compared to non-Industrial Minerals. The authors of this paper consider that, for Industrial Minerals, a minimum portion of Ore Reserves must be Proved and as such, defined within the JORC Code.

A minimum of 40 to 50 per cent Proved in Ore Reserves would be good starting point for regulations, whilst also stating that a higher percentage is encouraged due to its ability to lower the risk to commercial success of a new operation. By enforcing a mandatory minimum Proved Ore Reserve component for Industrial Mineral projects:

- Investors are better informed.
- Projects will be more likely to progress based on credible technical and commercial evidence.
- The industry will benefit from greater consistency and rigour in how Industrial Mineral assets are evaluated and communicated to the market.

EcoGraf's Epanko Graphite Project in Tanzania, demonstrates that by following a thorough path of technical studies and due diligence, a project can establish itself where the majority of its Ore Reserve is classified as Proved, greatly reducing the risk carried by investors and financers. In turn, these changes will have the effect of improving the attractiveness of investment into the mining sector, at a time when development financing for junior and medium scale mining companies is becoming increasingly difficult to secure.

Without change, the industry faces a situation where technically flawed projects continue to gain access to financing, and risk resulting in failed operations. Further failed operations have the potential to drive investors away from the industry, opting to focus on sectors where returns carry lower risk and quicker turnaround. A situation like this, at a time when the global requirement for minerals is continuing to increase, carries profound risks that will impact all in society, and not just mining professionals.

Given the critical role of Ore Reserves in supporting the economics of a project and the nuanced characteristics of Industrial Minerals, a requirement for a minimum proportion of Proven Ore Reserves is a reasonable safeguard. It would enhance the transparency and integrity of reporting, particularly in light of the expected emphasis on Modifying Factors in the forthcoming JORC Code update. This shift aligns with broader efforts to improve investor confidence and the quality of technical disclosures in the industrial minerals sector.

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Unlocking the potential of tailings through geometallurgical approaches for sustainable critical mineral recovery

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ABSTRACT

The transition to renewable energy and high-tech industries is driving a surge in demand for critical minerals, expected to more than double by 2030, prompting increased focus on alternate sources. Historically, extraction processes for many ores focused on obtaining specific target metals that were of interest at that time with other metals/minerals going to waste and tailings storage facilities (TSFs). This was compounded by inefficient methods available at the time of active mining. As a result, these residual materials, remaining after ore extraction, are now considered a near-future resource for reprocessing by many mining operations. However, TSFs are typically complex and heterogeneous, as they are generally deposited as a slurry that undergoes sedimentary processes that leading to the sorting of particles by size and density, and the formation of fan-shaped and stratified structures. This can lead to localised zones of metal enrichment or depletion, with increased complexity when tailings from different ore types or processing methods are mixed. A geometallurgical approach to characterisation of these 'deconstructed orebodies' is needed to provide a detailed understanding of the characteristics, enabling more effective strategies for addressing the challenges encountered during their reprocessing. By integrating geological, mineralogical, geochemical, and metallurgical data, this approach can lead to the development of spatial predictive models that optimise recovery and minimise reprocessing risks. It can be used to identify variations in particle size, mineralogy, and metal distribution, enabling more efficient extraction of valuable metals while also enhancing environmental management by assessing potential risks and guiding sustainable processing strategies. In this presentation, the principal aspects of the geometallurgical approach will be discussed, highlighting its integrative nature, predictive capabilities, and strategic value in the reprocessing of materials in TSFs.

Characterisation of antimony and tungsten minerals using ECORE – an application of automated mineralogy on a series of drill cores from Hillgrove Gold Antimony Project

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ABSTRACT

The Hillgrove Gold-Antimony Project, Australia's largest antimony resource, has been a significant source of critical minerals since 1857. Recent drilling at Clarks Gully and surrounding zones has uncovered high-grade Sb-Au-W mineralisation, renewing exploration interest in this New England Orogen (NSW) deposit. This resurgence aligns with global efforts to secure responsible supplies of energy-transition metals. Antimony's relevance in the production of fire retardants, lead-acid batteries, as well as its inclusion in multiple emerging electrical and energy-related technologies, highlights the need for advanced mineralogical characterisation workflows that support sustainable supply.

This study showcases the use of ECORE, an automated drill core scanner combining laser-induced breakdown spectroscopy (LIBS) with machine learning-driven mineral identification, as a tool for rapid characterisation of the mineralogy of Sb-W-bearing mineralised core sections from the Clarks Gully deposit, operated by Larvotto Resources Limited. LIBS-based imaging revealed geochemical signatures associated with stibnite and scheelite, while facilitating discrimination of textural styles (eg massive versus disseminated stibnite) and associated mineral assemblages.

The Tescan Integrated Mineral Analyzer (TIMA) was used as a supporting tool to verify ECORE-derived mineralogy and to investigate stibnite occurrences in greater microscale detail. TIMA analyses revealed stibnite in multiple textural settings, including massive to narrow veins in a stibnite-quartz-ankerite assemblage, or as fine intergrowths with potassium feldspar, quartz and chlorite. It also showed a correlation with pyrite and arsenopyrite.

The integration of large-scale ECORE scanning with targeted TIMA validation established a systematic workflow for Sb-W characterisation. This study demonstrates how automated mineralogy reduces exploration risk, reinforcing the role of digital geoscience tools like ECORE in securing critical minerals for the energy transition.

Deep sea mining – navigating the risks and opportunities of new frontiers for critical minerals

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ABSTRACT

Deep sea mining is attracting increasing attention as a potential source of critical minerals, but serious questions remain about its viability, governance, and impact. In this session, deep sea mining experts Jo Feldman and Lisa Koch will examine recent developments in this emerging sector. They will assess how it compares with land-based mining from a regulatory, commercial, and ESG perspective. As deep sea mining approaches a pivotal shift from exploration to exploitation, it is timely to explore whether it is ready to meet the standards set by land-based mining.

The presentation will contrast the evolving regulatory regime for deep sea mining, including in international waters where the ‘sponsoring’ state may be geographically removed from the extraction activity, against the more mature and locally accountable frameworks for land-based operations. It will also consider the commercial landscape, including licensing models, royalty arrangements, and the nature of relationships required between operators and state and non-state actors.

Consideration will be given to the legal and commercial risks facing investors, operators, and commodity purchasers, including the challenge of bankability for projects that are largely untested. The geopolitical overlay—especially in light of rising sovereign risk and strategic competition between the US and other major powers—adds further complexity.

From an ESG perspective, the session will critically assess whether technological advances can meaningfully address the environmental and social risks associated with ocean-floor extraction. It will also raise the issue of social licence, which in international waters must extend to a global community, as resources are intended to benefit ‘all humankind’.

By drawing on decades of experience in land-based mining, the discussion will offer grounded insights into whether deep sea mining can meet the same standards of accountability, sustainability, and benefit-sharing that the industry has worked hard to develop on land.

This topic covers various conference themes, including:

- mineral economics, geopolitics and the global supply chain
- circularity and ESG
- discovery and development
- showcasing new technologies.

Processing routes for the critical raw materials recovery from lithium hard rock deposits

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ABSTRACT

Top ten deposits account for more than 83 per cent of world lithium resources with a domination of the brines. Estimated 'hard Li deposits' resources were significantly increased recently due to the advanced exploration and discovery of new deposits. World Li resources were estimated by USGS to 105 Mt in 2023. while the Li reserves were doubled in 2023 to 28 Mt compared to 14 Mt in 2016. Brines and crystalline rocks, namely pegmatites and greisens enriched in silicate minerals and/or Li phosphates, are the main source of lithium in the Europe. Granitic pegmatites and rare metals granites (RMG) may be considered as an important Li source as well as the source of many other critical metals, such as Ta, Nb, Sn, Be, Cs, Sc, U, Th and REE. Thus, it is crucial to evaluate the potential and contribution of hard rock lithium deposits to decrease the supply risks of critical materials for the European economy.

This work is aiming at evaluation of the processing routes to unlock the 'hard Li' European deposits not only to produce the high-quality Li concentrate (4.0–4.5 per cent Li_2O), but also to increase the economic viability of the deposits exploitation by recovering the others critical metals (Ta, Nb, Sn,) and industrial minerals (quartz and feldspar) to reach near zero processing circuit.

The flotation is used for most mineral deposits as the main separation method for recovering Li-bearing minerals. There are some alternative methods such dense media separation, magnetic separation, electrostatic separation and ore sorting for the preconcentration of lithium-containing minerals (spodumene, lepidolite, zinnwaldite) from the pegmatites and greisens. The combination of the gravity concentration to recover the Ta-Nb and Sn bearing heavy minerals and flotation to recover the lithium bearing mica (lepidolite) was used in this work to process the rare metals granites from Beauvoir deposit (Allier, France) while the processing approach based on the optical sorting and electrostatic separation at coarse size followed by flotation was applied to process the pegmatite ores from Gonçalo deposit (Portugal).

Decision-making under uncertainty for the strategic implementation and development of the US graphite supply chain

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ABSTRACT

As the global transition to electrified transportation grows and accelerates, graphite has emerged as a critical material in the production of lithium-ion batteries irrespective of specific battery chemistry. Despite its importance, the graphite supply chain remains heavily dependent on imports from geopolitically sensitive regions, raising concerns over the strategic risks of its geopolitical vulnerability, market concentration and price volatility, and the lack of reliance on upstream and midstream operations. The study herein puts forth a strategic decision-making framework which accounts for these risks when developing graphite resources and processing facilities which support the US battery supply chain.

A Partially Observable Markov Decision Process (POMDP) model is constructed to assess the best strategies to develop a graphite supply chain supportive of the US battery electric vehicle (BEV) goals and growing demand, while reducing reliance on geopolitically sensitive imports to minimise risks associated with possible supply chain disruption. The model accounts for an exogenous BEV demand growth, imperfect information regarding graphite resources, and the option to gather more information to assess and account for the risks in developing and expanding production assets. The objective involves maximising the BEV output while minimising exposure to geopolitically sensitive materials, guided by an evolving belief state to reduce uncertainty with new information gathered over time. This POMDP framework enables optimal long-term strategic planning while modelling uncertainty to inform sound investment and development of production assets for strategic implementation of the US graphite supply chain.

Ultrafine recovery and concentration of tungsten using a modified reflux classifier known as the Grade Pro

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ABSTRACT

Tungsten is a critical and strategic metal often available at very low-grade in the form of the mineral wolframite and scheelite. This work is focused on the fines scavenging circuit of the plant where the feed material is often of very low-grade, dominated by the presence of a significant level of ultrafine particles including clays. In recovering the minerals, it makes sense to take advantage of the high mineral density, typically RD ~6–7. Thus, gravity separation is seen as an option. Enhanced gravity at high G forces is sometimes used given the particles involved are often excessively fine, even below 10 microns. This approach, however, is impacted by the need to operate at relatively high feed concentrations, preferably more than 30 wt per cent solids. The rheology of the feed was investigated, confirming the need to operate at lower feed concentrations due to an excessive slimes viscosity. This study therefore examined the potential of a modified Reflux Classifier, known as the Grade Pro, to be deployed, applying much lower feed pulp densities, targeting the recovery of the minerals below 10 microns. The Grade Pro has a reduced lower cross-sectional area, ideal for low yields. This work demonstrated the sensitivity of the performance to the volumetric feed flux but confirmed the potential to readily control the grade versus the recovery at satisfactory levels. By maximising the feed pulp density, it was concluded that a single Grade Pro could be used to replace the existing G force machines in the plant.

Germanium by-production from Australian zinc refining – challenges and opportunities

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ABSTRACT

Germanium is a minor but critical component of many advanced, high performance optical and electronic technologies such as: high bandwidth fibre optic cables, thermal imaging systems, and high speed electronic chips. Many of these technologies have essential military applications and so securing germanium supply is of strategic significance.

China is currently the world's largest producer of germanium (~70 per cent) and has recently restricted exports, creating a critical shortage of this key metal. A primary source of germanium is as a by-product from zinc refining processes. Australia produces 510 kt/a of zinc from the refining of sphalerite minerals, which has the potential to produce approximately 15–30 t/a of refined germanium metal equivalent as by-product, or approximately 10–20 per cent of current global supply.

This talk will provide an overview of the germanium production process from zinc refining operations, highlighting key processing challenges and opportunities presented by new technologies. This work is an initiative of the Australian Critical Minerals Research and Development Hub, a government funded program bringing together expertise from the Australia's leading research institutes; ANSTO, CSIRO and Geoscience Australia.

Geometallurgical evaluation of a tailings storage facility to address environmental concerns and maximise the extraction of contained resources

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ABSTRACT

A comprehensive geometallurgical evaluation of tailings material from a high-sulfidation epithermal gold deposit stored in a historic tailings storage facility (TSF) was carried out with the main objectives to: (a) constrain the presence and distribution of minerals and elements of environmental concern, in particular pyrrhotite; and (b) to provide a robust estimate of the resource potential (eg recoverable value) of the fine particulate material in the TSF. As resource potential not only the deportment and mineralogy of remaining gold, but also the possible use of the silicate fraction for industries such as ceramics, glass and geopolymer production was considered.

To achieve these objectives, a drill core campaign was initiated, strategically selecting six drill holes for optimal representativity based on expected sedimentation patterns in TSFs. Drill core material was thoroughly characterised using automated mineralogy, geochemical and hyperspectral methods. Geometallurgical domains were then defined based on 64 geochemical assays, particle size measurements, and quantitative mineralogical assessments. A hierarchical Mahalanobis distance cluster analysis was used to distinguish domains, and predictions for these domains were extended to all hyperspectral imaging samples. This comprehensive approach resulted in the delineation of four distinct domains, along meaningful spatial continuity patterns, each domain characterised by distinct modal mineralogy and geochemistry. The exercise provided valuable insight into the heterogeneity of the tailings material, laying the groundwork for targeted interventions to address environmental concerns and maximise the extraction of resources contained in the studied TSF.

The study was coordinated by the recomine-alliance, a nationally funded initiative that brings together companies, scientific and educational institutions, public authorities and non-governmental organisations from the extended region of the Ore Mountains. In the recomine-vision, the competences of the region come together with market innovative services worldwide, which is supported by the unique model region for concepts for contaminated sites.

Regenerating nature – mining's natural contribution to a circular economy

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ABSTRACT

Intensifying environmental degradation and nature loss are globally recognised as outcomes of a linear economic model, one that has reached peak maturity and is starting to fail. A circular economy (CE) presents a more sustainable alternative. A core, but lesser recognised principle of a CE is to 'regenerate natural systems'; this principle might be the most accessible to mining companies and yet often nature programmes are treated separately. There is a key opportunity for companies to integrate their work efforts as these agendas emerge.

Historically, the mining industry has had a more 'defensive' relationship with nature, attempting to minimise footprint to limit liability, with mixed success. Mining has also been identified as a key sector contributing directly to nature decline. As a result, the industry is facing increased scrutiny regarding its impact on nature; driving increasing approvals requirements and delays faced by projects, especially for those seeking to enter 'greener' markets. In an effort to activate an industry response to this challenge, the ICMM released its Nature Position Statement in 2024, in a charge towards Nature Positive goals. Also in 2024, the ICMM released key guidance on Circularity.

The mining industry is already practised in rehabilitating and restoring landscapes; most mining companies also have extensive understanding of their natural environment through survey and research efforts, holding significant data sets key to regeneration. However, while the circular economy model is increasingly understood in the mining industry, much of the application to date focuses on tailings reclamation, metals recycling or even metals as a service, while the principle of regenerating nature is largely not considered.

By positioning efforts to regenerate nature as part of a circular economy model, mining companies can align efforts in a way which strengthens connection to broader economic drivers and improves value creation through existing skillsets and data.

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A first principles-based approach to evaluating the environmental performance of nickel and cobalt materials production for the battery supply chain

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ABSTRACT

Insights into the environmental performance of battery materials production requires a holistic and fundamental understanding of the major unit operations and production processes involved in the upstream and midstream stages of the supply chain. A lack of data transparency from the industry, and comprehensive and auditable production inventory data for life cycle assessment (LCA), limits the ability to perform rigorous environmental impact assessment on battery materials production. The proposal for a first-principles approach to evaluate the environmental performance of battery materials production considers the value in producing auditable and verifiable data by process modelling and simulation to support reliable and in-depth life cycle assessment that allows industry to evaluate and scrutinise the environmental performance of materials production.

The study completed by the author in support of the Future Battery Industries CRC research program on the Certification and Life Cycle Analysis for Australian battery material aimed to determine the relative environmental performance of nickel (and cobalt) battery materials production, including battery-grade nickel sulfate and other intermediates, by generating mass and energy balance data on several feed sources and production pathways by simulating first principles-based models developed using commercial METSIM software. Balanced mass and energy data was then used for Life Cycle Impact Assessment (LCIA) tailored to the Australian context yielding a global warming potential (GWP) of materials production.

Analysis of the LCIA results for the modelled production pathways indicates that domestic production of nickel battery materials yields significantly lower potential environmental impacts than from current major international producers. Notably, the simulated production of mixed hydroxide precipitate (MHP) from limonitic laterite ore had a GWP impact of 12.9 t CO_2-e/t Ni (contained), approximately one-third to one-half of the impact from the production of MHP in Indonesia (and its subsequent refinement in China). Similarly, the simulated GWP impact of nickel sulfide concentrate from sulfide ore was 3.00 t CO_2-e/t Ni (contained), 6.12 t CO_2-e/t Ni (contained) for the production of nickel sulfate hexahydrate from sulfide concentrate, and 8.48 t CO_2-e/t Ni (contained) for the production of nickel cathode from end-of-life lithium ion batteries. In most cases, mass allocation of the GWP impact resulted in higher impacts due to the higher amounts of nickel produced relative to other co-products, where conversely economic allocation results in lower environmental impacts due to the lower value of nickel on a total revenue basis when considering the value of all saleable products. The largest drivers of impact were identified in the upstream chemical processing unit operations, with renewable power integration, upstream and downstream processing unit operation integration, and novel processing route development likely to provide the greatest opportunities for improving the environmental performance of nickel (and cobalt) battery materials production.

Data integration of hyperspectral and whole-rock geochemistry – new insights into Mt Weld carbonatite-hosted REE deposit

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ABSTRACT

Rare earth elements (REE) are essential for producing current and developing future technologies. Understanding existing REE deposits and identifying new viable REE resources is critical due to fragile supply chains and increasing demand in coming decades. The Mt Weld carbonatite-hosted REE deposit is one of the richest REE deposits in the world, however, remains relatively poorly understood.

This study extrapolates previously characterised major mineralogy and REE mineral distribution of selected samples from the fresh carbonatite, to an entire drill core (MWEX10270), providing unbiased and contiguous distribution of major carbonates and REE-host minerals. This is achieved by translating hyperspectral signatures – collected with HyLogger3™ technology – into relative mineral abundance and chemical composition. Six distinct zones are recognised within the central carbonatite:

1. Weathering profile.
2. Magnesiocarbonatite.
3. Phosphate-siderite-rich magnesio- and ferro-carbonatite (MF carbonatite).
4. Phosphate-rich MF carbonatite.
5. Phosphate-poor MF carbonatite.
6. Calcio-carbonatite.

Whole-rock geochemical reassessment, based on the newly defined zones, reveals a gradual variation in λ values (a quantitative descriptor of REE patterns) of MF carbonatite REE geochemistry, reflecting the progressive magmatic fractionation from Mg-rich to Fe-rich carbonatite magma. Meanwhile, the total concentration of REE is initially elevated in Mg-rich carbonatite but subsequently decrease as phosphorus concentrates within Fe-rich carbonatite. REE precipitate as monazite during the hydrothermal evolution of each magmatic stage, transitioning to REE-fluorocarbonates in the late-stage magma when REE and phosphorus become depleted.

The application of Hylogger3™ for Mt Weld carbonatite analysis demonstrates that the HyLogger is an effective tool for rapidly identifying REE-hosting minerals and their distribution precisely in fresh carbonatite drill cores. This study also establishes new knowledge that is important to better understand global carbonatite-hosted REE deposits and future explorations.

Characterisation of lithium pegmatites in the Ajmer Region, Rajasthan – an integrated geochemical, mineralogical, and isotopic approach

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ABSTRACT

India hosts lithium resources primarily in Lithium-Caesium-Tantalum (LCT) type pegmatites, concentrated in Karnataka, Bihar-Jharkhand, Rajasthan, Odisha, and West Bengal. However, the country lacks the domestic lithium production required for future battery production capacity. Characterising mineralised pegmatites and understanding their origin will improve exploration strategies, aid in identifying economic lithium deposits, and reduce India's dependence on future imports. This study focuses on the Ajmer region (Rajasthan) pegmatites, where Li-pegmatites are spatially associated with the Neoproterozoic Erinpura granites. Located within the Aravalli-Delhi Fold Belt, the Ajmer region hosts extensive pegmatite swarms within metasedimentary, metavolcanic, and igneous rocks of the Palaeoproterozoic to Mesoproterozoic Delhi Supergroup. This study applies a multidisciplinary approach to identify and characterise Li-bearing pegmatites across 11 sites by combining field mapping, geochemistry, mineralogy, and isotopic analyses. Geochemical and mineralogical characterisation using X-ray florescence (XRF), X-ray diffraction (XRD), laser induced breakdown spectroscopy (LIBS), scanning electron microscope (SEM) (automated mineralogy), optical petrography, and hyperspectral analysis confirmed lithium enrichment, with Li_2O concentrations reaching up to 5 wt per cent in the assay. The mineral assemblage includes spodumene, lepidolite, beryl, coloured tourmaline, and apatite, indicating advanced magmatic fractionation supported by low K/Rb and K/Cs ratios in the assay data. Preliminary geochronology (U/Th in zircon, Rb/Sr in mica, and K/Ar in micas and feldspars) suggests possible temporal relationships between the pegmatites and the surrounding regional granites, offering insights into their mineral system controls. SHRIMP–SIMS (Sensitive High-Resolution Ion MicroProbe – Secondary Ion Mass Spectrometry) analyses of stable oxygen isotopes ($^{18}O/^{16}O$) in quartz were performed on six pegmatite samples to gain insights into the source of the pegmatite-forming melts. This integrative analytical approach enhances the understanding of pegmatite genesis in Ajmer, India. It provides analytical tools to refine exploration strategies, improve vectoring toward fertile pegmatites, and support the identification of economically viable lithium resources in India, while also contributing to the global advancement of lithium pegmatite exploration.

Harnessing the true value of critical minerals – West Australian production of cathode materials

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ABSTRACT

With a rich endowment of battery-related minerals, Australia and Western Australia in particular are uniquely positioned to support the global energy transition away from fossil fuels. Nickel is a key element in modern battery technology, delivering higher energy density and greater storage capacity at a lower cost. Battery storage is a key enabler for renewables and decarbonising energy. Historically, Australia has predominantly exported intermediate nickel products including matte and mixed hydroxide product (MHP). An opportunity exists for Australia to capture significant additional value from further processing of intermediate products to battery materials. The establishment of a domestic precursor cathode active material (pCAM) industry is one pathway by which this can be achieved. Apart from development of a sovereign capability, onshore processing would be expected to provide lower emission pathways from ore to pCAM.

Research to identify improved pathways from Australian ore to pCAM is being undertaken by CSIRO and Curtin University in Australia's only Cathode Precursor Production Pilot Plant (C4P) facility, located in Perth. The two research institutions are partnered with and financially supported by the Minerals Research Institute of Western Australia (MRIWA) via project M10569. Leveraging the capability originally created by the Future Battery Industry Cooperative Research Centre (FBI-CRC), the current project aligns with the objectives of Western Australia's Battery and Critical Minerals Strategy 2024–2030 to increase onshore processing of raw materials to higher-value products. The C4P is the key component of the proposed Critical Minerals Advanced Processing (CMAP) common user facility.

The current presentation will outline results from R&D activities over the past year, including assessing pCAM tolerance to high impurity feed stocks, exploration of alternate battery chemistries, increasing operational flexibility (batch/continuous) and CFD modelling.

Securing graphite for the energy transition – insights from India–Australia resource and recycling strategies

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ABSTRACT

Graphite, the dominant anode material in lithium-ion batteries, is a critical mineral essential for electric vehicles and stationary energy storage. Demand for high-purity anode-grade graphite is projected to rise sharply, driven by global clean energy transitions. While Australia possesses significant natural graphite reserves (Siviour, McIntosh), India's domestic resources are limited and concentrated in states such as Jharkhand, Odisha, and Chhattisgarh, necessitating substantial imports for industrial use.

This work presents a comprehensive literature review on graphite's role in battery value chains, its sourcing and processing landscape in India and the emerging potential of recovery from spent lithium-ion batteries. Studies highlight that recovered graphite can achieve performance characteristics comparable to virgin material, while significantly reducing environmental impact and dependency on mined resources. India's evolving Battery Waste Management Rules provide a policy framework for large-scale recycling, and Australia's critical minerals strategy prioritises diversification of supply chains and downstream value capture.

By synthesising technical, policy, and market literature, this review explores how circular economy strategies, particularly, graphite recovery from battery waste can be integrated into a broader India–Australia critical minerals partnership. Such collaboration could combine Australia's upstream resource strength with India's downstream processing capacity and recycling potential, enhancing supply resilience, economic value, and sustainability outcomes for both nations.

Integrated water management in critical mineral mining – the role of digital innovation in sustainability and efficiency

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EXTENDED ABSTRACT

The global transition to net-zero is driving exponential demand for critical minerals such as lithium, cobalt, nickel, and rare earth elements—key components of batteries, electric vehicles, renewable energy infrastructure, and smart technologies (International Energy Agency (IEA), 2021). As production scales up, the mining of these minerals faces mounting environmental, operational, and regulatory pressures—none more critical than the challenge of water management.

Water is central to both open pit and underground mining operations. From ore processing and dust suppression to mine dewatering and tailings transport, nearly every phase of extraction relies heavily on water (World Bank, 2020). However, a large share of new critical mineral production is located in arid or drought-prone regions, with more than 50 per cent of global lithium output already occurring in high water-stress areas (World Resources Institute, 2023). This makes sustainable water usage not only an environmental imperative but a business-critical factor. Unchecked withdrawals or inefficient practices can trigger community conflicts, permit delays, and reputational damage, while also reducing operational resilience (Reuters, 2024).

The sector is experiencing increasing regulatory scrutiny. Governments are implementing stricter water use standards, requiring integrated water management plans, high recycling rates, and robust discharge controls (Anglo American, 2023). In parallel, investors and communities are demanding stronger ESG performance. In this context, water stewardship is no longer optional—it is a fundamental component of mining strategy and a determinant of long-term license to operate.

Integrated water management offers a pathway to address these challenges holistically. This involves aligning water sourcing, usage, treatment, and discharge within a closed-loop framework, minimising freshwater intake, maximising reuse, and ensuring water quality standards (Exxaro Resources, 2022). Beyond environmental benefits, this approach enhances resilience against drought and climate variability, reduces operational costs, and strengthens social acceptance.

Digital and automation technologies play a transformative role in making integrated water management practical and scalable. Platforms like Schneider Electric's EcoStruxure™ for Mining, Minerals and Metals enable real-time monitoring and predictive control of water consumption, storage, and quality across mining sites (Schneider Electric, 2023a). Leveraging IoT sensors, AI-driven analytics, and centralised dashboards, EcoStruxure™ empowers operators to identify leaks, reduce wastage, optimise pump schedules, and improve water reuse efficiency. Mines using EcoStruxure™ have reported up to 30–40 per cent improvements in water and energy efficiency, with lower maintenance costs and faster incident response times.

Complementing this, AVEVA's Unified Operations Center for Water offers an integrated command platform that visualises and manages entire water networks (AVEVA, 2023). By consolidating data from distributed assets—tailings dams, dewatering systems, treatment plants—it provides unified situational awareness and actionable intelligence. Its scalable architecture supports cross-functional coordination between field operators, plant managers, and sustainability teams, ensuring that water usage decisions align with ESG goals and operational needs.

Real-world applications underscore the value of these technologies. For instance, a major Latin American mining company achieved a 25 per cent reduction in freshwater withdrawal by deploying EcoStruxure™ with advanced metering and control systems (Schneider Electric, 2023a). Another mining complex in South Africa integrated AVEVA's Unified Operations Center to monitor and treat mine water for safe community discharge, earning regulatory recognition and community trust while reducing environmental liabilities (AVEVA, 2023). These digital tools also support scenario planning and regulatory compliance. AI-based simulation and forecasting tools enable mines to assess future

water risks, test contingency strategies, and optimise water allocation under different production or climate conditions (IEA, 2021). This foresight capability enhances strategic planning and mitigates the risk of costly downtime during droughts or supply interruptions.

Moreover, digital water management aligns closely with decarbonisation. Pumping, treating, and transporting water are energy-intensive processes (World Bank, 2020). By minimising unnecessary water use and enabling smarter scheduling, mines can cut emissions associated with water operations. This integrated approach—water stewardship coupled with energy efficiency—supports broader climate and sustainability commitments.

Schneider Electric's broader initiatives, such as the Materialize platform, further exemplify how cross-sector collaboration and shared best practices can help mining organisations fast-track decarbonisation and water sustainability (Schneider Electric, 2023b). Materialize provides a space for value chain actors to collaborate on responsible mineral sourcing, resource efficiency, and sustainable water-energy nexus solutions.

In conclusion, effective water management is pivotal to the future of critical minerals mining. As demand for these minerals continues to grow, so too does the scrutiny over their environmental and social footprint. Mining companies must move beyond compliance and adopt integrated water strategies that are efficient, transparent, and digitally enabled. By investing in smart platforms such as Schneider Electric's EcoStruxure™ and AVEVA's Unified Operations Center, mining operations can reduce costs, increase resilience, and build a credible sustainability narrative that meets the expectations of regulators, investors, and communities alike. In doing so, the industry not only safeguards its water resources but reinforces its role in enabling a more sustainable, electrified future.

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Trusted minerals – a vision and roadmap for provenance and traceability in critical minerals supply chains

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ABSTRACT

The growing global demand for critical minerals essential to the transition towards a decarbonised economy presents both significant opportunities and challenges. As governments and industries face increasing pressure to ensure responsible sourcing of critical minerals, provenance and traceability is indispensable to ensuring ethical extraction, transparent supply chains, and compliance with regulatory standards. Emerging regulations, such as the EU Battery Passport and the Carbon Border Adjustment Mechanism, highlight the urgency of verifying provenance and adhering to stringent sustainability standards.

Anticipating both the challenges and the opportunities of a rapidly evolving global landscape the Geological Survey of Queensland and FrontierSI collaborated to assess the current state and develop a future vision and roadmap for critical minerals provenance and traceability, guiding federal and state governments and industry through the complexities of digital credentialing, supply chain traceability, and ESG reporting.

The roadmap incorporates a maturity model that supports the staged implementation of provenance and traceability capabilities. Starting with foundational infrastructure and government stewardship, it advances toward digital verification systems, providing a framework for incorporating provenance and traceability into existing and developing supply chains. This phased approach enables seamless integration with broader strategic initiatives, including clean energy and a circular economy.

This roadmap offers a pathway for the Australian critical minerals sector to meet the regulatory challenges of the global marketplace while calling for government action to support smaller operators to meet these evolving demands. Our collective vision is for the Australian critical minerals industry to demonstrate leadership in environmental, social, and governance (ESG) practices, contributing to the global transition to a sustainable, net-zero economy.

Through this presentation we invite stakeholders from government, industry, and academia to engage with the roadmap and identify collaboration opportunities. Together we can ensure that the critical minerals sector is positioned for long-term success, embracing transparency, accountability, and sustainability.

KIGAM's technological approach to strengthening the resilience and sustainability of the lithium value chain – upgrading low-grade mineral resources and recycling spent li-ion batteries

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ABSTRACT

The rapid expansion of electric vehicle adoption and the global transition to renewable energy have driven a sharp increase in lithium demand. As a result, establishing a stable and sustainable lithium supply chain has become a global priority. In response, KIGAM is pursuing a dual strategy aimed at enhancing the resilience and sustainability of the lithium value chain by addressing both primary and secondary resources.

The primary focus is on eco-efficient recovery of lithium from low-grade ores, such as lepidolite, which are often considered economically unfeasible. KIGAM is developing advanced beneficiation technologies by thoroughly analysing conventional processes, designing innovative process flows, and customising flotation reagents to improve the grade and recovery of concentrates. Efforts are also underway to develop technologies for real-time monitoring and control of the beneficiation process.

The secondary focus is on advanced hydrometallurgical recycling of spent lithium-ion batteries (LIBs). To efficiently recover lithium, nickel, cobalt, and manganese, KIGAM is also developing pressurised and multi-stage leaching systems, co-extraction techniques, and automation of process operations. In addition, KIGAM is conducting greenhouse gas emission assessments and developing appropriate methodologies for the resulting recycling processes, contributing to the realisation of a circular battery system.

This dual strategy is expected to reduce reliance on high-grade imported resources and increase the use of domestic and secondary lithium sources. KIGAM's approach contributes to building an environmentally friendly and economically viable lithium value chain. Furthermore, the technologies under development offer scalability and adaptability, making them suitable for future deployment across diverse international contexts and creating new opportunities for global technical cooperation.

ACKNOWLEDGEMENTS

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By-products – maximising Australia's hidden critical mineral potential

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ABSTRACT

Gallium, germanium, and indium are critical minerals used in a variety of high-tech applications, net-zero emissions technologies and defence technologies, including semiconductors, solar cells, touchscreens and fibre optics. These elements are typically recovered as 'by-products' during the processing of major commodities such as aluminium and zinc. The association of gallium with bauxite, and germanium, indium and gallium with sphalerite in zinc ores is well described; however, the total resource endowment of these elements in mineral deposits at the national-scale is currently unknown.

Under standard mineral resource reporting codes such as the JORC Code, companies are obligated to report only those commodities material to the overall economic extraction of the deposit. As a result, elements produced as by-products are often overlooked in public announcements and are rarely publicly reported as part of a mineral resource. However, there is an increasing need for decision-makers to understand the potential national inventory of these commodities to prioritise resource development and establish domestic supply chains.

To address this knowledge gap, Geoscience Australia has developed a predictive methodology based on mineral system knowledge and mineralogical associations, using random forest-based machine learning algorithms, to estimate the *in situ* resources for gallium, germanium, and indium in Australian zinc deposits. Using this methodology, a by-products reporting tool to aid decision-makers and industry is under development. The tool will produce aggregate figures at a national-scale and report by-product estimates at the deposit-scale against known mineral systems and mineralogy. This will allow for an enhanced understanding of potential by-product production and will guide downstream processing requirements.

This capability establishes a foundation for future analytical techniques to estimate by-products in ores for a range of other commodities and mineral systems, and will improve national resource inventory estimates for critical minerals.

Mineralogical insights for antimony-gold flow sheet development – Hillgrove Project

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ABSTRACT

The Hillgrove Project, Australia's largest antimony mineral resource, has a long mining history dating back to 1857. Now entering a new phase of development following significant resource upgrades by Larvotto Resources, the project presents an opportunity to maximise value through modern mineral processing strategies. As part of the feasibility study, comprehensive mineralogical analysis was conducted to support the design of an efficient and selective flotation process for this complex antimony-gold system.

High-resolution characterisation using TESCAN Integrated Mineral Analyzer (TIMA), combined with targeted gold deportment studies, provided critical insight into mineral associations, textural complexity, and liberation behaviour. TIMA identified pervasive fine-grained intergrowths among stibnite, pyrite, arsenopyrite, and gangue minerals. Fine silicate inclusions within stibnite grains were shown to limit liberation, informing the selection of an optimal grind size to enhance recovery while managing downstream processing challenges.

Gold deportment results quantified the portion of free-gold, gold associated within stibnite and gold locked in other sulfides, highlighting opportunities and directions for selective processing. In addition, the presence of antimony oxide in flotation tailings was identified as a recoverable loss pathway.

The study demonstrates how detailed, early-stage mineralogical characterisation can drive smarter processing decisions and decrease the risk of flow sheet development. By combining TIMA mineralogy with gold deportment data, the project team gained valuable insight into the mineralogical controls on recovery, enabling more selective and effective flotation design. This case study highlights the value of modern mineralogical tools in unlocking the full potential of complex polymetallic ores, and their critical role in guiding successful project development.

Advancing sustainable lithium metal production – LithSonic™

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ABSTRACT

The advancement of next-generation solid-state batteries hinges on access to lithium metal – a material that is costly and constrained by limited global supply. Current industrial lithium metal production via antiquated molten salt electrolysis, a process largely unchanged since its introduction in 1923, is energy-intensive, expensive, and can be environmentally damaging. With its abundant lithium resources, Australia is well-placed to lead the development of a cleaner, more efficient production method that meets high environmental, social and governance (ESG) expectations and supports global supply chain diversification.

At CSIRO, we are developing a novel approach to lithium metal production through our patented LithSonic™ process, which utilises carbothermic reduction – a high-temperature reaction between lithium compounds and carbon at temperatures exceeding 1500°C – to produce lithium metal directly. The produced lithium metal vapour and CO gas are then rapidly quenched using a supersonic nozzle, a rocket-engine-inspired technology, cooling the gas mixture at over a million degrees per second and 'freezing' lithium metal in a non-equilibrium state to minimise the occurrence of reversion reaction commonly observed otherwise.

Crucially, the high-temperature reduction step not only drives the core reaction but also determines the flow dynamics and conditions essential for nozzle design. This study focuses on establishing a fundamental understanding of the carbothermal reduction kinetics and reaction dynamics under varying experimental conditions, such as temperature profile, sample and gas conditions. Small-scale experiments coupled with thermodynamic modelling provide valuable insights into the melt and gaseous chemistry and behaviour – key to scaling and optimising the process.

The latest findings and technological development progress will be presented, illustrating a significant step towards a more sustainable, scalable, and economically viable pathway for lithium metal production with improved ESG outcomes in response to global demand. Establishing this technology could support the creation of a downstream lithium processing industry in Australia and strengthen the resilience of global supply chains.

Unlocking Australia's unique opportunity in critical minerals while navigating uncertainties in geopolitics and the global economy

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ABSTRACT

Australia has substantial opportunities in critical minerals as we decarbonise the global economy. Our trading partners are also depending on us to be a key part of their evolving strategic and low-emission technology supply chains.

Despite these significant tailwinds, navigating the right path ahead is far from easy. Geopolitical tensions have dramatically magnified uncertainties in the global economy and reduced the short-term growth expectations.

As the dominant market for our minerals, how will China's growth outlook impact the mining sector's near-term performance and project development opportunities?

Australian has played an important role internationally as a stable and reliable supplier of resources.

While few win when the world's largest economies collide, are there potential benefits for Australian mining companies in this higher risk environment?

The presentation will explore how our minerals opportunities will be impact by these changes, particularly:

- the evolution of global relationships and international trade
- changes to global supply chains
- financial market responses, in the short and longer term
- potential increased market volatility
- how this impacts critical minerals markets (notably emerging markets)
- how greater collaboration (at both industry and regional levels) might provide solutions.

The presentation will also share our perspectives on a reimagined future. This includes accelerated M&A activity to increase capabilities across both the opportunity and risk horizons. Mining companies are already starting to explore different types of economic relationships with customers. How will mining, technology, industrial and other companies combine their resources to shape a better world ahead?

Selective flotation of fine spodumene with anionic polyacrylamide flocculant and calcium activator

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ABSTRACT

Froth flotation is widely used to recover spodumene, a key lithium-bearing mineral. However, the recovery efficiency of fine spodumene particles (<30 μm) remains a significant challenge due to their low mass and poor collision efficiency with air bubbles. Conventional flotation methods often struggle to effectively separate these fines, leading to significant lithium losses in processing operations. This study explores a selective aggregation-flotation strategy to improve fine spodumene recovery. Calcium ions (Ca^{2+}) are introduced to selectively activate spodumene surfaces, enhancing polymer and collector adsorption. Anionic polyacrylamide (PAM) flocculants are then applied to induce selective aggregation, forming larger spodumene aggregates (>50 μm) while quartz remains unaggregated. These larger aggregates exhibit improved flotation kinetics and separation efficiency. This method significantly improves the recovery of fine spodumene and offers a scalable and sustainable solution for lithium beneficiation. The findings contribute to optimising critical mineral processing and support the industry's transition toward more efficient and responsible resource utilisation.

Processing and refining – does Australia have what it takes to compete?

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ABSTRACT

Australia's critical minerals policy aims to capture greater value by expanding downstream processing and refining capabilities. However, this ambition faces significant challenges, particularly in the context of concentrated global supply chains and persistent non-market practices that distort competition. Despite strong resource endowments, Australia's critical minerals production has struggled to scale in the face of these structural constraints. Refining is technically complex and economically demanding, requiring supportive geographic, infrastructural, and market conditions. This presentation by the Critical Minerals Association Australia (CMAA) will examine the core factors influencing the feasibility of local processing and refining, including energy needs, co-location benefits, environmental requirements, and access to technology and skills. It will also assess the broader geopolitical context shaping supply chain realignments and highlight both the comparative advantages and systemic limitations of the Australian landscape. The session aims to contribute to a more grounded understanding of what is realistically achievable in Australia's critical minerals value chain.

Addressing Western Australia's critical minerals – opportunities, bottlenecks, and perspectives

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ABSTRACT

Western Australia is home to a vast range of critical minerals, including lithium, cobalt, nickel and rare earth elements, reinforcing Australia's leading role in the global supply chain. This study provides a systematic description of the multi-phase process of these minerals, including exploration, mining, processing and manufacturing. It also identifies and gives initial insights into popular and lesser-known minerals, such as key challenges and opportunities for the industry. Exploration efforts have delineated significant mineral resources, yet challenges persist due to insufficient geospatial data integration, underinvestment in lower-profile minerals and the complexities in processing low-grade ores. A substantial limitation in Western Australia's critical minerals sector is the lack of integrated midstream and downstream manufacturing capacity. While mining operations and primary beneficiation techniques are well-developed, refining operations are dependent on offshore expertise. Thus, tracking the life cycle of lesser-known minerals is another challenge due to their overseas processing, primarily in Asian countries. This also highlights the absence of data regarding minor minerals production in Western Australia. The absence of large-scale domestic manufacturing facilities results in the export of intermediate products, limiting the state's ability to capture value along the supply chain. Market volatility and geopolitical risks further discourage long-term investment in critical mineral production. Addressing these structural limitations requires targeted interventions, investment in downstream manufacturing, strengthening government-industry partnerships and integrating secondary processing and recycling frameworks.

INTRODUCTION

Access to critical minerals has become a defining factor in global industrial competitiveness, energy security and geopolitical strategy. As nations accelerate the deployment of clean technologies, the reliability of critical mineral supply chains has shifted from a niche concern to a central pillar of national policies. The limited availability and geographic concentration of several of these resources render them a strategic priority (Zhao and Zhao, 2025). Most countries have not yet adequately or efficiently explored their lands to identify potential mineral resources, limiting their ability to engage in global supply chains. Despite their importance, many resource-rich countries continue to grapple with inefficiencies in mineral utilisation due to technological gaps, inadequate infrastructure, limited expertise and constrained investment. Recent trade tensions have further exposed the fragility of global supply chains, highlighting their susceptibility to export restrictions, market manipulation and systemic risks.

As of February 2024, the Australian Government considers 31 resource commodities to be critical minerals (essential to modern technologies, economies, and national security) (Geoscience Australia, 2025). Western Australia (WA) is home to some of the largest recoverable critical mineral deposits on earth. Beyond its status as the largest (47 per cent) supplier of lithium globally and the sole producer of nickel in Australia, the state also hosts significant mineral resources of rare earth minerals (REE), vanadium, cobalt and high-purity alumina (HPA) (Western Australian Government, 2024). Despite the state's mature mining industry, WA faces critical bottlenecks in realising the value of its minerals. Strategic development is undermined by fragmented data sets, inconsistent resource classifications and limited integration of data from exploration and downstream processing. These limitations complicate investment decisions, obscure project pipelines and impede efforts to develop vertically integrated supply chains within the region.

To address this gap, the study presents the first integrated overview of the critical mineral supply chain across Western Australia. The objective was to develop comprehensive profiles for all 31 critical minerals, identify systemic bottlenecks and risks along the supply chain and propose a holistic framework that aligns geological potential with processing capabilities and policy mechanisms. Importantly, this study acknowledges the uneven level of attention given to these commodities where focus has traditionally been on well-known battery minerals and REEs, while lesser-known critical minerals remain underexplored. This work contributes by offering a balanced assessment that includes both major and minor commodities, shedding light on overlooked opportunities for processing and value addition.

In this study, major critical minerals are defined as those that are abundant in Western Australia, actively exploited and researched. Minor critical minerals refer to those present in low concentrations, with limited commercial development and minimal focus. This classification provides a basis for assessing processing pathways and identifying opportunities across the full spectrum of WA's critical mineral landscape.

LITERATURE REVIEW

Whereas critical and strategic mineral terms entered the lexicon at the beginning of the current century due to some events, global acceptance and recognition of such minerals have coincided with the onset of this century. World Wars I and II primarily were the main drivers for identifying critical commodities in the USA and essential commodities in the UK (US Congress, 1939; Hurstfield, 1953). Additionally, subsequent events, such as technological innovation in areas like satellites and the growing significance of computer chip materials, underscored the importance of critical minerals towards the end of the 20th century even more (NRC, 2008). Interestingly, history often repeats itself in different ways. Today's supply chain challenges seem more advanced, but they are still rooted in the same problems we've seen before, just influenced by new circumstances. Factors such as trade wars, technological advancements, fragile mineral markets, and net-zero emission goals are just a few of the many reasons for the increased popularity of criticality, creating significant concerns worldwide (Vivoda, Matthews and McGregor, 2024).

Global outlook

Numerous countries and unions have identified critical minerals and engaged in various discussions, debates, conferences, policies, and events that have been and are still ongoing about critical minerals. Although ten countries, namely Argentina, China, India, Japan, the EU, South Africa, South Korea, Turkey, the UK and the USA, have officially published their criticality schemes, 12 countries, including Australia and Canada, have officially identified and published their critical minerals lists, updating them several times (Zappettini, 2021; Mammadli *et al,* 2024; Department of Mineral Resources and Energy (DMRE), 2025). However, there are more scientific criticality publications and reports, many of which have not been officially published by various governments.

The USA was the first country to publish the first critical and strategic mineral lists just before the war in 1914 and the first criticality methodology scheme in 1939, as covered in the Strategic and Critical Materials Stockpiling Act of 1939 (USGS, 2019; US Congress, 1939). The 1974 Critical Imported Materials report by the Nixon Administration highlighted bauxite, platinum, and chromium as critical supplies because of price gouging and supply chain vulnerabilities (Council on International Economic Policy, 1974). In 1978, the US DOE assessed critical minerals needed for NASA's Satellite Power System, introducing five criticality categories (Kotin, 1978). The NRC's 2008 evaluation noted an increase in demand for chip materials from 12 in the 1980s to 60 in the 2000s, highlighting five critical commodities among the 13 studied (NRC, 2008). Subsequent US criticality schemes include the 2010 National Defence Stockpile, US DOE reports (2010, 2011, 2023), and

NSTC evaluations (2016, 2018). However, the USA is not the only country with numerous criticality assessments; at the same time, it has 46 official and scientifically recognised critical and strategic mineral lists (Thomason *et al,* 2010; US DOE, 2010, 2011, 2023).

In addition to the USA, several countries and unions have developed their own critical mineral lists and assessments. However, the insights from the USA are unique due to its historical context, the evolution of critical minerals, and the reasons behind their changing significance (Castro-Sejin, Mammadli and Barakos*,* 2023). It's crucial to recognise that while the USA has played a leading role in the critical minerals discourse, it is undeniable that every nation has different conditions not only geographically, but also politically and in terms of market conditions. Consequently, it remains essential for other countries to publish, update or review their criticality assessments and take appropriate measures based on their lists and insights to ensure their safety, defence, and progress. For example, the USA has primarily focused on energy independence, industrial growth, and defence.

Regarding critical minerals policies, the EU's objectives have centred around green technology, aiming to reduce supply dependence and enhance recycling. In Europe, the production of minerals and metals remains low, leading to a considerable reliance on imported critical raw materials. As a result, criticality assessments of raw materials in Europe have become increasingly significant in recent years, particularly since the European Commission (EC) has released five criticality assessments over the past 15 years, since 2010. While earlier assessments concentrated on supply risks and economic significance, the latest one also incorporates the environmental importance of critical commodities, aligning with the commendable goals of achieving Net Zero emissions. The initial assessment in 2011 identified 14 critical commodities (EC, 2011), with numbers rising from 20 in 2014 (EC, 2014) to 27 in 2017 (EC, 2017), 30 in 2020 (EC, 2020), and 34 in the latest 2023 update (EC, 2023).

The European Commission's criticality assessment is the most prevalent framework, shaping the approaches of countries such as the UK and India, which have modified the EU method to align with their own national priorities (Mammadli *et al,* 2024). Although their goals, such as energy security, industrial expansion, and green transition, are similar, their prioritised lists differ due to unique national contexts. India emphasises economic self-sufficiency and the 'Make in India' campaign, while the UK focuses on strengthening supply chains post-Brexit and building international partnerships. Although the UK depended on EU evaluations until 2019, earlier unofficial assessments were conducted by Oakdene Hollins (Eatherley and Morley, 2008) and the official risk minerals lists were identified by the British Geological Survey (BGS, 2011, 2012, 2015). The first official UK list was published in 2021, identifying 18 critical minerals (BGS, 2021). India released its initial list in 2012 and updated it in 2023 to include 30 critical commodities (Center for Study of Science, Technology and Policy (CSTEP), 2012; Ministry of Mines, Government of India (MMGI), 2023).

While Argentina's 2021 criticality assessment highlighted some points from international criticality groups, it applies its own distinct national methodology rather than indirectly adopting the EU methodology, despite its similarities. The evaluation, led by SEGEMAR (Argentine Geological Mining Service), considers local production capability, economic relevance, and geopolitical context using an especially tailored-to-Argentine-requirements scoring system. The country concentrates on minerals like copper and lithium to enable export expansion and its role in the global energy transition. This contrasts with the EU supply risk concentration, whereas Argentina's classification emphasises availability and economic opportunity due to its development-driven policy (Zappettini, 2021).

On the other hand, tech giants and significant global players in the processing and manufacturing sector, like Japan, rely heavily on minerals and metals. Since the 1920s, Japan has faced a significant shortage of minerals and metals and relies on external sources for most of the essential raw materials that support its growing industrial sector (Van Antwerp MacMurray, 1921). Political events like WWII and geopolitical ties, particularly with China, led Japan to experience defeat and trade restrictions (Yoshino and Lifson, 1986). In the 1980s, Japan expressed concerns regarding supply risks and released a list of essential commodities. However, it was not until 2009 that the New Energy and Industrial Technology Development Organisation (NEDO) carried out the first official criticality assessment. Despite the rising interest in various scientific criticality assessments for Japan (Hatayama and Tahara, 2015), the Japan Organisation for Metals and Energy Security (JOGMEC) conducted further official assessment in 2015 (JOGMEC, 2015). The Ministry of Economy, Trade and Industry (METI) finalised the latest assessment in 2020 (METI, 2020).

Interestingly, Japan's framework has influenced other nations, such as Turkey, which adapted the NEDO model to fit its national context. In 2025, Turkey officially published its list of critical and strategic minerals aligned with national priorities (Ministry of Energy and Natural Resources of the Republic of Türkiye, 2025). While both countries acknowledge the significance of securing mineral supply chains, their targets reflect distinct developmental and industrial requirements. Japan primarily focuses on securing high-purity materials necessary for advanced electronics, semiconductors, and green technologies, aiming to diminish reliance on China and ensure stability for its high-tech industries. Conversely, Turkey prioritises national resource development, energy transition, and industrial competitiveness, especially in mining and metallurgy. Despite these differences, both countries seek common objectives like enhancing supply chain resilience, lowering import dependence, and fostering technological innovation in material processing.

Like Japan, South Korea is also heavily dependent on imported minerals, whereas it is also a tech giant globally and has very sophisticated recycling technologies. Since the mid-1980s, the demand for minerals forced the country to develop its waste management and adopt the 3Rs principles, namely reduce, reuse and recycle, in the 1990s (OECD, 2017; Lee and Cha, 2018). In 2014, KIRAM and KITECH collaborated on a study that identified 11 essential commodities considering their rarity, supply instability, and price volatility, highlighting a proactive strategy for evaluating criticality (Lee and Ott, 2016; Schrijvers *et al,* 2020). The most recent list, officially announced by the Korean Ministry of Trade, Industry and Energy (MTIEK), identifies 33 minerals as critical for South Korea, with 10 of them classified as the most strategic commodities for the nation (MTIEK, 2023). South Korea, one of the global electronics leader and battery manufacturers, targets supply chain security, establishing international partnerships for critical minerals, foreign investment, and mining operations for bilateral partnerships. It has made large deals with resource-rich countries like Australia, Canada, Kazakhstan, and several African nations. In 2021, a Memorandum of Understanding with Australia focused on securing lithium, cobalt, and rare earths (Department of Industry, Science, Energy and Resources (DISER), 2021). This followed a 2023 agreement with Canada to further EV and battery supply chains, and a 2024 agreement with Kazakhstan to access its mineral resources alongside Korean technology (Government of Canada, 2023; Kim, 2024). During the 2024 Korea-Africa Summit, South Korea signed nearly 50 contracts with 23 African nations, including Tanzania and Madagascar, to increase access to battery minerals (Lee, 2024).

A country that holds the position as the largest importer of raw materials, nearly 100 per cent capable of processing REE (EC, 2023) and other critical minerals globally, and not only processes but also mines many more minerals. At the same time, it is one of the significant manufacturers of products made with critical commodities. China is currently the dominant player in almost every stage of the value chain. Interestingly, historical imperatives and strategic intent have shaped the Chinese approach to critical minerals. In response to mid-20th-century resource shortages, China entered the rare earth sector in the 1950s, gradually establishing a leading global role. This was based on Inner Mongolian mining and boosted by pro-investment policies, especially after cooperation with Japan in the 1970s (Kim, 1985; Barteková and Kemp, 2016; Hammond and Brady, 2022). In 2016, China issued the National Plan on Mineral Resources, naming 24 strategic commodities as its first key assessment. Compared to Western systems, China's classification comprises six criteria founded on strategic sector applicability, supply risk, and substitutability. The broader Chinese goal is not merely to guarantee supply but to maintain technological superiority, secure industrial competitiveness, and enhance national security. All these initiatives allowed China to turn the impossible into the possible (General Office of the State Council, 2016; Andersson, 2020).

In 2025, South Africa became the first African nation to release an official criticality assessment, which identified 21 minerals in order of their level of importance. Unlike methodologies from other countries, South Africa's plan emphasises its own national goals, such as industrial growth, local beneficiation, green hydrogen projects, and regional cooperation. The strategy aims to transform the country from a raw material exporter into a regional processing hub, fostering economic growth, employment opportunities, and participation in global clean energy supply chains (DMRE, 2025).

From a global perspective, only one country remains: Canada, which has never published its criticality assessments. However, it has published numerous critical mineral lists. The first critical mineral list was published in 2022 with 31 commodities, and the following updated list, with 34 minerals, was published in 2024 (NRC, 2022; Government of Canada, 2023). Interestingly, Canada was the first country to officially considered copper as critical. The reason behind it was the obvious need for clean energy. Another interesting fact about Canada is its province of Quebec, which published its list of critical and strategic minerals in 2020, just before Canada's official list. The report provided important insights into their uses. While not comprehensive, it briefly touched on significant details regarding the province's future in critical commodities (Ministry of Energy and Natural Resources Quebec, 2020).

An outlook to Australia's critical minerals

Australia, a resource-rich nation, holds many strategic and critical commodities and leads in various commodity production globally, which are strategic for many countries but also critical for some countries. Like Canada, Australia has also published its lists of critical minerals, yet it lacks an independent criticality assessment. In 2013, the Australian government issued a report detailing 33 critical commodities and the nation's capacity to fulfil global demand. However, the initial Australian critical mineral list, which includes 24 commodities, was released by the Australian Trade and Investment Commission (Austrade) in 2019 (DIIS and Austrade, 2019). In the same year, the 'Perth Usasia Centre' released a paper titled 'Critical Materials for the Twenty-First Century Indo-Pacific' following the EU methodology (Wilson, 2019). The Department of Industry, Science, Energy and Resources published the second report on critical minerals in 2022, covering 26 commodities (DISER, 2022). This was succeeded by a report in 2024 in which the government identified 31 critical commodities. In the same year, there was a scientific criticality evaluation scheme for Australia, which examined 32 commodities, and the assessment result was 14 critical and 18 strategic commodities (Mammadli, Barakos and Chang, 2024). It is important to note that Australia still lacks an official evaluation scheme that can provide insights into gaps within the sector. Generally, Australia's approach aligns with Western framework such as primarily focusing on supply chain resilience, economic growth and clean energy transition, at the same time such as Chinese approach the country also focusing on national priorities, supporting regional development through job creation, infrastructure investment, and the promotion of mining activities in remote and resource-rich areas like Western Australia and the Northern Territory (DISER, 2023).

The most up-to-date Australian critical minerals list is presented in Table 1, alongside 11 other official lists published by countries worldwide, forming a comprehensive global overview of critical minerals. In 2024, the Minerals Research Institute of Western Australia (MRIWA) initiated a project with Trailblazer, Curtin University, to prepare a collection of commodities' profiles based on Australia's most recent 31 critical mineral lists (Government of WA, 2025). This initiative marked the first globally state-based analysis of critical minerals conducted comprehensively, offering insights not only into recent trends or changes but also into historical production and processing data. The motivation behind this work was to analyse all commodities and provide insights within the state, identify potential opportunities, gaps, and bottlenecks, highlight the potential development of processing plants and manufacturing facilities, and emphasise environmental, social, and governance principles for each commodity.

TABLE 1

Critical mineral lists officially published by 12 countries (Mammadli *et al,* 2024).

CRM	Argentina 2021*	Australia 2024	Canada 2024	China 2021	EU 2023	Japan 2020	India 2023	South Africa 2025	South Korea 2023	Turkey 2025	UK 2021	USA 2023
Aluminium	√	√	√	√	√	√		√	√	√		√
Antimony		√	√	√	√	√	√		√	√	√	√
Arsenic		√			√					√		√
Barium												
Baryte					√					√		√

CRM	Argentina 2021*	Australia 2024	Canada 2024	China 2021	EU 2023	Japan 2020	India 2023	South Africa 2025	South Korea 2023	Turkey 2025	UK 2021	USA 2023
Beryllium		√			√		√					√
Bismuth		√	√		√		√		√	√	√	√
Borate					√							
Cadmium							√			√		
Carbon						√						
Cesium			√									√
Chromium	√	√	√	√		√		√	√			√
Cobalt	√	√	√	√	√	√	√	√	√	√	√	√
Coking Coal				√	√			√		√		
Copper			√	√	√	√	√	√	√	√		
Feldspar					√					√		
Fluorine		√				√						
Fluorspar			√		√			√				√
Gallium		√	√		√	√	√			√	√	√
Germanium		√	√		√	√	√			√		√
Gold				√		√		√				
Hafnium		√			√		√					√
Helium			√		√							
HREE	√	√	√	√	√	√	√	√	√	√	√	√
Indium		√	√			√	√		√	√	√	√
Iron			√	√		√		√		√		
Lead						√				√		
Lithium		√	√	√	√	√	√	√	√	√	√	√
LREE	√	√	√	√	√	√	√	√	√	√	√	√
Magnesium		√	√		√	√					√	√
Manganese		√	√		√	√		√	√	√		√
Molybdenum		√	√	√		√	√		√	√		
N. Graphite	√	√	√		√		√	√	√	√	√	√
Nickel	√	√	√	√	√	√	√	√	√	√		√
Niobium		√	√		√	√	√		√	√	√	√
PGM	√	√	√		√	√	√	√	√	√	√	√
Phosphate					√			√				
Phosphorous	√		√	√	√	√	√					
Potash			√				√					
Rhenium		√				√	√					
Rubidium												√
Scandium		√	√		√							√
Selenium		√					√		√			
Silicon metal		√	√		√		√		√		√	
Silver						√				√		
Strontium					√	√	√		√			

CRM	Argentina 2021*	Australia 2024	Canada 2024	China 2021	EU 2023	Japan 2020	India 2023	South Africa 2025	South Korea 2023	Turkey 2025	UK 2021	USA 2023
Tantalum		√	√		√	√	√		√		√	√
Tellurium		√	√				√				√	√
Thallium												
Thorium												
Tin			√	√		√	√		√	√	√	√
Titanium		√	√		√	√	√	√	√	√		√
Tungsten		√	√	√	√	√	√		√		√	√
Uranium			√	√				√				
Vanadium		√	√		√	√	√	√	√		√	√
Yttrium						√						
Zinc			√			√			√	√		√
Zirconium		√		√		√	√	√	√			√

The information above focuses on countries that have officially published lists of critical minerals. While Australia and Canada are included for having official lists, they have not yet conducted comprehensive criticality assessments. Including Australia, numerous scientific papers exist on the criticality assessments of other countries, primarily in scientific publications rather than government reports. Nevertheless, all countries have different targets, strategies, conditions, and needs, except for supply risk (not necessarily for minerals, it can be technology), which is a significant concern for all countries. To decrease these concerns, the EU acted and started the Horizon project for critical commodities, for which a mineral profile has been conducted within three years and published in 2023 (Grohol and Veeh, 2023). At the same time, USGS conducted a mineral profile, which mainly highlighted their production, major producers and the reasons behind the decrease and increase in production (USGS, 2024). Unlike the EU, the USA keeps it brief, whereas the EU has conducted detailed profiles for each critical commodity.

The literature review gave essential insights regarding the number of critical commodities and countries' targets. However, there was a lack in that many countries still have not conducted detailed commodity profiles, and there is a lack for many nations, including Australia, specifically Western Australia. Given insights highlighting that having mineral resources is not enough to consider a commodity strategic. If the country does not have the technology to mine it, lacks processing plants and facilities, or has scarce or lacking manufacturing capabilities, it highlights that the government will face problems eventually. Argentina, Australia, Canada, and many more countries have mineral resources but face processing and manufacturing hurdles (Shiquan and Deyi, 2023).

On the other hand, Japan and South Korea are leaders in processing and manufacturing, whereas they have a supply risk problem with commodities. This is a holistic landscape of mineral criticality; all puzzle pieces should be gathered to understand the whole concept. Therefore, this work aims to conduct each critical commodity profile based on four pillars (exploration, mining, processing, manufacturing) to understand all opportunities, bottlenecks and difficulties within various sectors in WA.

METHODOLOGY

This study adopts a mixed-methods approach, combining quantitative resource data analysis with qualitative policy evaluation to assess the critical mineral supply chain in WA. The scope spans the entire value chain, from exploration through to manufacturing within the context of WA. The analysis covers the period (1980–2025), allowing for the identification of long-term trends in production, processing, and strategic planning. A global perspective on processing techniques was also incorporated to benchmark national performance against international best practices.

Data sources on mineral occurrences and location, resource and reserve tonnages, production volumes in WA were obtained from Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) Data and Software, WA Geological Survey, Geoscience Australia, Statista, as well as peer-reviewed journal articles accessed through Google Scholar, Scopus. Overall, about 200 articles assessed as illustrated in Figure 1. Keyword for search included 'critical minerals WA', 'mining', 'strategic metals', 'reserves', 'production', 'mineral export WA', 'battery metals', 'ESG policy frameworks'. All data points were cross-referenced with multiple sources where possible to ensure validity.

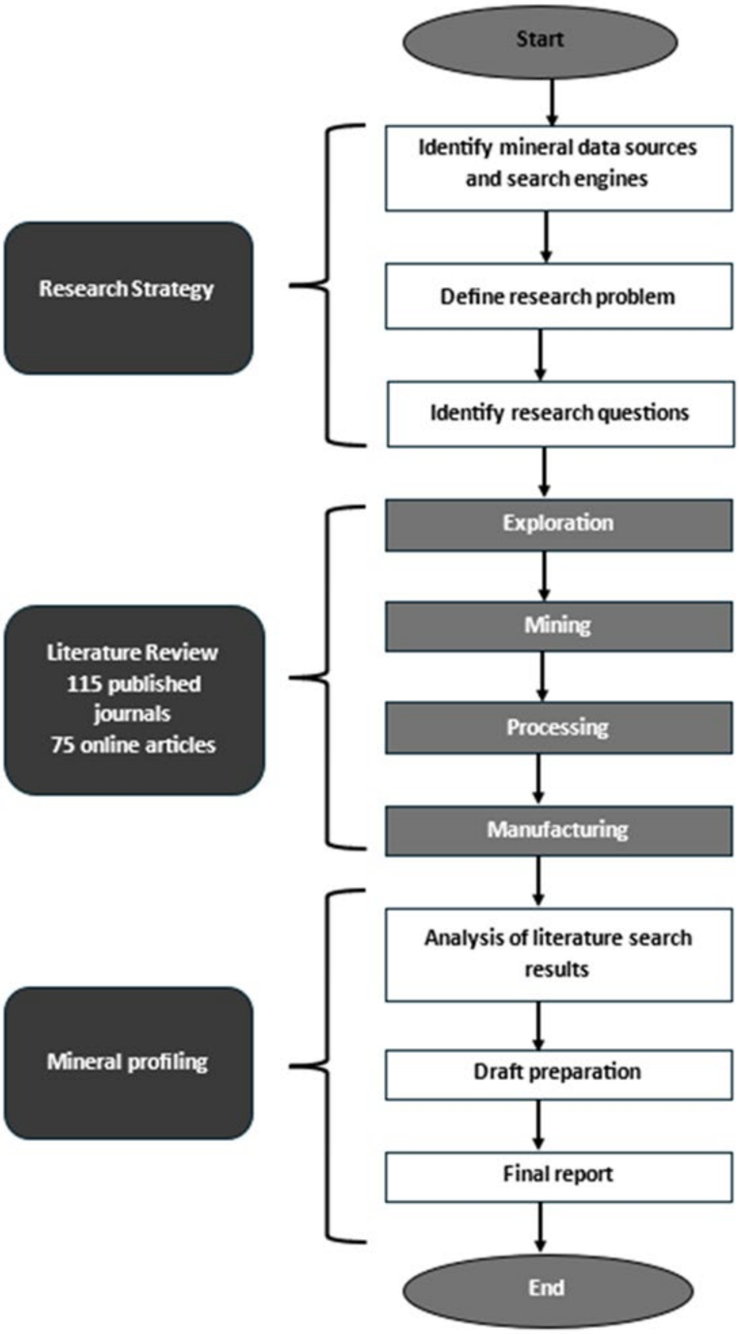

FIG 1 – Overview of the methodology.

To facilitate a structured assessment, the critical minerals supply chain was divided into four sections: exploration, mining, processing and recycling, and manufacturing. This classification enabled a modular analysis aligned with the structure of the research team, where each subgroup focused on one stage while ensuring interconnectivity with others. The framework was adapted from international models, including those developed by the EC (EC, 2023; USGS, 2024).

The data sets were standardised and prepared in Excel by correcting inconsistencies in units, formatting tonnage and concentration data. The data were then analysed to map the distribution of critical mineral resources, identify high-value deposits in mining cities in WA. Existing flow sheets and processing technologies were reviewed to assess technical capabilities and identify inefficiencies, particularly in midstream, processing. Comparative assessments with international reports were undertaken to benchmark performance, identify technological gaps and highlight best practices. To ensure consistency across all commodity profiles, a structured content development process was used, summarised in Table 2. This table outlines the standardised value chain phases, and the scope of content included in each.

TABLE 2

Summary of the table of contents applied across all critical commodity profiles in Western Australia.

Value chain phase	Description of included content
Overview of commodity	This section provides a general description of the commodity, including its key properties, major uses, and an overview of its significance in both global and local markets.
Exploration phase	This section covers the geological context, locations of known deposits, estimated resources/reserves, and details of active exploration projects in WA.
Mining and extraction	It highlights existing mining operations, developing, care and maintenance mine sites, ownership and production levels, and outlines the extraction methods (surface or underground) used.
Processing phase	Describing the primary processing techniques, efficiency levels, and the current or proposed processing facilities and their capacities in WA.
Manufacturing phase	This section highlights the commodity’s end-use applications, key demand sectors, and any associated manufacturing activities or capabilities within WA.
Recycling and substitution	Discusses the potential for recycling, the current infrastructure in WA, and the extent to which the commodity can be substituted in its key applications.
Sustainability and ESG	Explores environmental, social, and governance principles, including sustainability concerns, regulatory frameworks, and social license to operate.

Stakeholder engagement was conducted through consultation with the Minerals Research Institute of WA (MRIWA), which helped shape the project’s direction and ensured alignment with industry and government priorities. Validation of findings was achieved through cross-verification of data with government publications, academic sources, and previous national and international critical minerals assessments. This triangulation approach enhanced the robustness of the analysis and the credibility of the conclusions.

RESULTS AND DISCUSSION

Exploration

Out of WA’s 31 critical commodities, only a few, including both well-known and lesser-known resources, have been selected for comparison based on their total resource estimates, deposit distribution, and exploration difficulties. The gaps in lesser-known minerals, with no recent exploration and only historical records, are also outlined. Table 3 highlights that in WA, well-known critical minerals such as bauxite, cobalt, and rare earth elements (REEs) have a rich exploration history, large resource reserves, and clearly defined deposits, and are consistently classified under modern standards. These commodities benefit from ongoing industrial focus, facilitating systematic drilling, sophisticated geological modelling, and dependable data collection. Conversely, lesser-known minerals such as antimony, arsenic, bismuth, gallium, germanium, and scandium face substantial exploration challenges. These include limited or outdated information, low-grade or dispersed occurrences, and their status is often secondary rather than primary.

TABLE 3

Well and lesser-known critical minerals in WA currently at the exploration phase (Jones, 1980; DEMIRS, 2025).

Mineral	Resources (Mt)	Number of deposits	Main deposits (tonnage-based)	Data gaps/bottlenecks
Aluminium/ Bauxite	2985.47	46	Cape Bougainville, Prairie Downs	No exploration bottleneck
Antimony	0.04207	3	Blue Spec, Mt Clement	Volatility reduces interest
Arsenic	0.01845	4	Silver Swan, Mt Edwards	Toxicity and handling risks Limited exploration and outdated data
Beryllium	0.000242 (1973–1978)	> 5	Mt Francisco, Wodgina, Roebourne	Toxicity and handling risks Limited exploration and outdated data
Bismuth	N/A	N/A	N/A	No active exploration projects Volatility
Cobalt	2.69	62	Wingellina, Murrin Murrin	Geopolitical concentration Market Dynamics
Gallium	N/A	3–5 (associated)	Ajana, Wildflower, Salazar	Associated with other deposits Limited and outdated data
Germanium	N/A	3–5 (associated)	Ajana, Salazar, Lort River	Associated with other deposits Limited and outdated data
REE	2504.84	18	Mt Weld, Cummins Range	Complex geology affects exploration accuracy
Scandium	0.0155	6	Kalgoorlie Nickel Project, Mangaroon	Limited resource data, low-grade deposits

Additionally, some minor minerals, especially arsenic and beryllium, pose toxicity risks and require complex handling, reducing their economic viability. Coupled with low market demand and insufficient processing facilities, these issues limit their development despite growing strategic interest.

Mining

Western Australia is the leading state hosting many critical commodities, such as rare earth elements, nickel, lithium, and cobalt, which the Australian government has also officially identified as critical minerals (Government of Western Australia, 2023a). Although these commodities are present in WA, bottlenecks remain in downstream operations, reinforcing their classification as critical for Australia. WA also produces essential commodities such as gold, iron, and copper, which are considered strategic for Australia due to their significance to domestic needs and international partners, including the EU, USA, Japan, and India, where these commodities are classified as critical. While the mining landscape for well-known commodities is solid and extensive, developing lesser-known critical minerals such as arsenic, scandium, gallium and germanium remains hindered by limited data, low economic viability, and a lack of integrated extraction strategies as shown in Table 4.

TABLE 4

WA's critical minerals production status (Jones,1980; Department of Mines of Western Australia (DMWA), 1990; Department of Mines, Industry Regulation and Safety (DMIRS), 2021; Environmental Protection Authority (EPA), 2022; Department of Jobs, Tourism, Science and Innovation (DJTSI), 2024).

Mineral	Current/ historical production (t or Mt)	Number of active mines	Key mine sites (current/ historical)	Current/ past key operators	Export value (AUD)	Mining bottlenecks	Key export destinations
Alumina-Bauxite (well-known)	14.36 Mt alumina, 1.84 Mt bauxite (2020–2021)	6	Willowdale, Huntly, Worsley	Alcoa, South32	$5.668 billion (2020–2021)	No Al smelters in WA High energy cost	China, UAE, India
Antimony (lesser known)	5430 t antimony metal (1978)	N/A	Moonlight-Wiluna, Blue Spec	N/A	N/A	By-product dependency Scarcity of updated reserves	N/A
Arsenic (lesser known)	39 291 t (1949)	N/A	Wiluna	N/A	$1.5 million (1900–1945)	By-product dependency Environmental and health-related restrictions	N/A
Beryllium (lesser known)	350 t (1957) 160 t (1973)	N/A	Wodgina, Yalgoo	N/A	N/A	By-product dependency Environmental and health-related restrictions	N/A
Cobalt (well-known)	4600 t (2023)	6	Murrin Murrin, Nova-Bollinger	Glencore	$368 million (2022–2023)	By-product dependence Market volatility	China, Japan, South Korea
Gallium (lesser known)	1.767 t (1988–1989) 42.986 t (1989–1990)	N/A	Pinjarra Alumina Refinery	Alcoa	$60 641 (1988–1989) $1.5 million (1989–1990)	By-product dependency Very low concentration economically unfeasible	N/A
Germanium (lesser known)	N/A	N/A	N/A	N/A	N/A	By-product dependency Very low concentration	N/A
Lithium (well-known)	83 500 t (2023)	7	Greenbushes, Pilgangoora	Talison Lithium	$20.9 billion (2022–2023)	Price fluctuations and investment uncertainty	China, South Korea, Japan

Mineral	Current/ historical production (t or Mt)	Number of active mines	Key mine sites (current/ historical)	Current/ past key operators	Export value (AUD)	Mining bottlenecks	Key export destinations
Nickel (well-known)	156 200 t (2023)	6	Northen Operations, Cassini, Murrin Murrin	BHP, Nickel West, Glencore	Around $6 billion A$(2022–2023)	High operating costs Suspension of operations due to geopolitical and market instability	China (47%), Japan and South Korea (12–13%)
REE (well-known)	27 000 t (2023/2024) 18 000 t (2022/2023)	2	Mt Weld, Eneabba Stockpile	Lynas Rare Earths	$505 million (2022–2023)	High processing costs Complex HREE/LREE separation	China, EU, Japan, South Korea, USA
Scandium (lesser known)	N/A	N/A	N/A	N/A	N/A	By-product dependency Very low concentration	N/A

This work classifies minerals in WA as well-known if they have established production and detailed resource data. Minerals with limited occurrence, exploration, or output are considered lesser known. This regional classification might differ internationally. For example, rare earth elements (REEs) may be lesser known in countries with limited development, but they are well established in WA. Conversely, minerals considered lesser known in WA could be regarded as well-known elsewhere due to their greater availability or industrial significance. Table 4 presents lesser-known and well-known critical minerals in WA, highlighting the differences in their development, infrastructure, and strategies. Lesser-known minerals often suffer from limited availability, by-product dependency, low demand within the state, and global competition. The infrastructure to process them is limited, and low revenue makes their economic viability questionable, rendering them critical for WA. Interestingly, although there is currently no production, historical data indicate that some of these minor minerals were previously mined. Additionally, environmental regulations, lack of exploration interest, and competition from dominant global suppliers further hinder their recovery and commercialisation. Nevertheless, estimated resources of these lesser-known minerals suggest that, in very critical cases, they can be extracted and could benefit WA financially. Their existence also forms a strong foundation for national security and defence purposes.

Conversely, WA's strong global reputation in mineral production is supported by well-known minerals like lithium, nickel, alumina-bauxite, cobalt, and REEs. WA ranks among the top countries worldwide to produce mined raw materials, including lithium, rare earth elements (REE), alumina-bauxite, and others. For example, lithium and nickel are key drivers of WA's economy, with export values reaching $20.9 billion and $6 billion respectively (2022–2023) (Government of Western Australia, 2023b). However, nickel and cobalt faced significant challenges, mainly due to China's and Indonesia's monopolisation of processing in 2024, combined with market issues like price volatility and high operating costs. Initially, more than 12 nickel and cobalt mines were active before some were suspended or closed. Currently, only six are still operating because of these impacts. Despite these challenges, WA maintains a robust competitive stance due to its advanced logistics, an appealing investment climate, and solid international alliances, particularly with Asia, Europe, and even North and South America.

The primary difference between these two groups lies in their level of integration into global markets. Well-known minerals benefit from large-scale industrial mining, established supply chains, and high export demand, but they remain susceptible to market fluctuations and geopolitical changes. In contrast, lesser-known minerals lack up-to-date data, often have limited operational activity, and rely on associated metals. They also face technological and economic challenges that hinder independent development. Future prospects might involve secondary recovery, technological advancements, or strategic policy measures, but overcoming current limitations is crucial to realising the potential of these lesser-known critical resources.

Processing

Of the 31 critical minerals identified in WA, only 13 are currently processed at commercial scale. These include cobalt, lithium, high purity alumina (HPA), manganese, molybdenum, nickel, rare earth elements (REEs), selenium, silicon, tantalum, titanium, vanadium and zirconium. In most cases, processing is limited to midstream beneficiation, with concentrates exported offshore, primarily to Asia, for downstream refining and final product manufacturing. Minor critical minerals are often recovered as by-products during the exploration or processing of major ores.

Recent initiatives have aimed to expand domestic processing capacity; however, challenges persist due to technological, regulatory and economic constraints. Of the 18 minerals not currently processed in Australia, some including arsenic, antimony, fluorspar, tungsten etc were previously produced, but operations have been suspended or mothballed due to low feed grades, processing complexity, environmental regulations or limited technical expertise. Current processing capabilities, limitations and opportunities for downstream development for some major and minor critical minerals have been discussed in subsequent chapters.

Lithium stands out due to the scale of operations at mines. Greenbushes alone accounts for over 40 per cent of global spodumene concentrate production. However, downstream processing is mainly dependent on export. In 2023, about 99 per cent of the spodumene concentrate produced are exported to China (Kelly *et al,* 2021). Australia is seeking to capture more value onshore by expanding its domestic processing capacity. For instance, facilities like Albemarle's Kemerton plant and Tianqi's Kwinana refinery are now operational for conversion of spodumene concentrate into battery grade lithium hydroxide, although further expansions have been delayed due to lithium price volatility. Simultaneously, direct lithium extraction (DLE) of brine resources in South and WA are being explored (Geoscience Australia, 2013). Notwithstanding, the low lithium concentrations and complex brine chemistries continue to constrain commercial viability.

Other major critical minerals, including cobalt, vanadium, HPA and REEs, are increasingly important in Australia's midstream processing agenda. Cobalt is primarily recovered as a by-product of nickel operations. However, low feed grades, complex polymetallic matrices and residue management challenges continue to hinder process efficiency. In 2022, Glencore's Murrin Murrin produced about 40.4 kt of nickel and 3.3 kt of cobalt, with proposed future expansion. HPA is typically produced from low-grade bauxite via the Bayer process at Alcoa and South32 facilities. However, the process is constrained by high thermal energy demand and red mud generation. Vanadium is typically recovered as a by-product of vanadium slag during steelmaking. Its purification involves solvent extraction, ion exchange and chemical precipitation, with solvent extraction preferred for its selectivity, operational stability and economic feasibility (Dong, Zhang and Yan, 2022). Projects led by Australian Vanadium Limited and Windimurra are ongoing; however, the generation of waste streams with potential ecological impact necessitates rigorous and costly waste management protocols.

The discovery of rare earth deposits in WA outpaces the industry's processing capacity. Hence, WA is working on characterising clay-hosted rare earth element deposits. REE projects are perceived as high-risk investments, making financing difficult. Efforts are being made to de-risk rare earth projects by fostering government support and investor confidence. Rare earth production has significant environmental impacts, including habitat destruction and contamination of water resources. Supply chain disruptions impact processing, as seen with Lynas Rare Earths' sulfuric acid shortage due to BHP Group's nickel shutdown. Strategic partnerships and alternative sourcing are being explored to address supply chain vulnerabilities. Despite advancements in extraction technologies, REE recoveries form ore are limited to 50–80 per cent. While recycling can partially alleviate supply constraints, meeting the increasing demand for REEs requires enhanced process efficiencies and reduced production costs (Goode, 2019).

Minor critical minerals such as tantalum, tellurium, gallium, germanium, beryllium, antimony and arsenic are in early-stage development or inactive. Tantalum is often separated from niobium as a byproduct of lithium processing. Trace elements like tellurium, gallium, and germanium are also recovered from copper, zinc and bauxite processing residues, with recovery technologies. Minerals like arsenic processing is constrained by health and safety concerns. Across both major and minor mineral sectors, downstream refining in Australia faces consistent barriers: high capital and operating costs, infrastructure gaps, permitting delays, and energy intensity. To address these, WA's critical minerals strategy emphasises the expansion of midstream processing, supported by targeted incentives, advanced processing technologies, and strategic international partnerships to strengthen integration into global battery and energy transition value chains. Some minor critical minerals and processing tonnages in 2024 are provided in Table 5.

TABLE 5

Summary of key critical minerals processed in WA.

Mineral	Li	Co	REE	HPA	Be	Sb	Ta
Tonnage	3.6 Mt	3 kt	26.5 kt	15.1 Mt	3.2 kt	1.5 kt	0.06 kt

Figure 2 illustrates a generalised midstream beneficiation flow sheet highlighting key unit operations such as comminution, dense media separation (DMS), and flotation commonly used in the concentration of critical minerals. While this applies to most minerals including such as lithium, tantalum, REE they are not universally applicable to all. The suitability of these techniques depends on the specific mineral and its physical and chemical properties, as well as the surrounding matrix.

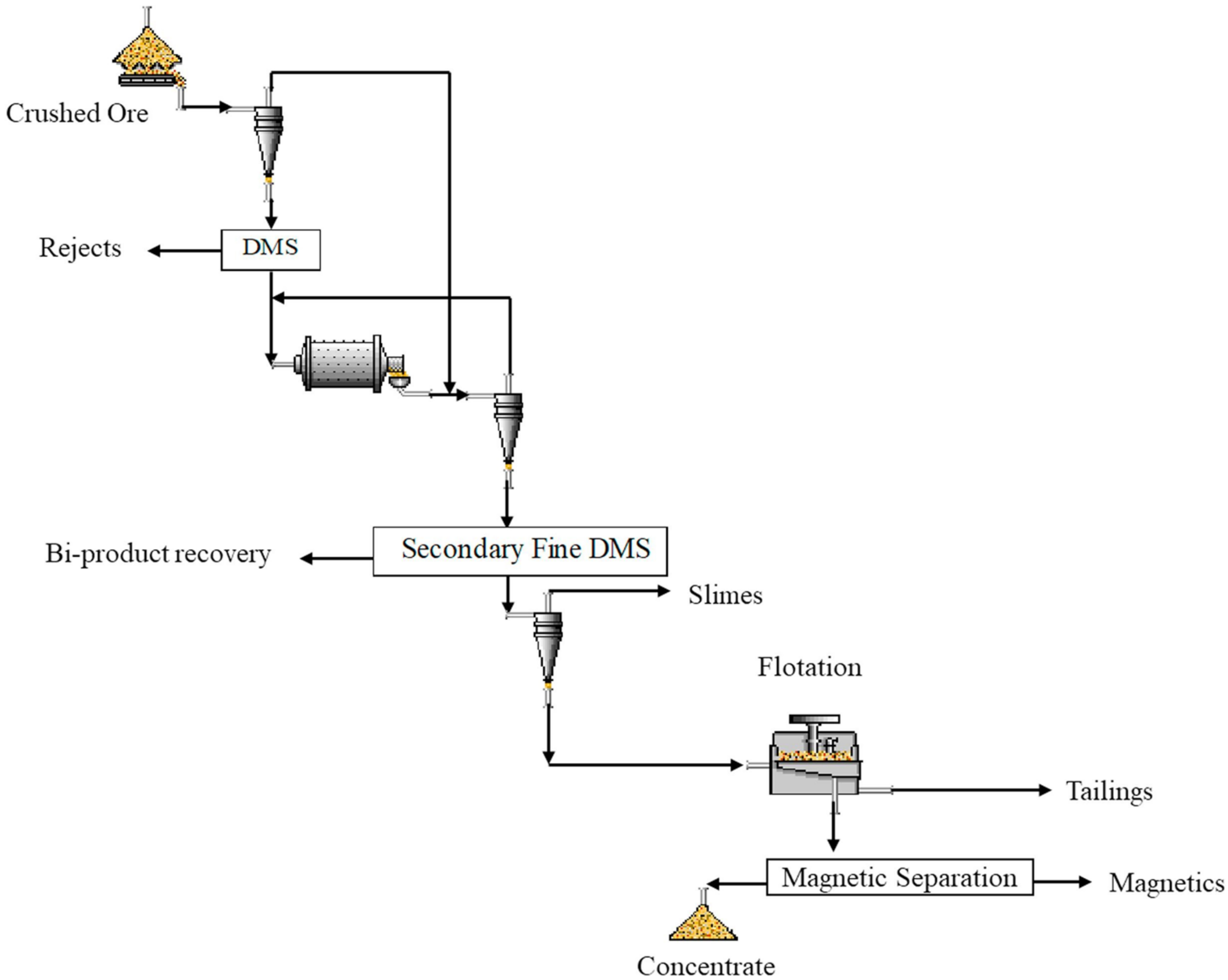

FIG 2 – Simplified flow sheet for the midstream upgrading routes (Tadesse *et al,* 2019).

Manufacturing

Although WA is rich in critical and strategic minerals, it currently does not have enough domestic manufacturing capacity for many essential technologies, such as those used in lithium-ion batteries, cobalt-based products, and rare-earth-element (REE) applications. This manufacturing gap affects even commodities like lithium, cobalt, and REEs used in batteries, EVs, magnets, and clean energy systems. Consequently, Australia still relies on importing end products, such as batteries, motors, and energy storage systems, even though it mines and sometimes processes the raw materials domestically. This disconnection acts as a major bottleneck in the value chain, reducing economic returns and strategic independence. However, recent efforts are underway to change this story. New manufacturing initiatives have been announced, emphasising emerging investment prospects in downstream facilities and vanadium redox flow battery (VRFB) projects, which are vital for large-scale energy storage. These developments mark a significant step toward creating a cohesive domestic manufacturing ecosystem. Nonetheless, expanding these efforts into complete industrial capacity faces obstacles, including the necessity for substantial investment, specialised labour, and supply chain infrastructure. Effective coordination among government, industry, and research sectors is crucial for the success of these initiatives and the establishment of a fully integrated value chain.

Strategic value chain insights and discussion

Figure 3 provides a visual summary of the status of each critical mineral in WA, clearly highlighting gaps in exploration, production, processing, and manufacturing stages. The analysis indicates that WA is a leader in upstream mineral activities, with exploration and geological data available for nearly all critical and strategic commodities. However, data on many lesser-known resources is outdated. Active mining persists for key minerals such as lithium, nickel, and rare earth elements (REEs). Conversely, minor elements like gallium and germanium either only have historical data or lack current production. ESG considerations are implemented for ongoing mining operations but are limited for commodities not currently in production.

CRMS	Exploration Projects	Geological Data	Production	ESG	Processing	Recycling	Substitute	Manufacturing	Map
Bauxite	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Antimony	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes
Arsenic	Yes	Yes	No	Yes	No	No	Yes	No	Yes
Beryllium	Yes	Yes	No	No	No	No data	Yes	No	No data
Bismuth	No	No	No	No	No	No	Yes	No	No data
Chromium	Yes	Yes	No	No	No	No	Yes	No	Yes
Cobalt	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes
Fluorine	Yes	Yes	No	No	No	No	Yes	No	No data
Gallium	Yes	Yes	No	No	No	No	Yes	No	No data
Germanium	No	Yes	No	No	No	No	Yes	No	No data
Graphite	Yes	Yes	No	No	No	No	Yes	No	Yes
Hafnium	Yes	Yes	No	No	No	Yes	Yes	No	No data
Indium	Yes	Yes	No	No	No	No	Yes	No	No data
Lithium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Magnesium/Magnesite	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Manganese	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Molybdenum	Yes	Yes	No	No	Yes	Yes	No data	No	Yes
Nickel	Yes	Yes	Yes	Yes	Yes	Yes	No data	No	Yes
Niobium	Yes	Yes	No	No	No	No	Yes	No	Yes
PGM	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes
REE	Yes	Yes	Yes	Yes	Yes	No data	Yes	No	Yes
Rhenium	No	Yes	No	No	No	No	Yes	No	No data
Scandium	Yes	Yes	No	No	Yes	Yes	No data	No	Yes
Selenium	No	Yes	No	No	No	No	Yes	No	No data
Silicon	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tantalum	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
Tellurium	Yes	Yes	No	No	No	No data	Yes	No	No data
Titanium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tungsten	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Vanadium	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Zirconium	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes

FIG 3 – Critical minerals in Western Australia: overview from exploration to manufacturing status.

The midstream and downstream stages show notable gaps. Processing mainly focuses on a few minerals like lithium, alumina, and REEs, while most commodities lack local value-added facilities. In manufacturing, a major bottleneck is exporting raw and semi-processed minerals abroad to produce end-products. The most promising local opportunity is developing vanadium redox flow batteries (VRFB). Recycling remains underdeveloped, especially for niche minerals, but it offers a clear chance to promote a circular economy. Although substitution is acknowledged in many cases, it is often not practically adopted in strategic technologies.

These findings highlight WA's dependence on overseas processing and end-use manufacturing, creating a strategic vulnerability amid local supply chain disruptions. Overcoming these challenges will necessitate coordinated policy measures, greater private-sector investment, infrastructure upgrades, and a skilled workforce in downstream sectors. Developing midstream processing facilities and establishing downstream manufacturing hubs will be essential for transforming WA's mineral resources into long-term strategic and economic benefit.

CONCLUSION

This study investigated bottlenecks and unexploited opportunities throughout all stages of the mineral value chain in WA, encompassing both upstream and downstream processes. Additionally, it addressed ESG principles, recycling, and sustainability as both potential opportunities and challenges. While widely recognised commodities benefit from strong data and infrastructure, lesser-known critical minerals often face outdated geological data, limited exploration efforts, and insufficient midstream capabilities. Nevertheless, despite some well-known resources having current exploration and mine production data, several of them are still considered critical for the country due to limited domestic processing and manufacturing activities. For minor commodities, the lack of by-product recovery and local processing reduces domestic value. To tackle these challenges, WA needs to enhance exploration data for minerals that are underreported, develop infrastructure for recovering by-products, and create midstream processing and early-stage manufacturing hubs. Additionally, government authorities are required to keep detailed records of mined and processed commodities, as well as all materials exported internationally. For instance, in 2023, Australia extracted 492 kg of PGMs, but only 490 kg were documented as palladium and platinum. The remaining 2 kg of other commodities were not specifically recorded, leaving it uncertain which commodity these 2 kg belong to. Recording data for each mineral will improve value chain integration. Moreover, monitoring this data and expanding processing and manufacturing facilities in WA will decrease dependence on external processors and establish WA as a global leader in both resource extraction and sustainable, value-added mineral production.

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Comparative study of kaolin – acid routes to produce high purity alumina (HPA)

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ABSTRACT

HPA (≥99.99 per cent α-Al_2O_3) is one of the key materials essential for the energy transition, driven by its use in batteries and LEDs. Rising HPA demand is projected to result in a supply shortfall over the next decade, with significant research and development underway to capitalise on Australia's plentiful supply of cheap feed materials such as aluminous clays. While various mineral acids have been successfully used to extract aluminium from kaolin, limited comparative information is publicly available on these acid systems and the implications for producing HPA. In this context, the CSIRO is evaluating different acid systems for HPA through the Australian Critical Minerals Research and Development Hub, funded by the Australian Government.

Kaolin clay was thermally treated to form metakaolin, and subsequent calorimetric data was collected isothermally to evaluate the aluminium leaching kinetics (50, 65 and 80°C and various acid concentrations). The activation energies for aluminium extraction using HCl, H_2SO_4, and HNO_3 were calculated to be 114.8, 101.3, and 90.4 kJ/mol, respectively. These values are consistent with concentration-time experiments (within 6 per cent agreement), demonstrating the effectiveness of the calorimetric approach. No significant differences in liquor purity or aluminium extraction were observed for the three acids tested. First-pass crystallisation of the respective pregnant leach solutions produced $AlCl_3 \cdot 6H_2O$ (99.94 per cent), $Al_2(SO_4)_3 \cdot 17H_2O$ (98.07 per cent), and $Al(NO_3)_3 \cdot 9H_2O$ (98.22 per cent) which influences subsequent purification steps. Thermogravimetric analysis and high-temperature X-ray diffraction revealed the salts' decomposition pathways, the intermediate phases formed before transformation to α-Al_2O_3, and conditions for potential acid regeneration. The results are discussed in terms of the purities of precursor salts formed through various processing steps and the alumina yields achieved after salt decomposition. The cost of reagents, the extent and efficiency of acid regeneration, and materials of construction are additional criteria that need to be considered when evaluating different acid routes for producing high purity alumina.

Pioneering sustainable industrial transformation – developing a critical minerals technology hub at Masan High-Tech's Nui Phao operations in Northern Vietnam

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ABSTRACT

The global shift toward sustainable industrialisation necessitates innovative approaches to resource development, particularly in the critical minerals sector. This presentation explores the potential for establishing an advanced industrial technology hub at Masan High-Tech's Nui Phao existing poly-metallic mine in northern Vietnam, leveraging the existing licensed mining space and downstream tungsten processing site. The aim is to expand on the initial mining, mineral processing, and refining to the next phase of industrial development. Building upon the established expertise in complex hydrometallurgical processing, this proposed expansion represents the next logical step in developing a fully integrated, high-value industrial hub.

This initiative aims to create a vertically integrated processing and refining centre that enhances Vietnam's critical minerals supply chain role by drawing parallels with successful global models such as HC Starck's industrial hub in Goslar, Germany and the Kwinana Strategic Industrial Area south of Perth, Western Australia. By capitalising on an educated workforce, competitive power costs, and lower CAPEX and OPEX, the hub will drive innovation while incorporating best practices in energy efficiency, waste reduction, and circular economy principles. Beyond economic benefits, this development will support global sustainability goals and supply chain security, demonstrating how emerging economies can leverage existing strengths to pioneer responsible industrial growth.

Critical minerals for hydrogen technologies – just transitions perspectives in the Indo-Pacific

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ABSTRACT

Clean energy transitions and critical minerals have been highly interlinked since the emergence of criticality studies in the last 15–20 years. Many of the critical minerals are key to providing functionality in clean energy technologies, even if some of the demand for these minerals is not dominated by the energy sector itself. At the same time, most of the critical minerals assessment methods do not explicitly consider the local environment, economy or social implications (and subsequent risks). 'Just transitions' work has also been expanding across a similar time period, highlighting the need to consider the community and social implications of clean energy transitions. The combination of considering critical minerals (including how we assess criticality) and the justice of energy-resource transitions is thus an area that needs increasing attention. The Indo-Pacific is a region with highly varied development levels, countries across the supply chain of minerals, highly dependent on fossil fuels for energy and income, but likewise committed to energy transition. In this context, it is an ideal region to consider just resource-energy transitions for a variety of technologies. In this study, we focus on hydrogen supply chains, which are receiving enhanced attention (again) to support clean energy transitions. The study examines the implications of hydrogen transitions across multiple countries in the region, considering firstly the available resource capacity for critical minerals to enable these technological shifts, and subsequently the impacts of a transition away from fossil fuels in the region.

Demands of critical minerals and energy – effects and limitations of moving towards the fifth industrial revolution

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ABSTRACT

The demand for critical minerals has skyrocketed as the world shifts towards renewable energy sources and cleaner technologies. Critical minerals—lithium, cobalt, nickel, and rare earth elements—are essential components in electric vehicles (EVs), battery storage, and renewable infrastructure. According to the International Energy Agency (IEA), the demand for these minerals could multiply four to six times by 2040 if the world pursues its climate goals. This article explores the essential role of critical minerals, examines prominent companies across different regions, and evaluates the challenges of sustainable and ethical sourcing. Critical minerals serve as the backbone of many energy-efficient technologies required for the green transition. Lithium, cobalt, nickel, and rare earth elements power battery storage, electric motors, and renewable infrastructure, making them indispensable to achieving net-zero targets. Three energy scenarios, each with three levels of uptake of renewable energy, are assessed for the potential of critical minerals to restrict growth under alternative mineral supply patterns. Under steady material intensities per unit of capacity, the study indicates that selenium, indium and tellurium could be barriers in the expansion of thin-film photovoltaics, while neodymium and dysprosium may delay the propagation of wind power. For fuel cells, no restrictions are observed. According to the IEA, if the world achieves its net-zero emissions goals by 2050, the demand for lithium alone is expected to increase over 40 times its current levels. This soaring demand highlights the urgency of developing sustainable, secure supplies of these minerals.

A lot is not enough – critical metals deportment in complex secondary raw materials

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ABSTRACT

With the increasing global demand for raw materials and the consequent depletion of the global natural resource base, the possible utilisation of secondary raw material sources is receiving more attention. Slags are often touted as a raw material type of particular promise. Many slags are currently either landfilled – or alternatively downcycled into low value applications. This is despite the fact that some slags are known to contain elevated concentrations of critical raw materials (CRM). Most studies aimed at recovering CRM from slags have considered them as being a simple bulk material, ignoring the inherently complex and variable phase composition. In the present study, results are presented from a detailed deportment study for vanadium as a CRM in three large bulk samples of basic oxygen furnace slag (BOFS). Complementary analytical methods were used to quantify the abundance and composition of V-containing phases, including scanning electron microscope - energy dispersive X-ray spectroscopy (SEM-EDS)-based automated mineralogy, X-ray fluorescence spectrometry X-ray powder diffraction as well as electron probe microanalysis. The vanadium deportment was quantified using Monte-Carlo simulations of the data obtained from automated mineralogy and electron microprobe analysis. The total V concentrations in the three slag samples range between 1.7 and 2.2 wt per cent V. The most important hosts of vanadium are larnite-, brownmillerite- and portlandite-solid solutions. In two samples Ca carbonates also significantly contribute to the V deportment, while wuestite, lime, and native iron do not have significant V concentrations. A thorough consistency check identifies considerable uncertainties in the density of the V-bearing phases as the most likely reason to explain remaining discrepancies between measured and calculated V contents. Results suggest that enrichment of vanadium by mechanical beneficiation will not be possible. Instead, the slag will either have to be metallurgically treated, either by re-smelting or by (near) complete dissolution/leaching. Both these approaches do not appear economically nor ecologically feasible.

Machine learning landscape mapping and anomaly detection for the exploration of critical metals

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ABSTRACT

Early-stage mineral exploration, commonly involves surface soil, lag or chip sampling and analysis of elements. This has not changed significantly over the past decades: that is, digest a sample and, subsequently, analyse the solution, examine key target and pathfinder elements, then rinse and repeat at the next tenement package. As an industry, we need to change the way we explore to improve success, especially in covered terrains. The CSIRO research team has developed tools that fundamentally change the soil analysis and interpretation approach in Australia with the development of UltraFine+® (soil analytical technique) and LandScape+® (a machine learning workflow) as outcomes of two major R&D projects with ~40 industry and government collaborators.

In this presentation we highlight briefly the evolution of the analytical method and data processing that assist exploration for multiple commodities. More importantly, we focus on the machine learning analytics and the approach of using spatial data to generate landscape types (with dimensionality reduction and clustering methods). We highlight the new web-based software application that makes it easy for any explorer to generate a first-pass analysis and interpretation of their surface geochemistry for areas of up to 2000 km^2.

While landscape maps are available for some regions, using machine learning to derive landscapes using remotely-sensed spatial data allows this approach to be employed in most regions even where traditional map products are not available or only at a coarse resolution (as is often the case when explorers advance into true greenfields settings). These data driven landscapes can accelerate interpretation and reduce risk by understanding where cover is thicker, or surface sampling may be problematic. There are limitations to the unsupervised machine learning landscape models and these will be discussed along with the value of identifying coherent anomalies in landscape settings that are notoriously difficult to explore.

Green engineering approach to screening leaching processes for critical metals

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ABSTRACT

Recovery of critical minerals from secondary sources, such as mineralised waste rock, mine tailings, process waste streams, and low-grade ores, has been recommended as a priority to help meet growing demand for critical minerals in Australia and globally (Lambert, 2023). The difficulty is that these sources often have a broad mineralogy, and in the case of post-processing waste, can be significantly modified, which poses design challenges for a centralised hydrometallurgical extraction process.

There is a clear need for a robust approach for: (1) rapidly assessing the suitability of secondary sources for leaching activities; and (2) screening the necessary process settings that enable efficient leaching conditions. The problem is that there are a considerable number of process factors that influence leaching efficiency which ultimately influence how suitability can be assessed. The goal for this work was to develop a strategically designed experimental methodology that can be used to rapidly model a multi-dimensional leaching system and estimate performance.

This work demonstrated a definitive screening Design of Experiment (DoE) as a primary experimental step for assessing low-grade kaolin as a source of critical minerals. The screening DoE required 28 batch leaching studies which surveyed four continuous process variables: process temperature (22–80°C), leaching time (0.5–4 hrs), slurry concentration (5–20 wt per cent), and acid concentration (4–20 wt per cent); and stirring behaviour as a categorical variable (on-bottom and uniform suspension). The critical metal recovery (in mg/kg) was modelled as a response variable to enable preliminary prediction and optimisation. The expected outcome of this approach is to quickly identify which secondary source can be rejected or proceed to more advanced leaching studies, such as response surface methodology.

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Recovery of rare earth elements from goethite-rich monazite tailings via soda roasting and deep eutectic solvent leaching

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ABSTRACT

The demand for various rare earth elements (REEs) has grown due to their significant role in electronic devices, manufacturing, medical science, renewable energies, etc. This has led to numerous studies investigating the processing of REEs-bearing tailings as secondary sources of REEs. In this study, a weathered carbonatite flotation tailing sample from an Australian mine was examined. The tailing contained about 8.4 per cent total REO_T and 48.3 per cent Fe_2O_3 where the REEs were present as REE-phosphates and the main gangue mineral goethite.

Pretreatment prior to leaching the REEs was conducted through high-temperature roasting with sodium salts to convert the REE-phosphates into REE-oxides. Two sodium salts were investigated in this study; Na_2CO_3 (roasted at 900–1100°C) and NaOH (roasted at 400–700°C) with different proportions added to the tailing. After Na_2CO_3 roasting, the iron was mostly in the form of magnetite (dominant) and hematite, whereas after NaOH roasting, most of the iron was converted into $NaFeO_2$. In both, the phosphorous was mostly present as Na_3PO_4. The roasted samples were then leached with water at 65°C to remove mainly the Na_3PO_4 phase and other water-soluble phases.

The solid residue after water leaching was then leached with a deep eutectic solvent (DES) composed of an ethylene glycol-maleic acid mixture (EG-MA) at 70°C for six hrs. In general, a higher dissolution of REEs after DES leaching was achieved in the NaOH-roasted samples compared to the Na_2CO_3-roasted samples. However, REE extractions were modest and selectivity with respect to gangue elements was below target. The highest leaching of REEs was observed in the sample roasted with NaOH at 400°C with La (49.8 per cent extraction), Ce (3.27 per cent), Pr (44.7 per cent), Nd (31.6 per cent), Sm (30.1 per cent), Eu (34.1 per cent), Gd (30.9 per cent), Dy (42.5 per cent), Sc (70.68 per cent), and Y (69.42 per cent). The results are discussed with a view to optimising the leaching performance.

Strategic ligand design for Nd/Dy separation from coal fly ash leachates

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ABSTRACT

Neodymium (Nd) and dysprosium (Dy) are essential components of high-performance permanent magnets used in renewable energy systems and electric vehicles. Global demand for these rare earth elements (REEs) is rising, while primary deposits are limited and concentrated in a few countries. Their frequent co-occurrence in REE sources and nearly identical ionic radii make separation particularly challenging. Therefore, ensuring sustainable Nd/Dy supply chains has become a critical global priority.

This study introduces a novel ligand for selective Nd/Dy separation from coal fly ash leachates, an abundant and underutilised secondary REE resource in India. The modified di-(2-ethylhexyl) phosphoric acid (D2EHPA) ligand replaces conventional alkyl chains with naphthyl groups and incorporates an oxalate functionality. These structural changes enhance π-electron interactions and introduce an additional chelation site, fundamentally altering the coordination environment compared to unmodified D2EHPA.

Density functional theory (DFT, Gaussian 16) simulations reveal stronger binding energies and more negative Gibbs free energy (ΔG) values for Dy(III) than Nd(III). This predicted Dy selectivity can be leveraged to reduce the number of solvent extraction stages in industrial circuits, lowering reagent consumption, operational costs, and environmental impact. Computational screening of ligand-metal interactions also identifies promising candidates before synthesis, reducing experimental failure rates and accelerating the development cycle. Such advances can make REE recovery from secondary sources commercially viable, supporting the adoption of circular resource use in critical minerals processing.

Future work will explore nitrogen donor group incorporation into the naphthyl-oxalate framework, evaluated through combined computational and experimental methods. The approach aligns with India-Australia collaboration opportunities, combining India's large-scale secondary REE feedstocks with Australia's expertise in REE separation. Potential outcomes include ligand synthesis, laboratory and pilot-scale trials with real leachates, joint research, knowledge exchange, and potential co-development of intellectual property. This research supports sustainable, diversified, and sovereign REE supply chains by linking molecular-level design to industrial application.

Securing innovation – navigating IP challenges and opportunities in new critical minerals technologies

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ABSTRACT

Patent attorney's work at the intersection of intellectual property (IP) law and technological innovation. In the critical minerals sector, they witness firsthand the transformative role that new technologies play. These include low-impact extraction methods, advanced processing systems and AI-driven exploration tools. The pace of innovation is accelerating in response to the global demand for sustainable and efficient mineral production.

However, with rapid development comes a unique set of legal and strategic challenges. Protecting IP is not merely about filing patent applications. It's about securing competitive advantage, enabling cross-border collaboration and navigating a complex global landscape of IP regimes. This is particularly critical in an industry where technological edge and proprietary know-how can impact long-term viability.

In this presentation, I will explore current trends in patent filings and technology licensing within the critical minerals sector. I will highlight how innovators are leveraging IP to attract investment and form strategic partnerships. I will also address the growing emphasis on green technologies.

The session will also offer insights into common pitfalls. These include premature disclosure, insufficient freedom-to-operate undertaking and inadequate IP due diligence in M&A transactions. Such failures can undermine otherwise groundbreaking innovations. Finally, I will outline opportunities for stakeholders to better align their IP strategies with business goals.

Through the unique lens of an intellectual property expert, we can ensure that the sector not only continues its rapid advancement of new technologies but does so with strategic foresight.

Critical minerals challenges for accelerating the UK's green economy

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ABSTRACT

Critical minerals are the raw material enablers of technologies needed for transition to a low carbon green economy. *Resilience for the Future*: The UK's first Critical Minerals Strategy (Department for Business, Energy, and Industrial Strategy, 2022; Department for Business and Trade, 2023) sets out the government's 'ACE' plan to secure the UK's supply chains by: **A**ccelerating growth of the UK's domestic capabilities; **C**ollaborating with international partners; and, **E**nhancing international markets to make them more responsive, transparent and responsible. The UK recently released a new Industrial Strategy that defines eight growth sectors (eg digital, defence, advanced manufacturing etc) and will soon release an updated Critical Minerals Strategy expected to focus on 'growth' minerals (ie lithium, tin, tungsten etc), and to set out specific actions and targets for domestic production, international collaborations, and sustainable supply. South-west England is the leading UK region for potential production of critical minerals, with active exploration and development companies, a history of mining, and many service and equipment companies. The new Critical Minerals Challenge Centre for the Accelerating the Green Economy (CMCC-AGE, 2025), is based in SW UK at the University of Exeter (funded by UKRI grant and project partner contributions). This new Centre builds on: previous research at the Camborne School of Mines, including Good Growth Prosperity Fund investments in equipment and laboratory facilities, and the Geo-resources sector strengthening activities; previous UKRI-funded research and circular economy roadmaps on Technology Metals (Met4Tech, 2025); as well as projects for the IUK-CLIMATES programme. The CMCC will address critical minerals challenges encountered in exploration and extraction technologies, sustainable resource management (eg valorisation of mine wastes), and development of new analytical and geo-metallurgical protocols; along with new research in environment/ecology, social sciences/community, green jobs/skills, and sustainable green finance. These applied research activities will help address the challenges in accelerating the domestic production and responsible supply of critical minerals in the UK and globally.

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Thermodynamic analysis and extraction of copper and cobalt from smelting slag

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ABSTRACT

The extraction of copper and cobalt from smelting slag could significantly augment the supply of these metals, which are essential to facilitating the transition to green energy while simultaneously addressing environmental concerns regarding slag disposal. However, the complex mineral composition of copper slag poses an enormous challenge. This study investigated thermodynamic simulations using the HSC Chemistry software, mineralogical characterisation and carbocatalytic reduction for extraction of copper and cobalt from smelting slag. X-ray diffraction (XRD) and field-emission scanning electron microscope with energy dispersive X-ray spectroscopy (FESEM-EDS) were employed to examine the morphologies of copper slag before and after the reduction process. The XRD analysis revealed that the primary phases in the smelting slag were Fe_2SiO_4 and Fe_3O_4. The FESEM-EDS analysis verified the presence of these phases and yielded supplementary details regarding metal embedment in the Fe_2SiO_4, Fe_3O_4 and Cu phases. The HSC Chemistry results review that carbocatalytic reduction process expedited the transformation of copper slag microstructures to amorphous and metallic phases. The equilibrium phase composition shows that the carbothermic reduction of Fe_3O_4 at various temperatures proceeded stepwise as $Fe_3O_4 \rightarrow FeO \rightarrow Fe$. Meanwhile, Fe_3O_4 was first catalysed at low temperature of 300°C before being reduced to metallic phase at 545°C. Finally, leaching experiments using H_2SO_4 yielded high extractions of Cu, Co, and Fe.

Mineralogical domaining for resource characterisation

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ABSTRACT

Chemical assay is widely employed in the minerals industry with mineral resource estimation and as a valid, though indirect input to factors to drive key decision points across exploration, resource development, mine planning, metallurgical functions and through project study phases. However, a quantitative assessment of mineral composition provides a robust understanding of mineral system configuration that enables a direct correlation to recoverable metal assessments and project optimisation assumptions.

Since January 2022, Automated Scanning Electron Microscopy (SEM) based mineralogical data has been routinely acquired to support resource characterisation across three strategic projects and operational mines within BHP's Nickel West (NiW) portfolio. The samples were analysed with the NiW in-house TESCAN TIMA (TESCAN Integrated Mineral Analyzer) instrument, validated and reported into a geological database. The database captured SEM generated assay, mineral abundance, elemental deportment, size distribution, liberation and facilitates a direct connection to 3D modelling software.

Mineralogical domaining and numeric block model estimation via traditional linear methods was completed using 3D modelling software packages alongside routine resource estimation projects. Key output variables included nickel deportment across mineral phases and mineralogical flags.

The case studies presented in this paper outline key observations from the output numeric block estimates and highlight contrasting nickel-sulfide mineral abundance characteristics that are challenging to identify through assay-based proxies. The numeric estimation of mineralogical variables brings to surface the nuance of nickel mineral systems that can have a material impact to key assumptions and decisions from the initial exploration phase through to mine planning and the operational success of a project.

The integration of mineralogical data into the resource and grade control model appropriately characterises the mineral system, facilitating a spatial and direct diagnostic link through to metallurgical analysis, project planning, optimisation opportunities, risks, mineral resource classification and operational decisions.

INTRODUCTION

In the minerals industry, chemical assays are a cornerstone for mineral resource estimation and serve as inputs for critical decision-making activities across various stages, including exploration, resource development, mine planning, metallurgical, studies and ESG (environmental, social and governance) functions. Despite this broad application, chemical assays alone may not provide an appropriate level of understanding to enable fit for purpose decision-making. A quantitative assessment of mineral composition offers a robust framework, enabling direct correlations to recoverable metal assessments and project optimisation assumptions.

Since January 2022, BHPs Nickel West (NiW) has incorporated Automated Scanning Electron Microscopy (SEM) based mineralogical data to enhance resource characterisation for two strategic projects and operational mines. Utilising the in-house TESCAN TIMA (TESCAN Integrated Mineral Analyser), samples were analysed, validated, and integrated into a geological database. This database captures a range of data, including SEM-generated assays, mineral abundance, elemental deportment, size distribution, and liberation, which are directly linked to 3D modelling software.

Traditional linear methods were employed for mineralogical domaining and numeric block model estimation using 3D modelling software, alongside routine resource estimation projects. Key output variables, such as nickel deportment across mineral phases and mineralogical domain flags, were identified. The case studies presented in this paper highlight significant observations from numeric block estimates, revealing contrasting nickel sulfide mineral abundance characteristics that are often challenging to detect through assay-based proxies.

The integration of mineralogical data into resource and grade control models provides a nuanced understanding of nickel mineral systems. This integration facilitates a spatial and direct diagnostic link to metallurgical analysis, project planning, optimisation opportunities, risk assessment, mineral resource classification, and operational decision-making. By appropriately characterising the mineral system, this approach supports informed and effective project management from initial exploration through to operational success and closure.

PROBLEM STATEMENT

Geochemical proxies are routinely used to estimate metallurgical recovery in nickel sulfide systems. While these proxies offer a practical and scalable approach, they often fail to capture the complex mineralogical characteristics required to better support minerals processing. As a result, they can misrepresent metallurgical performance outcomes, leading to inaccurate recovery predictions.

Metallurgical test work, although more accurate, is costly and typically limited in spatial coverage. Even when distributed across a deposit, these tests may not adequately sample the full range of mineralogical domains. This disconnect between geochemical prediction and mineralogical reality introduces significant uncertainty into resource estimation, mine planning, and downstream value assessments.

The challenge, therefore, is to develop a cost-effective and practical methodology for acquiring quantitative mineralogical data at a resolution sufficient to model intra-deposit variability. Such an approach must support the definition of Selective Mining Units (SMUs) and enable reliable integration of mineralogical complexity into mine planning and metallurgical forecasting.

MINERALOGY

Geological setting

The komatiite-hosted nickel deposits of the Agnew Wiluna Belt occur as two distinct types; Type 1 mineralisation consisting of mainly massive sulfides and Type 2 mineralisation of large low-grade disseminated sulfides (Barnes and Hill, 2004). The deposits where the studies were undertaken are of a Type 2 mineralisation style.

The deposits can generally be broken down further into weathering domains. The assumed linear alteration profile consists of:

- Oxide: This domain comprises oxidised material or near surface regolith.
- Supergene: Characterised by sub-horizontal supergene ultramafic material containing nickel sulfides with low pentlandite content and moderate to high mineralisation predominantly consisting of pyrite-violarite sulfides.
- Transitional: This domain consists of ultramafic material situated below the supergene domain and exhibits a mixture of various sulfide minerals.
- Primary: The primary domain hosts well-preserved NiS mineralisation and is generally composed of pentlandite and heazlewoodite, with isolated zonation of millerite, gersdorffite, violarite and silicates.

  Information adapted from Grguric (2020).

Most of the recoverable material is found in primary ultramafic rock with reduced recovery in the transitional zone. Oxide and supergene material are often classified as waste due to the low recovery of secondary sulfide minerals (eg violarite and nickel silicates).

Nickel sulfide mineralogy

Type 2 deposits often exhibit complex mineralogical associations that significantly influence metallurgical performance. Nickel is hosted in a range of sulfide and non-sulfide minerals, each with distinct textural, chemical, and flotation characteristics that influence how they behave through the plant. This section outlines key nickel sulfide minerals and their respective behaviours across comminution, flotation, and downstream circuits.

The main nickel minerals present are pentlandite and violarite which both have similar chemical composition however have different responses through a processing plant. Sulfur to Ni ratio is regularly used across exploration, processing and resource definition to infer NiS mineral speciation. However, utilising chemical assay proxies such as S:Ni ratio becomes complicated with the presence of iron sulfides which will be accounted for in the ratio. Table 1 highlights the similar chemical composition across most NiS minerals present.

TABLE 1

Shows the theoretical chemical formula and compositions of some of the main Ni minerals present. Data sourced from Webmineral (2025) and Mindat (2025).

Mineral	Chemical Formula	Composition (wt%)				
		Ni	Fe	S	As	Total
Pentlandite	$(FeNi)_9S_8$	34	33	33		100
Violarite	$Fe^{2+}Ni_2^{3+}S_4$	39	19	43		100
Millerite	NiS	65		35		100
Heazlewoodite	Ni_3S_2	73		27		100
Nickeline	NiAs	44			56	100
Gersdorffite	NiAsS	35		19	45	100

Pentlandite is a primary nickel sulfide and is typically associated with pyrrhotite. It is optimal for processing and provides high Fe:MgO in the concentrate. Figures 1 and 2 show back scatter electron (BSE) images of pentlandite association with different minerals and highlight the complex textures present throughout the NiS minerals. Normally a product of alteration, supergene violarite mainly exhibits porous, spongey, fine grain and fragile morphology. When violarite is porous it is difficult to recover in concentrate (Grguric, 2024) and smelt. The Ni content in both pentlandite and violarite can vary highly from the theoretical chemical composition.

Millerite is a low-sulfur nickel sulfide mineral with a similar chemistry to heazlewoodite. When supergene millerite is present it has good concentrate grades however has poor recovery and does not contribute Fe to the concentrate. Heazlewoodite has poor concentrator recovery however provides high Ni concentrate grades. It does not contribute Fe to the concentrate. Figures 3 and 4 show BSE images of heazlewoodite mineral association.

Gersdorffite is a Ni-As sulfide mineral which recovers well through the concentrator. Arsenic recovers significantly in gersdorffite relative to some other minerals.

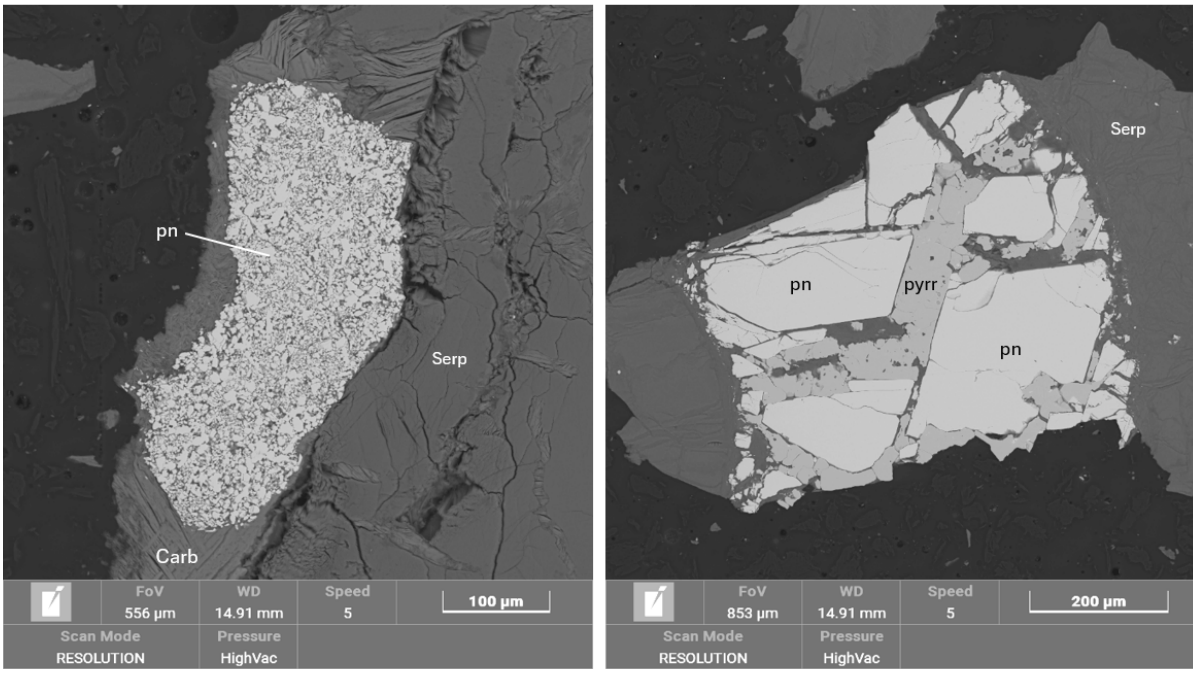

FIG 1 – BSE images showing pentlandite associations with other NiS minerals. Left: Fine-grained anhedral pentlandite (pn) infill hosted within a carbonate (Carb) vein associated with serpentine (Serp). Right: Fractured coarse grain pentlandite (pn) with pyrrhotite (pyrr) infill associated with serpentine (Serp).

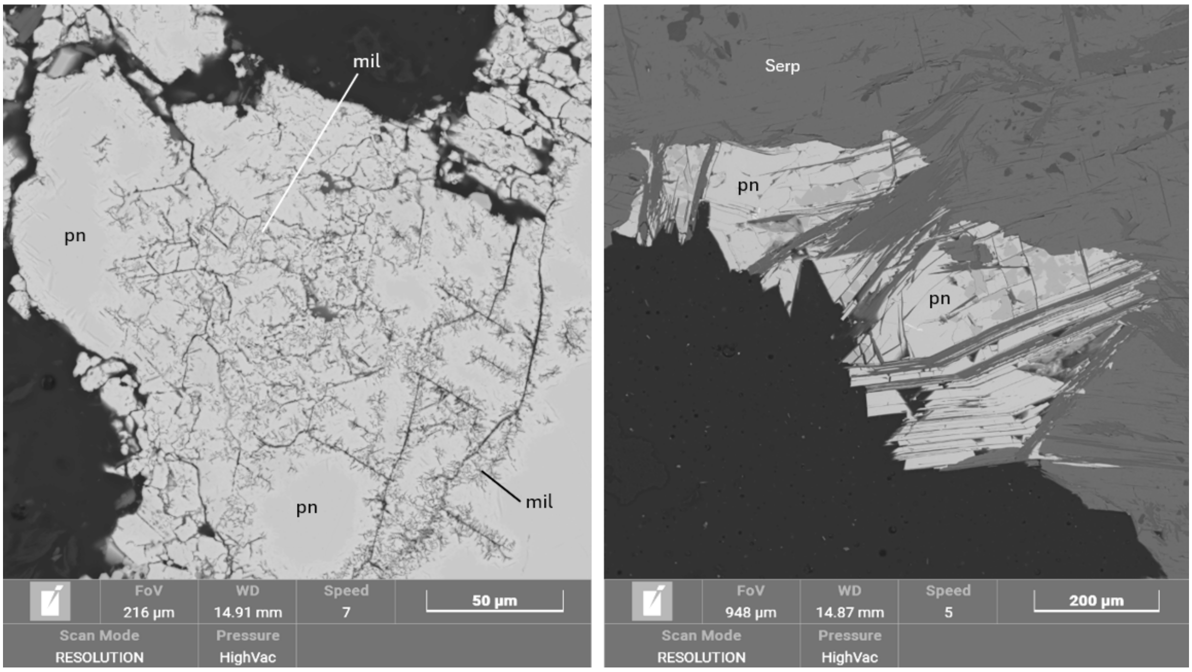

FIG 2 – BSE images showing pentlandite associations with other NiS minerals. Left: Millerite (mil) replacement of pentlandite (pn), with grain-boundary and microfracture control on distribution of millerite. Right: Pentlandite (pn) in serpentine (Serp) cleavage/sheets.

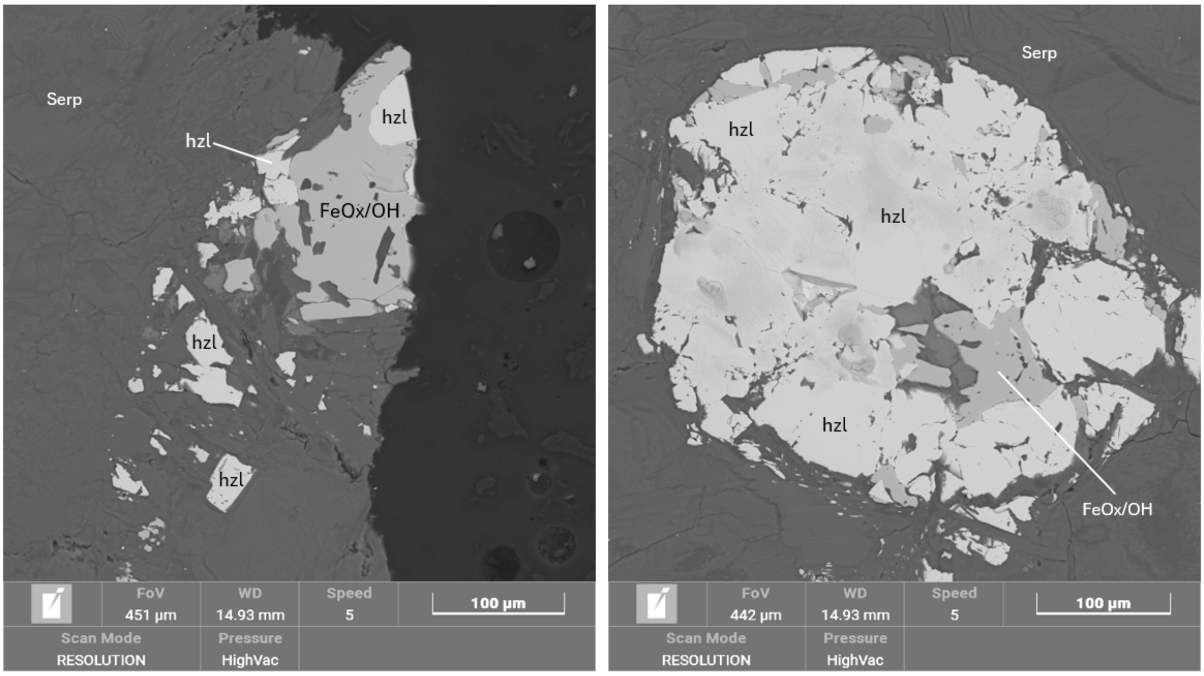

FIG 3 – BSE images showing heazlewoodite dominant mineral assemblages. Left: Fine grain heazlewoodite (hzl) associated with iron oxides (FeOx/OH) and serpentine (Serp). Right: Round coarse grain heazlewoodite (hzl) with iron oxide (FeOx/OH) inclusions bound by serpentine (Serp).

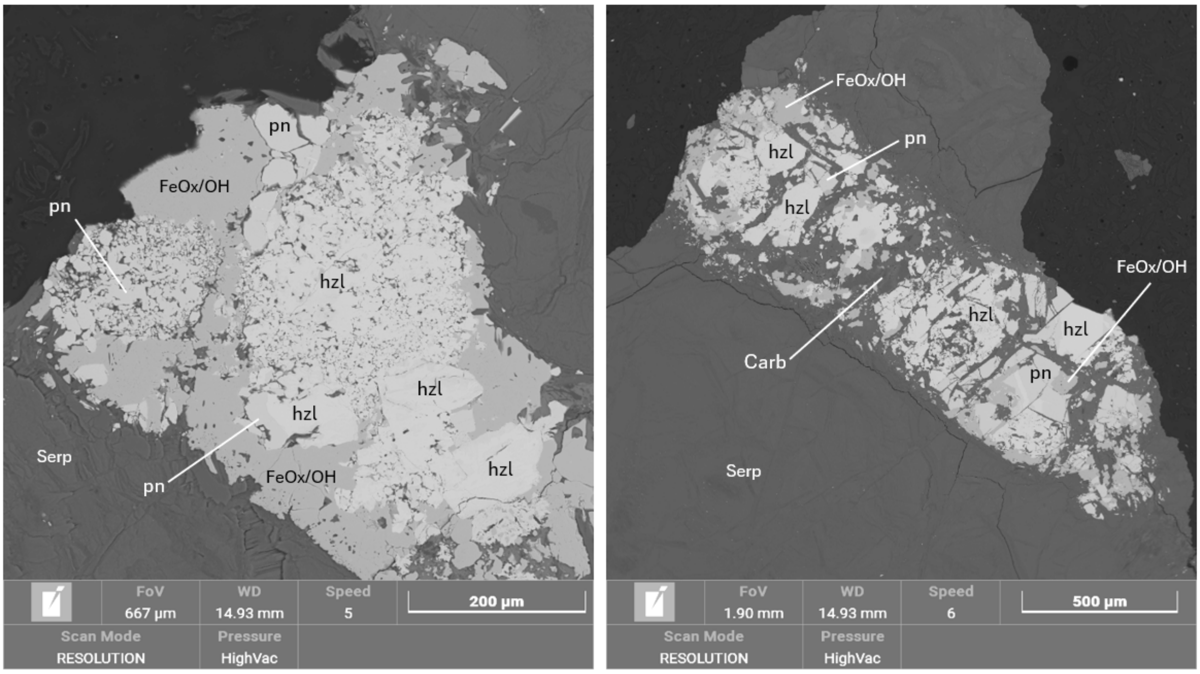

FIG 4 – BSE images showing heazlewoodite dominant mineral assemblages. Left: Heazlewoodite (hzl) and pentlandite (pn) with iron oxides (FeOx/OH) Bound by serpentine (Serp). Right: Pentlandite(pn), heazlewoodite (hzl) and iron oxide (FeOx/OH) inclusions in a carbonate (Carb) vein bound by serpentine (Serp).

MINERALOGY PROPOSED SOLUTION, INSTRUMENT SELECTION AND PURCHASE PROCESS

To address the limitations of traditional chemical assays and qualitative data in providing a comprehensive understanding of mineral systems, automated SEMs were evaluated to determine the appropriate instrument to purchase.

While a range of analytical techniques are available for obtaining quantitative mineralogy SEM-based methods are the most effective for accurately quantifying minerals present at trace concentrations. In the deposits studied, key nickel-bearing minerals typically occur at less than ~2 wt per cent. Techniques like X-ray diffraction (XRD) are limited in this context, as background noise and peak overlaps can prevent accurate detection and quantification of phases below ~5 wt per cent, making SEM-based analysis the most suitable analytical approach for the situation.

Instrument selection

The three major suppliers of automated SEMs were selected and provided five nickel sulfide samples from exploration drill core and processing samples (feed, concentrate and tail). The samples were provided to understand the capabilities of the suppliers regarding operational statistics, sample analysis, reporting and software development.

All sample blocks were prepared and analysed by a commercial laboratory prior to despatch. Extensive chemical assays, quantitative XRD (with amorphous content and data validation) were obtained on the samples for data validation and to ensure no sample preparation errors in the sample blocks sent to the suppliers.

With the suppliers being given the demonstration samples, direct comparison to key performance indicators could be performed and a decision made.

Based on the information and data gathered from the demonstration samples, the TESCAN TIMA automated SEM was selected as the preferred instrument. The TIMA provided advanced and efficient automated mineralogical analysis, offering detailed outputs including mineral abundance, elemental deportment, size distribution, liberation, mineral associations, textural information, amongst many other outputs. Additional benefits included batch reporting capabilities, data validation report, customisable report templates and different measurement modes. Ongoing software support and development from TESCAN further strengthened the decision to adopt the TIMA platform.

Lab location

The decision on where to establish a laboratory to house the TIMA instrument was guided by both logistical and collaborative considerations. After approaching universities, government agencies and a commercial lab, The University of Western Australia (UWA) emerged as the ideal choice.

The laboratory is leased from UWA, allowing for a dedicated set-up, co-located with additional expertise, while maintaining flexibility for future collaborative developments.

Business case

The acquisition of the TIMA required a clear and well-justified business case to ensure long-term viability and impact.

The legacy state of mineralogical characterisation was limited with the use of chemical proxies and qualitative data to inform resource, reserve and grade control models. These methods provided limited results with considerable caveats attached. Production reconciliation results also exposed some of the clear limitations with the use of chemical proxies for metallurgical recovery prediction.

Utilising automated SEM mineralogy negated many of these issues and enabled bulk analysis of drill core, chips, process feed, concentrate, tailings and downstream processing samples. Given the indirect link between geochemistry and mineralogy, a lack of accuracy and precision (repeatability) through internal XRD analysis and the qualitative nature of petrography, a robust business case was presented for capital consideration.

SAMPLING, DATA ACQUISITION AND DATABASE

A robust data acquisition and management process was essential for maximising the value of the TIMA instrument. Standardised workflows were implemented to maintain data integrity, while a dedicated (low-cost) database allowed for secure storage and retrieval of results. The structured approach ensured, consistency and enabled long-term accessibility of mineralogical data sets.

Sample selection

A standardised workflow for TIMA sample selection was developed to ensure reliable data collection. Samples for mineralogy were selected based on a number of criteria:

- deposit priority
- key variables of interest; Ni, S, As, Co, Cu, Mg, Fe, non-sulfide-nickel (NSNi)
- elemental ratios
- geological observations and uncertainty assessments
- SMU
- spatial location.

Sample preparation

Sample preparation is essential for obtaining high-quality mineralogical data from TIMA. For these projects, selected samples were sent to an external laboratory for preparation.

To gain statistically reliable data, each sample was split from coarse residue material (~3 mm) and then stage crushed to 100 per cent passing 150 μm. A low number of samples were mounted as coarse residue and assay pulps. All samples were set in 30 mm round moulds with resin, polished and carbon coated for TIMA analysis.

Fine material, which is less than 5 μm, can interfere with automated SEM analysis, complicating mineral classification. To mitigate this issue, stage crushing was undertaken as it reduces the production of fine material. Test work on stage crushed material demonstrated that the quantity of fine material entering the <5 μm fraction was sufficiently low, ensuring minimal impact on the final data and thus removal of <5 μm material was not required for future samples from these projects.

TIMA analysis

For the studies presented, TIMA analysis was conducted following standardised parameters to ensure consistency and reproducibility. Initial development work was undertaken to understand the optimal parameters for analysis. TIMA analysis was undertaken on stage crush, assay pulp and coarse residue material.

TIMA settings were tailored to suit the particle size and analytical objectives of each sample type. The pixel spacing was selected based on particle size of each material to ensure an appropriate balance between resolution and analytical efficiency. Finer material, such as assay pulps, was mapped at 3 μm spacing to capture detailed mineral textures and fine-grained associations. Stage-crushed material, being slightly coarser, was analysed at 5 μm pixel spacing to maintain representative resolution across broader areas. For coarse residue, a 3 μm pixel spacing was again used to preserve detail, while dot mapping with a 9 μm dot spacing was applied to manage run time over the larger particle sizes. Refer to Table 2 for TIMA analysis parameters.

TIMA analysis, mineral library and mineral list development, data generation, data validation and reporting were all done in-house.

TABLE 2
TIMA analysis parameters.

Properties	Stage crush	Assay pulp	Coarse residue
Measurement type	Liberation analysis	Liberation analysis	Liberation analysis
Acquisition mode	High resolution mapping	High resolution mapping	Dot mapping
Field width	1000	500	1000
Stitching	Yes	Yes	Yes
Pixel spacing (μm)	5.00	3.00	3.00
Minimum Brightness (%)	12	12	12
Maximum Brightness (%)	100	100	100
Dot spacing (μm)	NA	NA	9
X-ray counts	1000	1000	1000
Maximum minutes	60	60	90
Segmentation method	Standard segmentation	Standard segmentation	Standard segmentation
Separation of phases	18	18	18
Separation of touching particles	5	5	5
Minimum particle size (μm)	Unlimited	Unlimited	Unlimited
Maximum particle size (μm)	Unlimited	Unlimited	Unlimited
Boundary particles	Measure	Measure	Measure

NA – Not available.

QA/QC

To ensure the accuracy and reliability of TIMA mineralogical data, a comprehensive QA/QC (quality assurance and quality control) program was implemented. This involved validating the TIMA data for every sample analysed. The primary QA/QC processes included:

- Visual inspection of the sample blocks for marks, scratches, agglomerates.
- TIMA project structure and mineral library checks.
- Validation of TIMA generated assays against actual chemical assay.
- Validation of particle size using P_{80} (passing 80) against the stage crush size.
- Nickel deportment to silicates against non-sulfide nickel (NSNi) assay – performed on some samples.
- Validation of TIMA mineral abundance compared to XRD data – this was not conducted on every sample.

A set of guidelines was established to assess the consistency and accuracy of the TIMA results. These limits were determined by reviewing data sets from a range of sample types, grades and textures. In setting benchmarks, consideration was given to the inherent limitations of each method and the complexity of certain elements, such as NSNi. These QA/QC thresholds provide a framework for evaluating TIMA performance and ensure confidence in its analytical capabilities for detailed mineralogical assessments.

Reporting and data types

TIMA reporting plays a critical role in transforming raw mineralogical data into usable information. This section outlines how the data is reported and the key reporting outputs.

A standardised report template was implemented to enable batch exporting of TIMA data, ensuring uniform reporting. The key reporting outputs were:

- mineral abundance
- elemental deportment – Ni, S, As, Fe, Mg
- particle size P_{80}
- grain size P_{80} – violarite, pentlandite, NiFeS minerals combined, Mg OH/CO_3 minerals, talc, serpentine combined
- liberation – violarite, pentlandite, NiFeS minerals combined, Mg OH/CO_3 minerals, talc, serpentine combined.

This set-up enhanced reproducibility and supported seamless integration with downstream workflows.

Database

The TIMA mineralogical data were housed in an SQL Server database with a Microsoft Access front end, created to load and interact with the data. Primary drill hole, sample and despatch information were initially managed within the acQuire database, which served as the central repository for field and laboratory data. Relevant data were then replicated to the Mineralogy database to support downstream mineralogical interpretation.

The database allowed for a direct connection to 3D geological modelling software, enabling the spatial interrogation and modelling of mineralogy.

MINERALOGY ESTIMATION WORKFLOW

Exploratory data analysis

The raw TIMA mineral abundance and elemental deportment data was extracted from the database and back flagged using the 3D geological domains. This data set was then imported into Snowden Supervisor software for Exploratory Data Analysis (EDA). The global distribution of mineral deportment data was visualised using box plots, probability plots, and 3D trends plots. This EDA informed the development of the TIMA mineralogy weathering domains (OXSTP) and mineral domains (MINDOM field) categorised by Ni mineral deportment. Mineral domains are nested within the primary mineralisation system as well as the discrete weathering horizons.

Modelling and estimation

Elemental concentration and deportment data were imported into Leapfrog Geo. Source percentage calculations were conducted to estimate the nickel contribution from various minerals. An example calculation for pentlandite is provided below:

Ni_sp_pn = Ni_Pentlandite * Ni_pct/100

where:

Ni_sp_pn:	Source percentage of nickel in pentlandite
Ni_Pentlandite:	Total proportion of nickel contained in pentlandite (eg 70 per cent of the nickel is within pentlandite)
Ni_pct:	the nickel assay grade from the corresponding sample

This calculation ensures that pentlandite with high tenor, but low nickel content is appropriately weighted in the modelling and estimation processes. Nickel contributions were expressed as nickel tonnes (NiT), where 1 NiT refers to 1 t of contained nickel metal.

Estimation domains were defined based on standard nickel grade estimation criteria. Additional domains were developed case by case using TIMA-derived mineralogical data. Source percent intervals were composited to 2 m intervals to align with typical Diamond core and Reverse Circulation (RC) sample lengths.

Estimation was conducted using ordinary kriging for each domain and corresponding source percent values. Where data permitted, variograms were individually modelled for each nickel-bearing mineral. In cases with limited data or where a single mineral was clearly predominant, variograms derived from nickel grade were used. Large anisotropic search ellipsoids using dynamic anisotropy or aligned with the principal direction of continuity were applied to the estimators.

Block size and sub-blocking configurations were consistent with the existing resource model framework, ensuring compatibility with previous interpretation.

Post processing

The mineralogy model was integrated with the existing resource model. Insignificant proportions of uncoded blocks were applied default values. Weathering and primary mineral domains were calculated and applied across the model. The final output mineralogy variables are summarised in Table 3.

TABLE 3

Block Model output variables.

	Model fields	
Weathering – (OXSTP)	**Mineral domain (MINDOM)**	**Ni source %**
0 (Primary)	0 waste / oxide	
1 (Transitional)	1 Pentlandite Dominant (>50%)	Ni_Pn
2 (Supergene)	2 Heazlewoodite Dominant (>50%)	Ni_Hz
3 (Oxide)	3 Millerite Dominant (>50%)	Ni_Mi
	4 Others Dominant (>50%)	Ni_Ot
	5 Violarite Dominant (>50%)	Ni_Vi
	6 Silicates Dominant (>50%)	Ni_Si
	7 Gersdorffite Dominant (>50%)	Ni_Gs
	8 Nickeline Dominant (>50%)	Ni_Ni
	12 Pentlandite + Heazlewoodite Dominant (>70%)	
	13 Pentlandite + Millerite Dominant (>70%)	
	14 Pentlandite + Others Dominant (>70%)	
	15 Pentlandite + Violarite Dominant (>70%)	
	16 Pentlandite + Silicates Dominant (>70%)	
	17 Pentlandite + Gersdorffite Dominant (>70%)	
	18 Pentlandite + Nickeline Dominant (>70%)	

CASE STUDIES

This paper presents three case studies utilising TIMA data to estimate mineralogy in open pit Type 2 disseminated nickel mineralisation.

Geochemical proxies such as Ni, S, and NSNI have been employed to delineate oxide, transitional and primary alterations while qualitative petrological analysis was used for the supergene. The TIMA mineralogy of certain samples revealed significant discrepancies between expected mineralogy generated from chemical proxies in the transitional, and primary zones, indicating that these proxies are often ineffective.

Case study 1 – Deposit A

Deposit A is currently at an early resource definition stage and is supporting a scoping study. Spatially, the deposit is located in regions distal from existing operations legacy mining/processing. This, coupled with the pretence of geochemical indicators that imply high mineral variability, presents a mandate to characterise and inform scoping studies with an adequate level of mineralogical understanding. To characterise this undeveloped deposit, which was fast-tracked in strategic mine plans, and to establish the standard Nickel West aims to achieve, a substantial amount of spatially representative TIMA data (over 2600 samples) was collected. TIMA was undertaken on mainly stage crushed material.

The large amount of TIMA data allowed for mineralogical domaining across Deposit A, a first for Nickel West. The global distribution of mineral deportment data revealed notable contrasts between zones across the deposit for the nickel sulfide minerals including pentlandite, heazlewoodite, millerite and violarite. Figures 5 through to 10 are taken from Leapfrog Geo and show the mineralogy domains for some of the main nickel minerals. The images have a nickel deportment concentration scale bar, which changes from mineral to mineral.

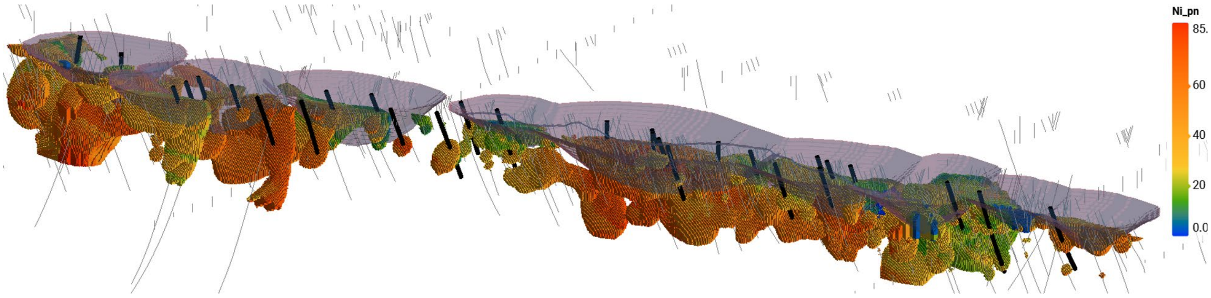

FIG 5 – Mineralogical domaining of Ni deportment in pentlandite showing pentlandite is dominant across the deposit however there are areas where pentlandite drops out.

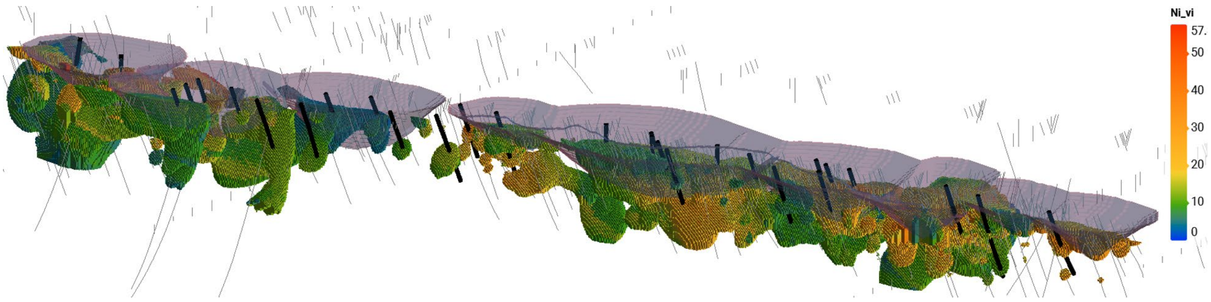

FIG 6 – Mineralogical domaining of Ni deportment in violarite showing concentrated areas of high violarite in the Southern region of the deposit.

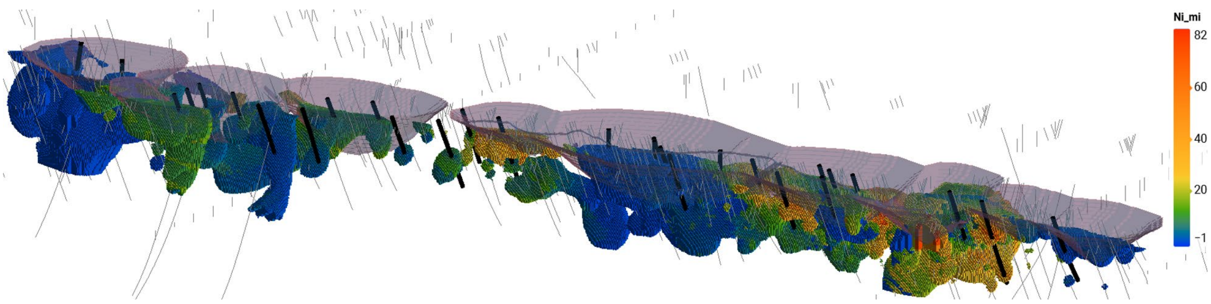

FIG 7 – Mineralogical domaining of Ni deportment in millerite showing concentrated areas of high millerite towards the South end of the deposit.

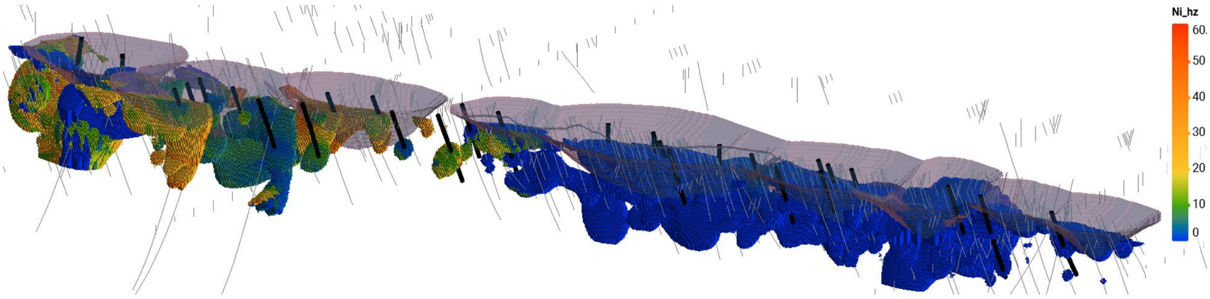

FIG 8 – Mineralogical domaining of Ni deportment in heazlewoodite showing the North end heavily concentrated in heazlewoodite.

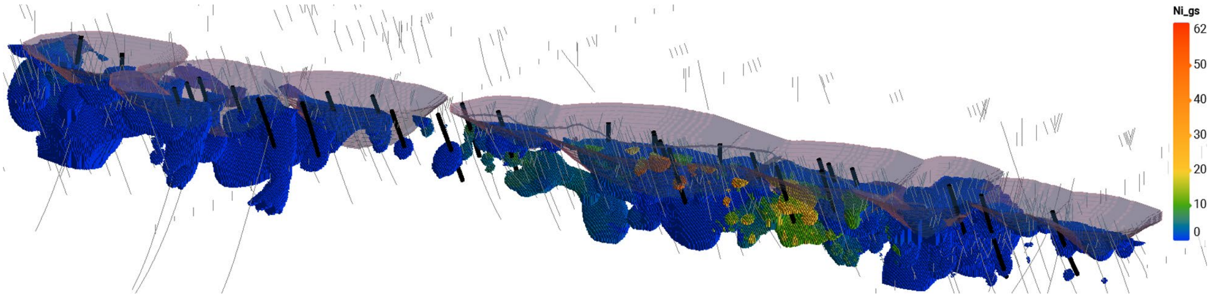

FIG 9 – Mineralogical domaining of Ni deportment in gersdorffite showing concentrated areas towards the middle of the South end of the deposit.

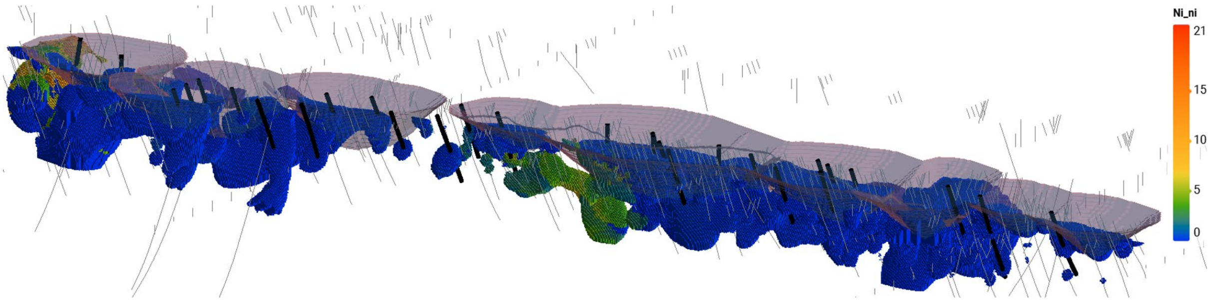

FIG 10 – Mineralogical domaining of Ni in nickeline showing concentrated areas towards the North end and middle of the deposit.

The mineralogical domaining shows the variable nature of the nickel minerals across the global deposit. There are concentrated areas of problematic nickel minerals which when known in advance can be accounted for within the mine planning assumptions.

Further to this, the mineralogy domains can be interrogated on a local scale. Unlike the standard distribution of sulfide alteration minerals, Figures 11 and 12 show a plan view and cross-section of the pentlandite primary domain and significant amount of pentlandite and secondary sulfide minerals (transitional material) identified at depth. This transitional material identified at depth was relatable to the presence of brittle structures.

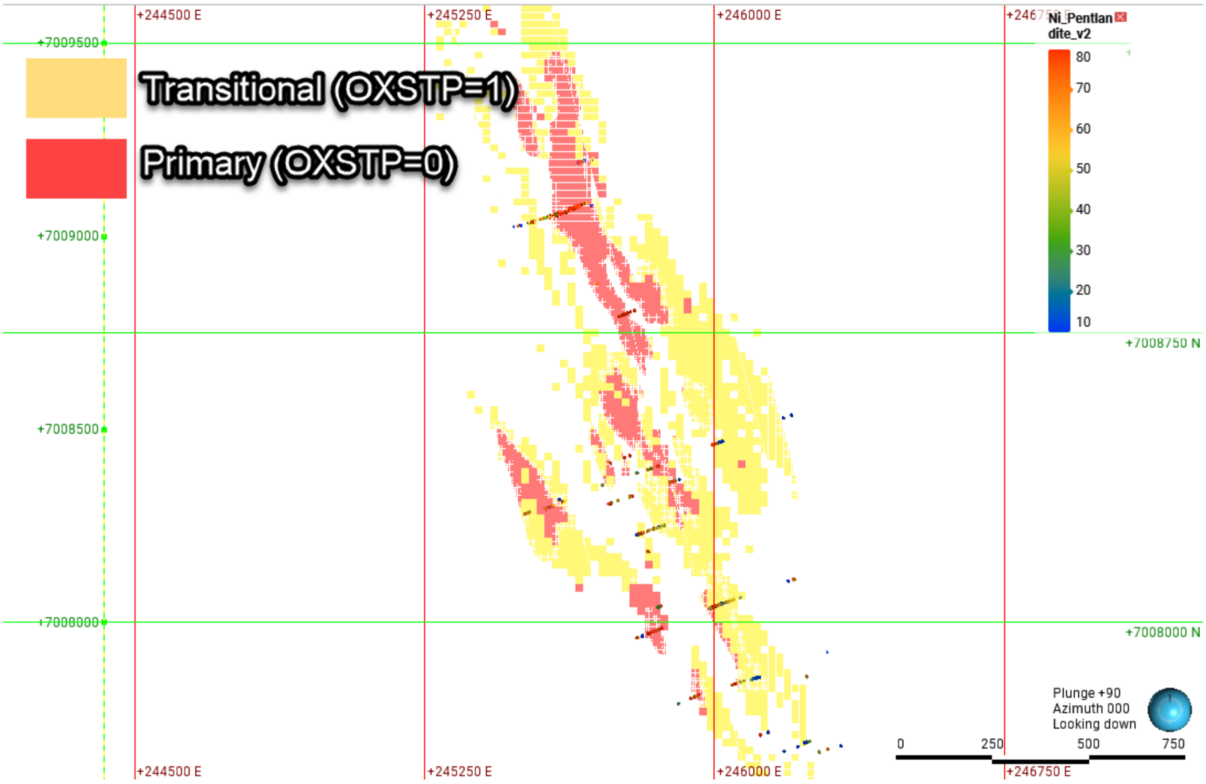

FIG 11 – Plan view of mineralogy weathering classification (OXSTP) showing transitional material at depth >300 m to the northern end of the deposit. The drill holes have been coded by Ni deportment in pentlandite.

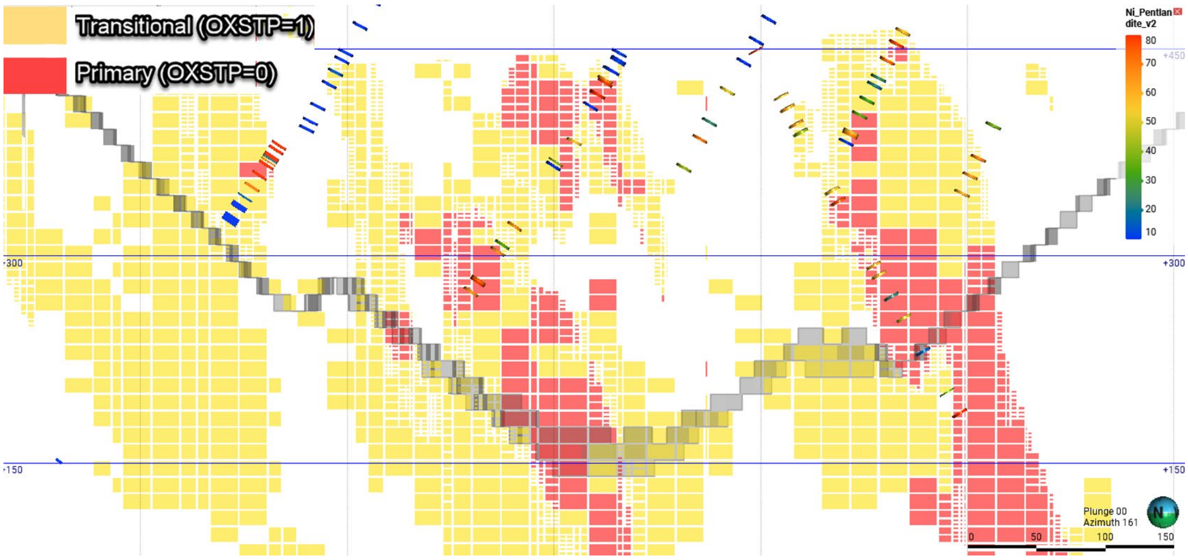

FIG 12 – Cross-section of mineralogy weathering classification (OXSTP) and pit shell showing transitional material at depth >300 m to the northern end of the deposit. The drill holes have been coded by Ni deportment in pentlandite.

Investigation into the weathering classification based on geochemical proxies showed it did not perform as expected for the primary material – likely a result of preferential weathering via subvertical structures. The geochemical weathering (OXSTM) was defined using geochemical proxies, typically using Ni, S, NSNi. This resulted in three weathering domains: Oxide, Transitional and Fresh. These domains were generally used to estimate the grades. TIMA analysis revealed elevated variability in pentlandite distribution, which contrasted with the anticipated 60–70 per cent pentlandite deportment (Figures 13 and 14). Instead, significant variability was observed, with discrete zones of heazlewoodite and millerite identified.

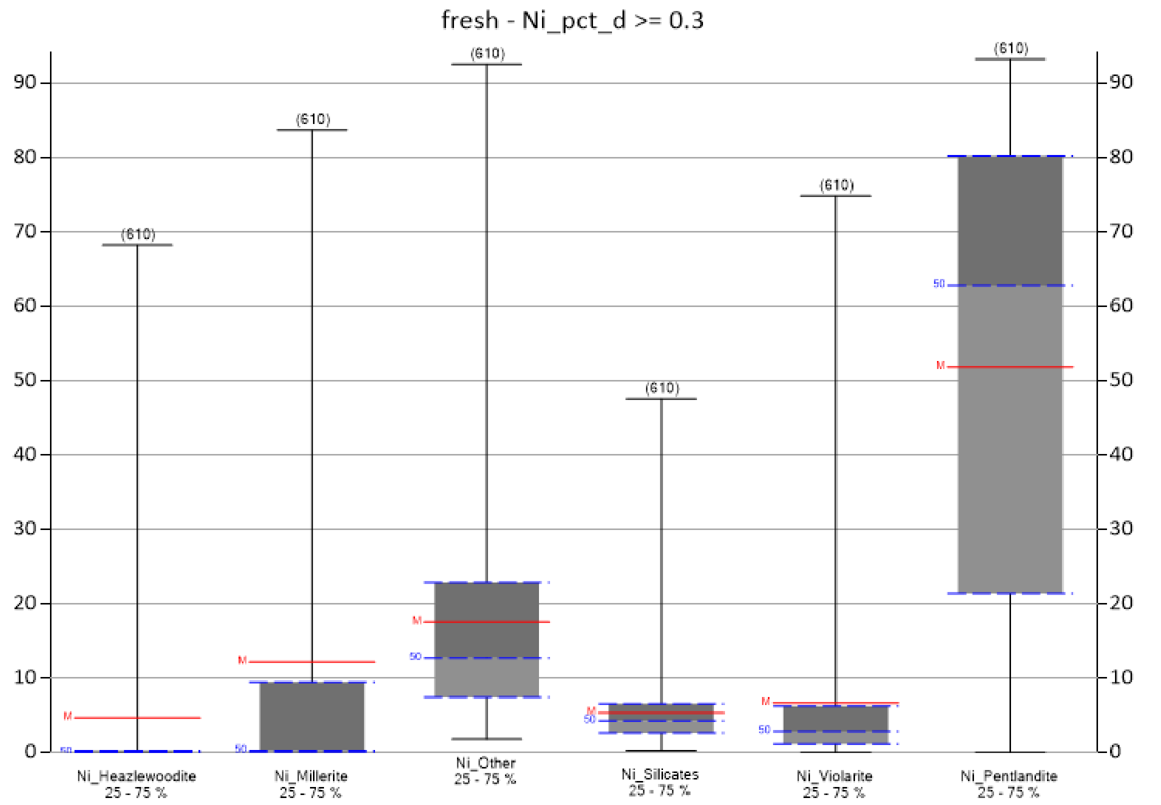

FIG 13 – Box and whisker plots showing TIMA mineral distribution in 'fresh' domain defined by geochemical proxies.

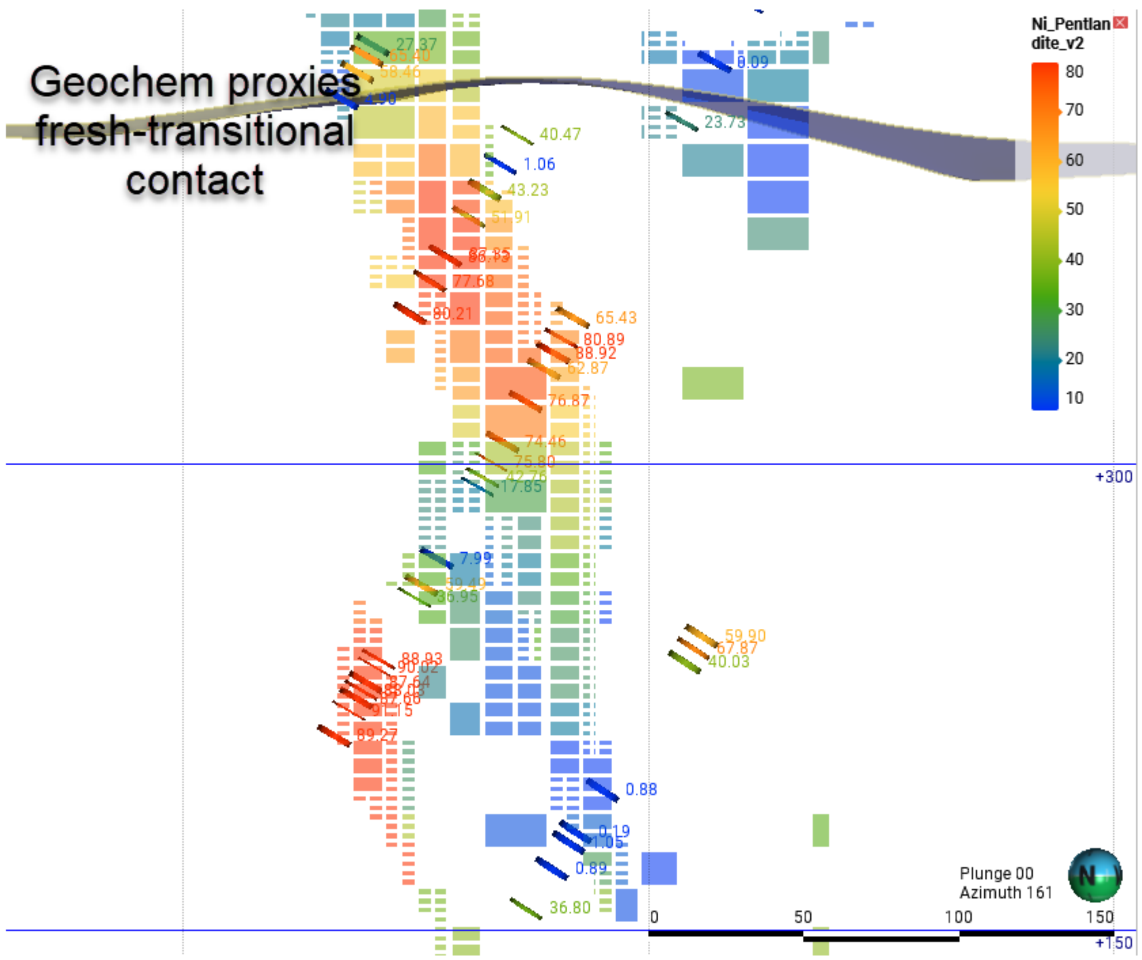

FIG 14 – Cross-section showing pentlandite variability in drill holes and blocks within the mineralised Ni04 domain.

The output mineralogy model presents features that carry materially contrasting processing outcomes between these various sulfide minerals. It is critical that Mine Planning and optimisation activities generate modifying factors and processing assumptions to honour this inherent variability. Infill strategy, grade control practices, pit sequencing, fleet size, stockpiling regimes, blend strategy, comminution, flotation, tailings disposal and downstream processing assumptions all need to be considered based on these outcomes.

Case study 2 – Deposit B and Satellite B

Deposit B is an active mining operation, while Satellite B is a shallow brownfields exploration satellite project located approximately 200 m north-west of the main deposit (Figure 15). A total of 600 assay pulp samples were collected across both deposits to characterise the sulfide mineralogy by TIMA.

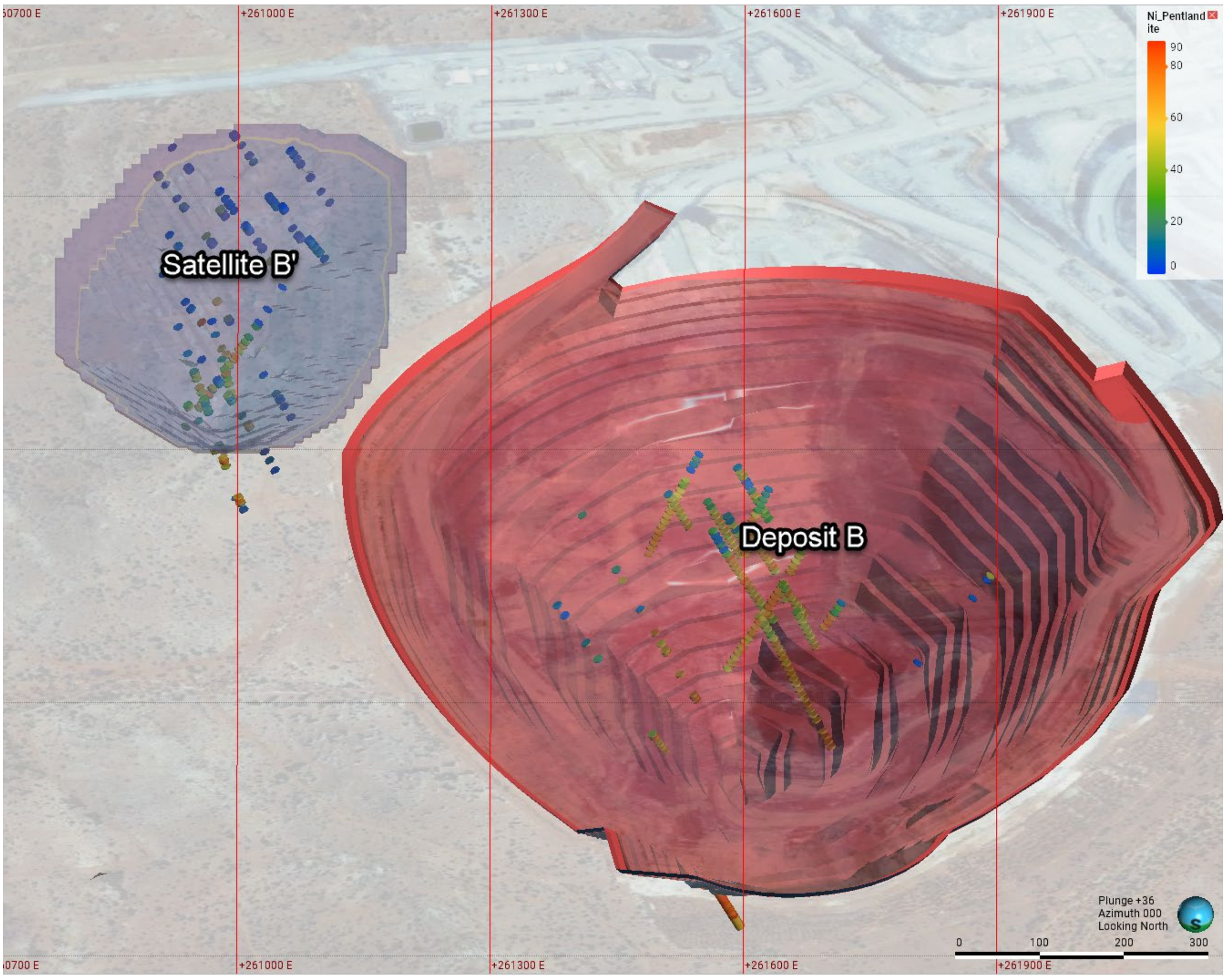

FIG 15 – TIMA data collection spatial distribution in deposit B and its satellite B. The drill holes have been coded by Ni deportment in pentlandite.

The global distribution of mineral deportment data revealed notable contrasts between domains and between the two deposits. The Deposit B orebody performed very well with nickel mineralisation being highly pentlandite dominant (Figure 16) and with negligible deportment to silicates or complex sulfides. This provided confidence in recovery being as predicted and confirmed by adequate production reconciliation results. Satellite B, even if closely located to the main orebody, presented very high variability and a limited amount of pentlandite deportment relative to violarite, silicates and complex nickel sulfides.

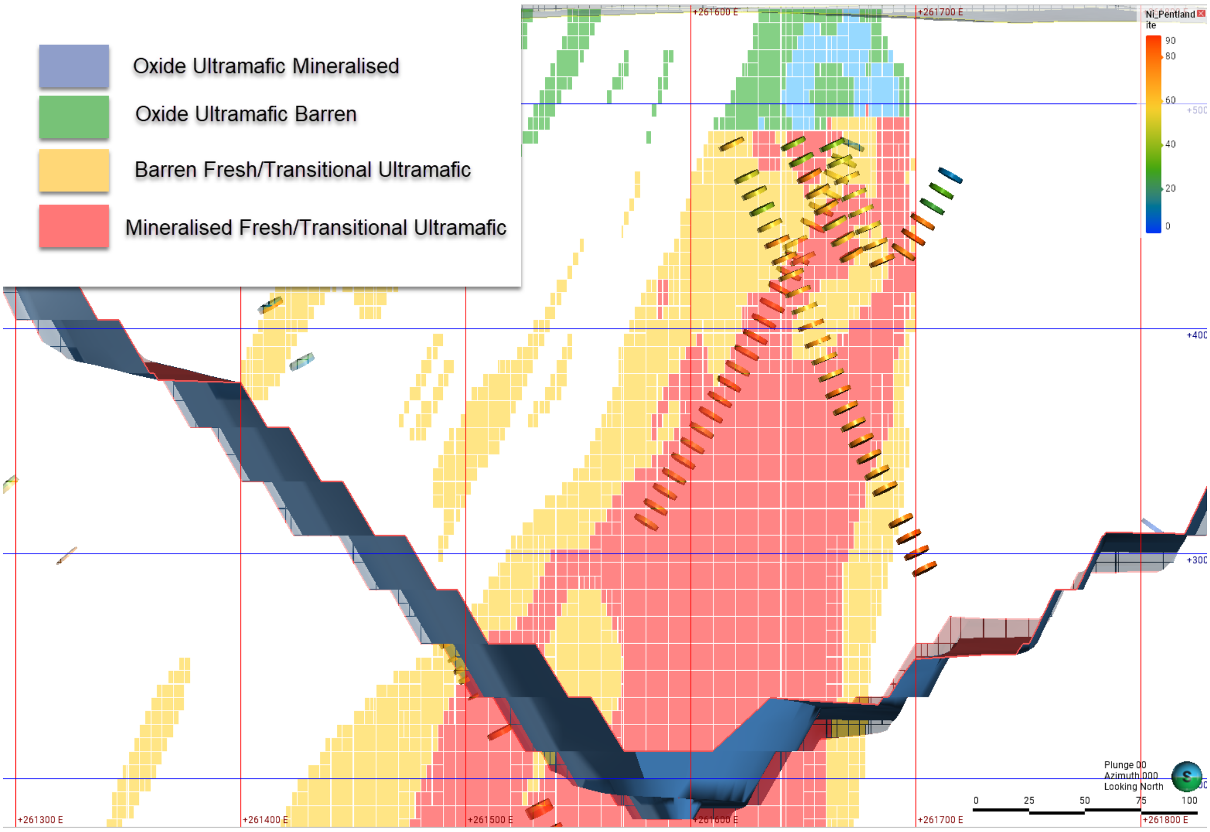

FIG 16 – Cross-section showing geological domains used for mineralogy estimation in Deposit B. The drill holes have been coded by Ni deportment in pentlandite.

Figures 17 and 18 presents a mineralogy distribution box and whisker plots for Deposit B and Satellite B. From this mineralogical data, it can be expected that the metallurgical recovery expected for Satellite B is minimal.

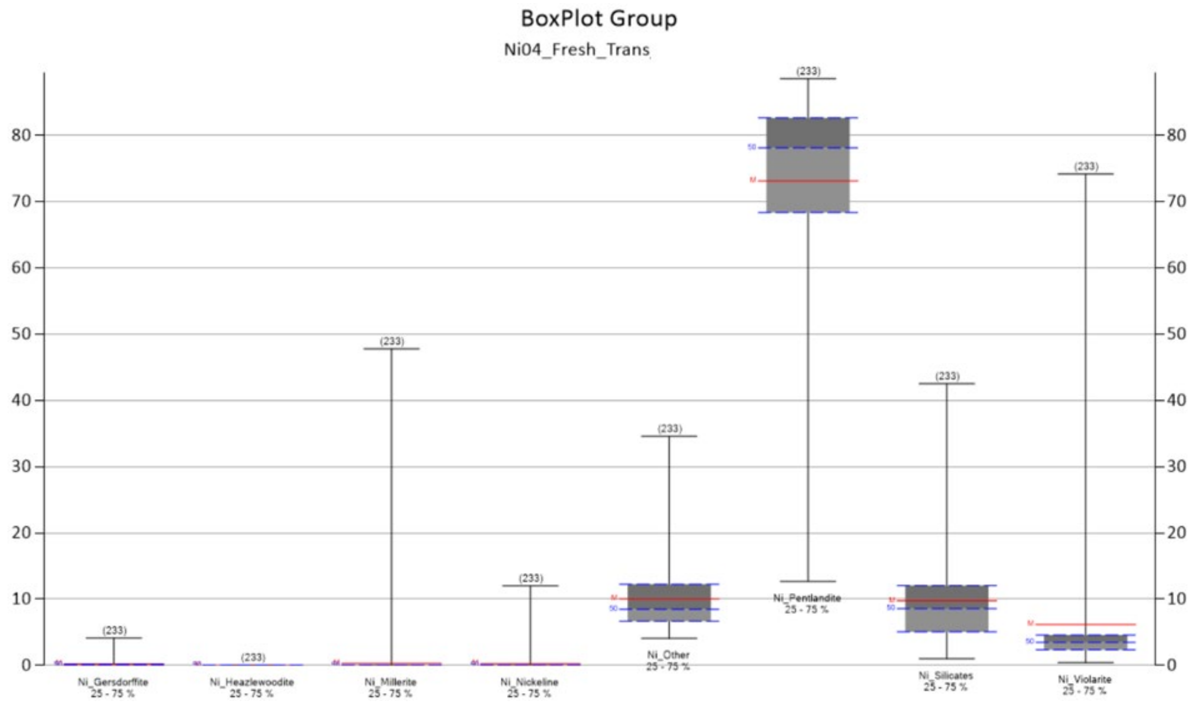

FIG 17 – Box and whisker plots showing mineralogy distribution in Deposit B.

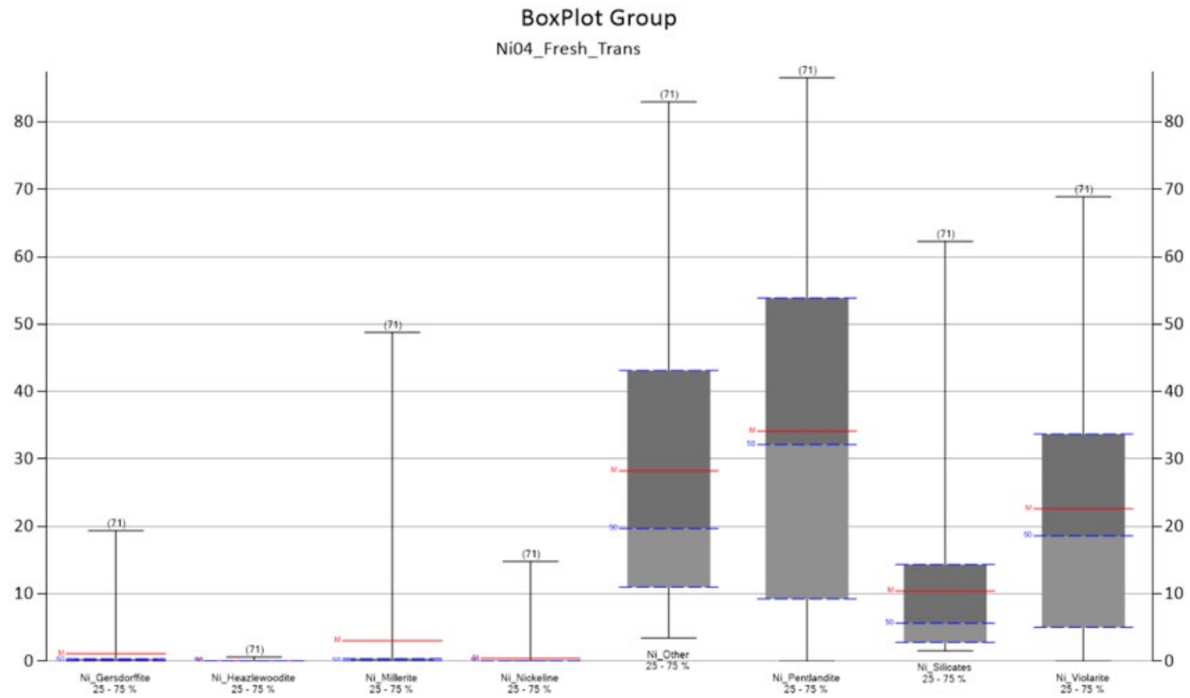

FIG 18 – Box and whisker plots showing mineralogy distribution in Satellite B.

The grade shell cut-off for Ni in this deposit is 0.4 per cent, which aligns with other similar deposits and serves as a reasonable proxy for economic potential and sulfide deportment. However, the mineralogy model indicates a significant amount of subgrade material (eg Ni 0.3 per cent – 0.4 per cent) with high pentlandite values, presenting an opportunity to domain, extract and recovery this material (Figure 19).

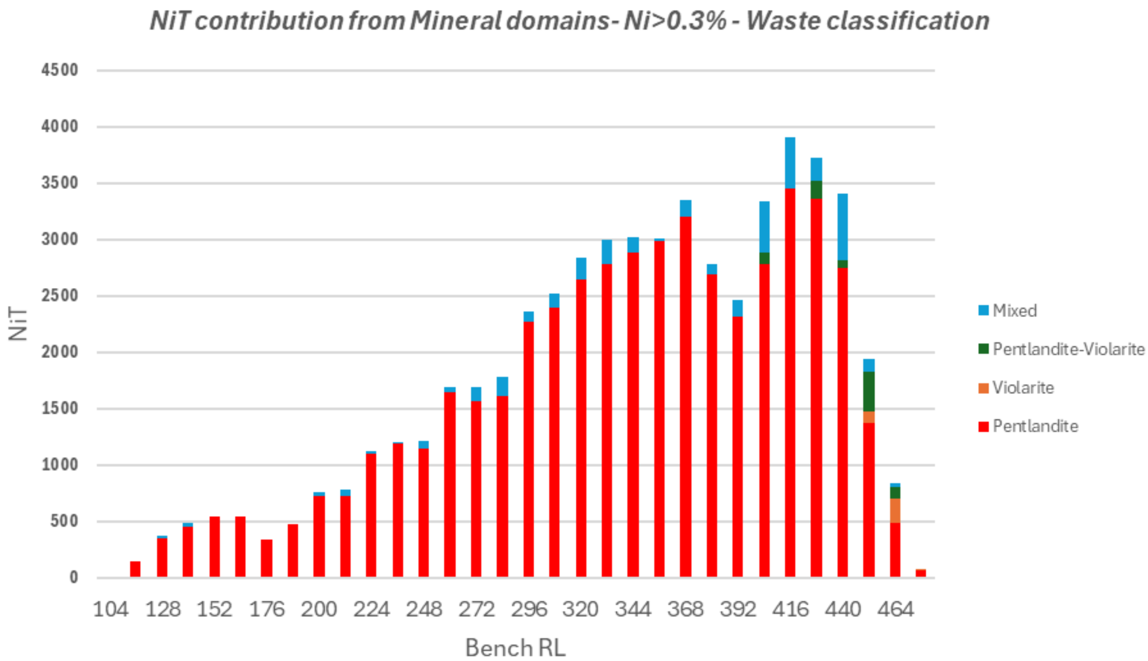

FIG 19 – NiT contribution per bench for material classified as waste with the metallurgical algorithm and with Ni > 0.3 per cent, opportunity to upgrade pentlandite dominant material to ore.

Case study 3 – Deposit C

Deposit C is an early-stage active mining area where only the first three benches of oxidised material have been mined. A total of 400 assay pulp samples were collected for TIMA analysis after mining had commenced with 95 per cent of the data within the ultramafic domain and mineralisation horizon. Figure 20 shows the spatial distribution of the TIMA samples. A significant amount of data was collected at shallow depth to help characterise the supergene material (Figure 21) which is critical for stockpiling requirements and tactical planning. As previously mentioned, supergene mineralisation is difficult to identify by geochemical proxies and often results in misclassification.

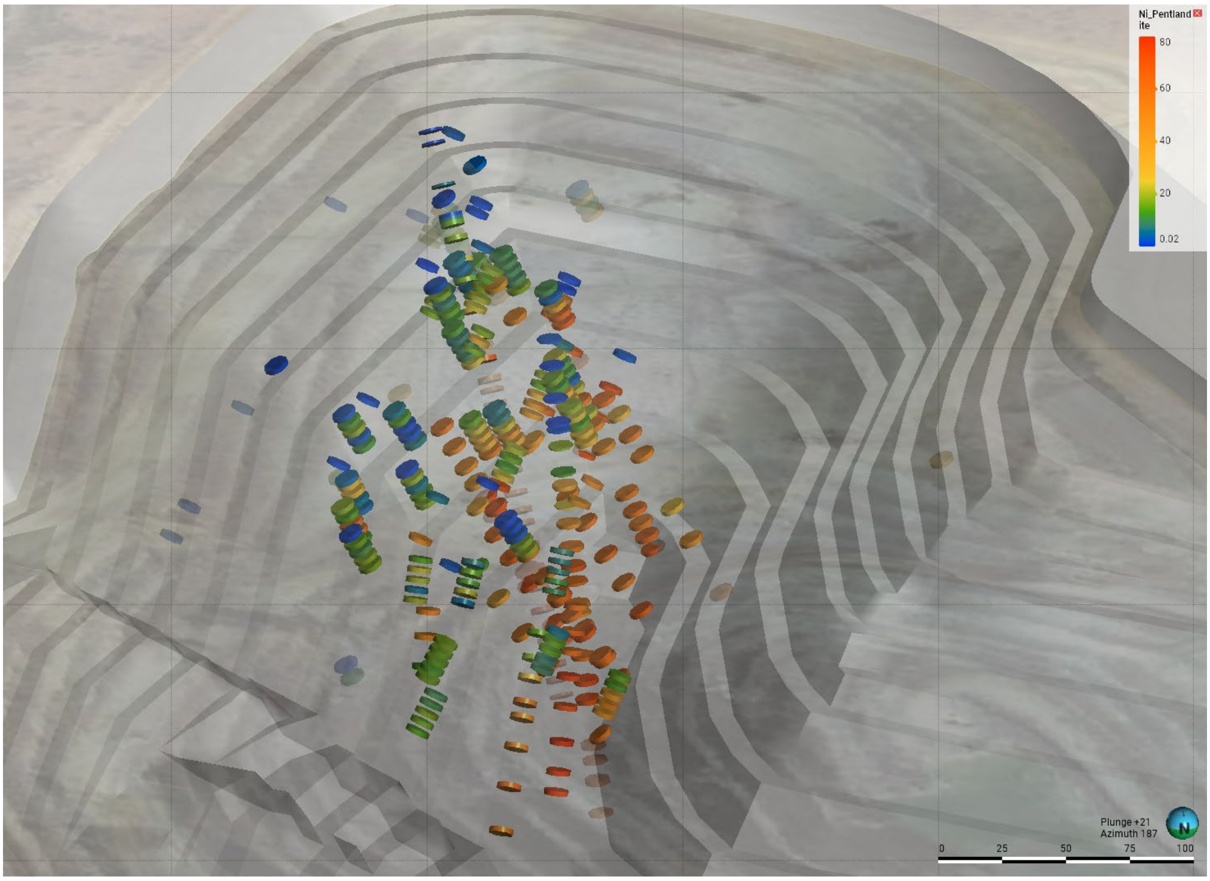

FIG 20 – TIMA data collection spatial distribution with a Ni in pentlandite colour scale bar.

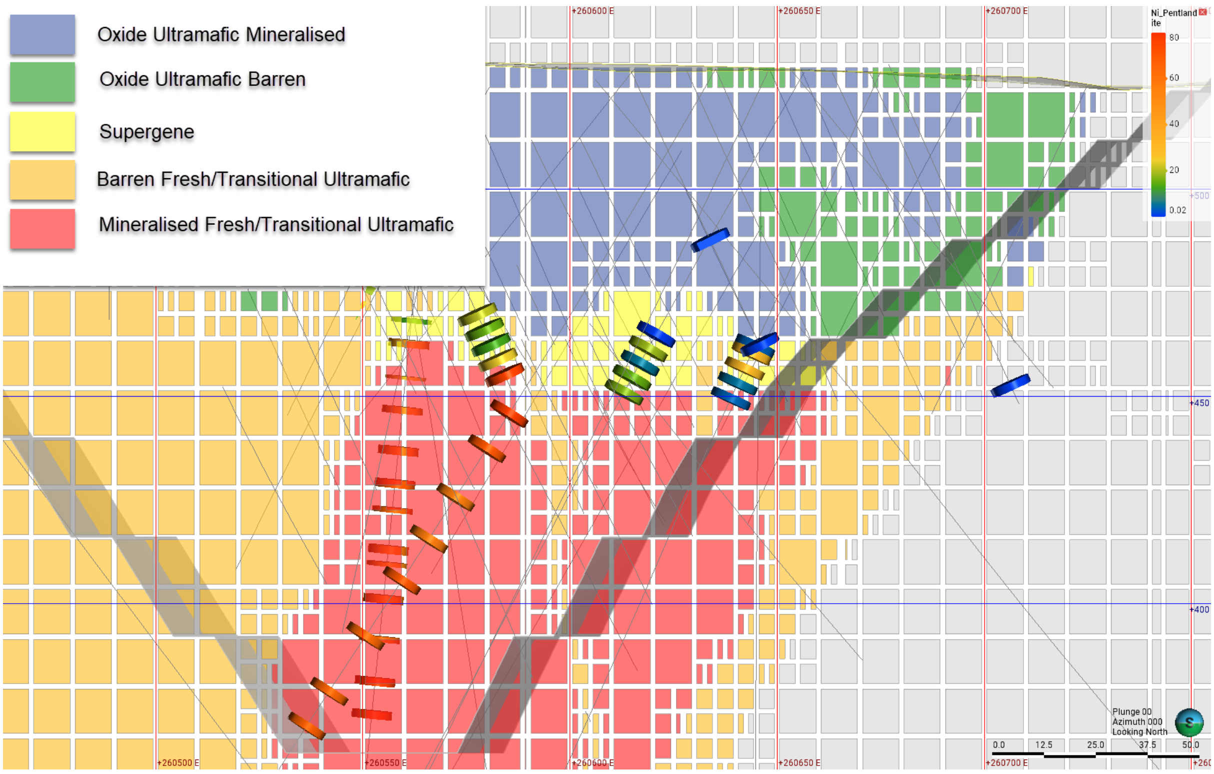

FIG 21 – Cross-section showing geological domains, including supergene, used for mineralogy estimation in Deposit C.

The transitional domain is characterised by high concentrations of pentlandite and low levels of silicates, violarite, and complex nickel sulfides. In contrast, the supergene domain exhibits minimal pentlandite content but elevated levels of violarite, silicates, and complex nickel sulfides. Probability plot (Figure 22) indicates that a combination of pentlandite and heazlewoodite (exceeding 60 per cent) constitutes a population representative of primary material (OXSTP=0). Conversely, the supergene material (OXSTP=2) can be classified by a proportion of violarite, silicates, and complex nickel sulfides greater than 70 per cent (Figure 23). The transitional material (OXSTP=1) is a mixture of pentlandite, silicates, millerite, and complex sulfides.

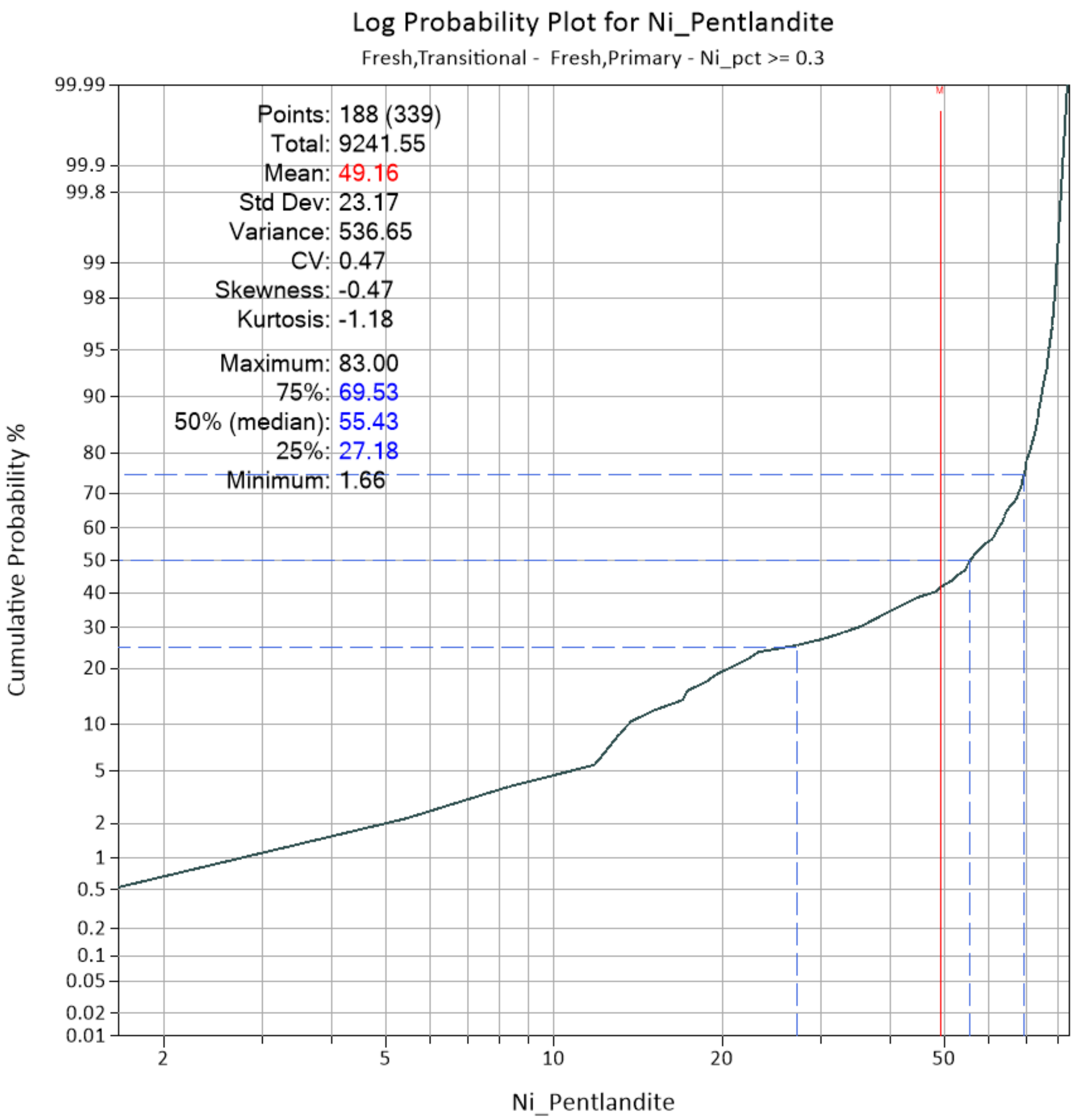

FIG 22 – Probability Plot for Ni Pentlandite in fresh/transitional showing two populations around 60 per cent cut-off.

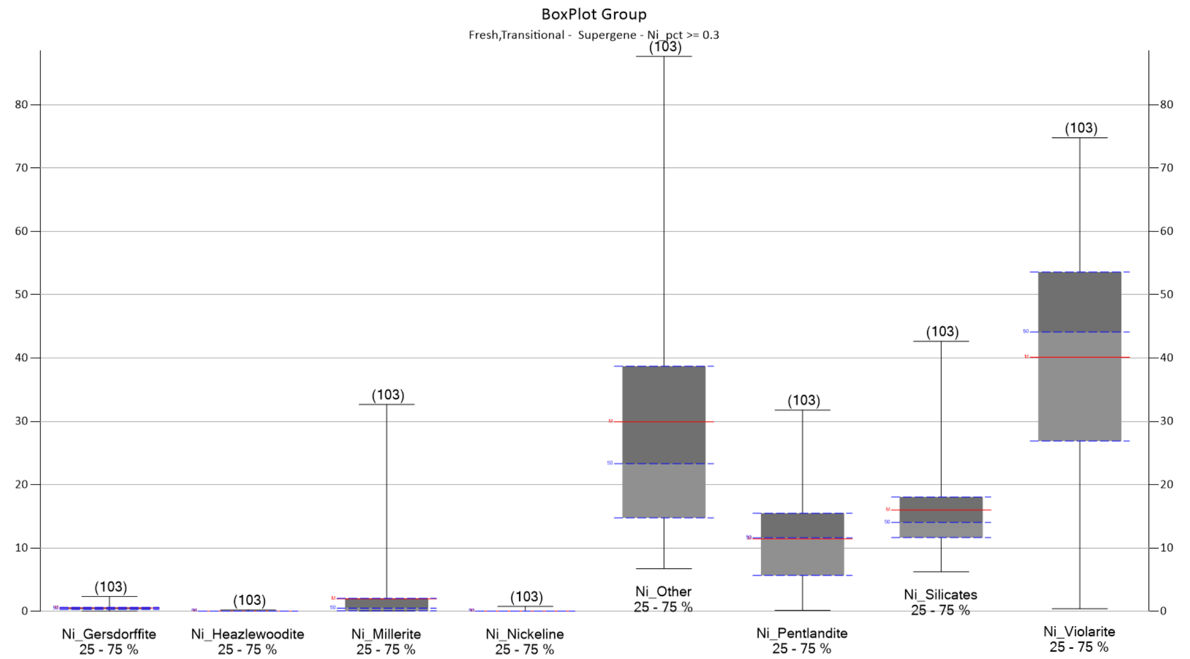

FIG 23 – Box and whisker plots of Supergene material showing violarite, silicates and other (complex) Ni sulfides as dominant minerals.

The mineralogy distribution and alteration of pentlandite appears structurally controlled by a significant NNW fault. Figure 24 shows elevated pentlandite in the footwall, while the hanging wall exhibits secondary sulfide assemblages.

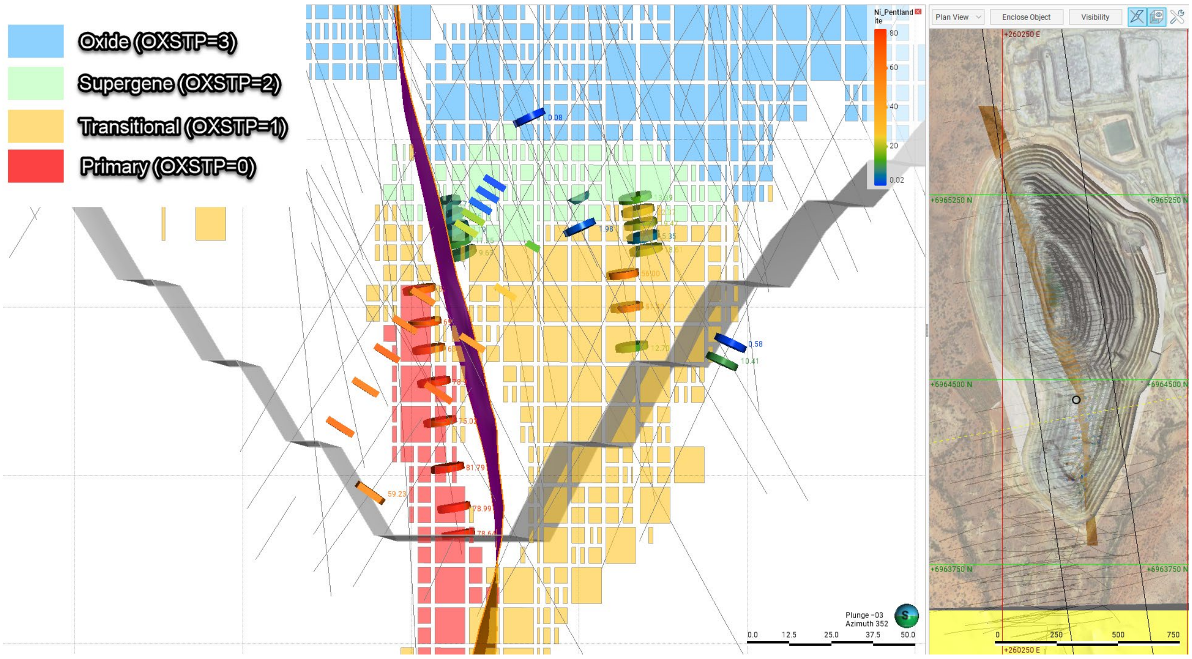

FIG 24 – Cross-section of petrology weathering classification (OXSTP) showing structural control of mineralogy distribution.

The mineralogy distribution and OXSTP were compared to the ore classification, which is derived from a geometallurgical algorithm utilising geochemical proxies. The findings indicate that, although the geometallurgical algorithm generally performs well, yielding low recovery in supergene material, moderate recovery in transitional material, and high recovery in primary material, there are specific zones where discrepancies arise. In these zones, geochemical proxies suggest the presence of primary ore, while mineralogy data indicates transitional material with low pentlandite values (Figures 25 and 26). These zones are not expected to perform as anticipated and should be stockpiled with lower recovery material as a precautionary measure.

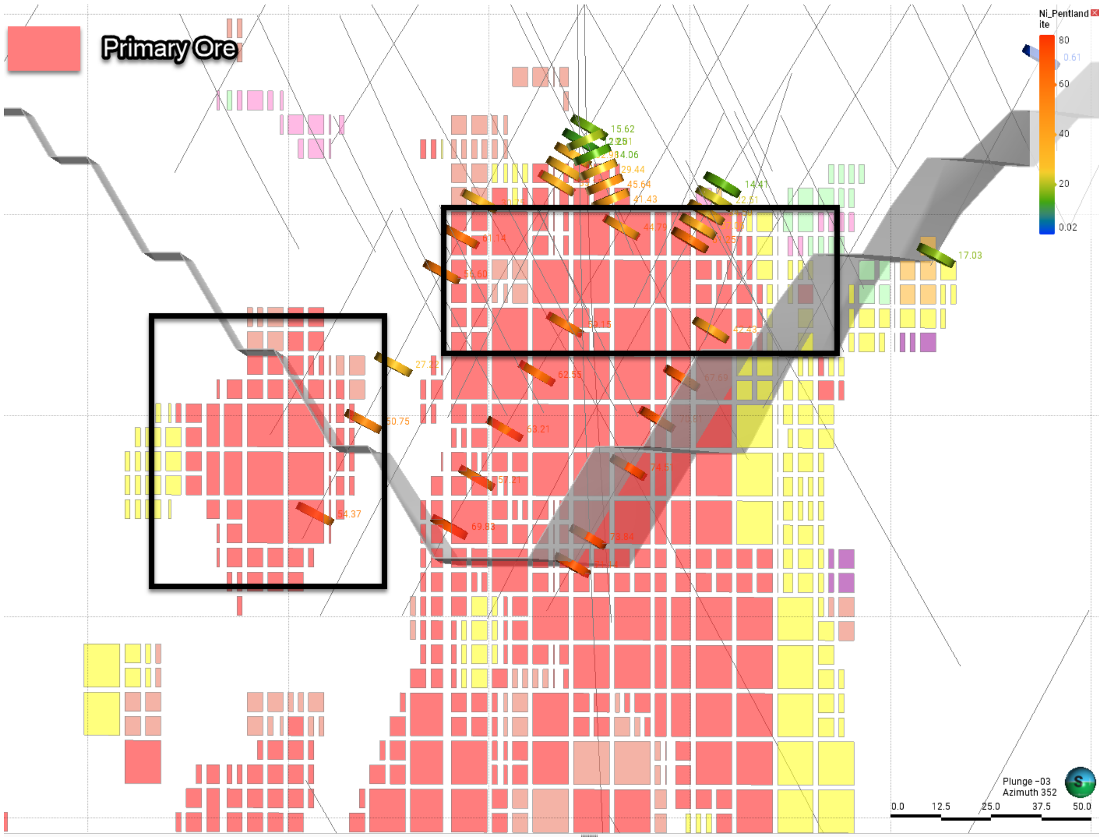

FIG 25 – Ore classification based on geochemical proxies. Black rectangles highlight high risk areas where geochemical proxies indicate material with high recovery while TIMA samples show mixed material with lower recovery expected.

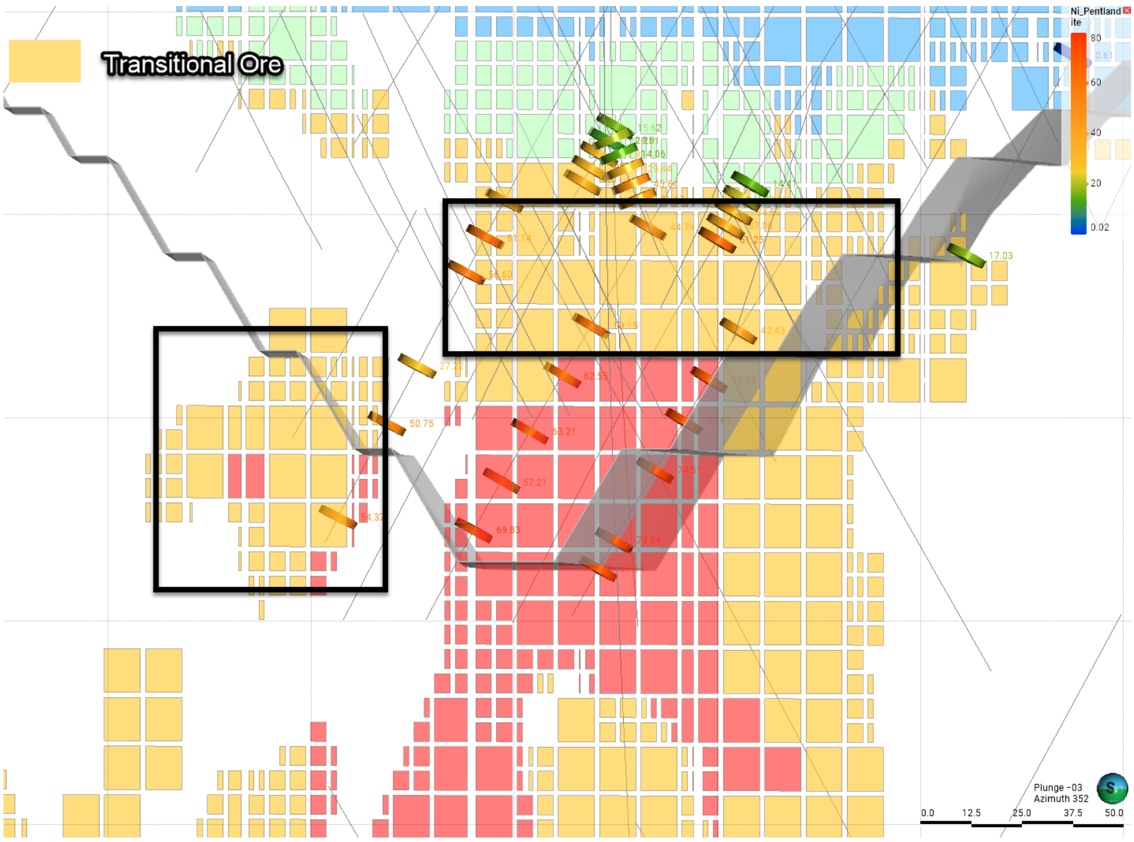

FIG 26 – Ore classification based on OXSTP. Black rectangles highlight high risk areas where geochemical proxies indicate material with high recovery while TIMA samples show mixed material with lower recovery expected.

CHALLENGES AND OPPORTUNITIES

Upfront capital cost of instrument procurement and laboratory set-up was significant; however, this cost is negligible relative to the monetary value of effective orebody characterisation where the data can be integrated with the complete mine planning value chain. This value can be demonstrated when establishing a business case.

Due to the early-stage nature of the project, validation of the mineralogy model was primarily limited to visual assessments comparing TIMA samples with block model outputs. There is an opportunity to apply the same rigorous validation protocols commonly that are used for geochemical analytes.

The next advancement is the planned integration of hyperspectral techniques – specifically VNIR-SWIR reflectance (ASD) and mid-infrared FTIR spectroscopy – combined with machine learning for mineralogical domaining across a deposit. This approach presents a cost-effective and scalable solution for routine mineral mapping, offering fast turnaround with minimal sample preparation. TIMA will serve a key training and validation tool, supporting the development and refinement if the FTIR-derived mineral models by providing detailed mineralogical context.

A clear opportunity lies in extending the mineralogical domaining approach to incorporate grain size distribution (eg P_{80}) and mineral liberation data, particularly for the key minerals of interest. Domaining these attributes would provide a more predictive understanding of mineral behaviour during processing and unlock further potential for metallurgical targeting at both the resource and operational scale. This level of mineralogical resolution is a logical next step in evolving from presence/absence mineralogy toward diagnostic, process-relevant characterisation – enabling stronger linkages between geology, metallurgy and project value.

TIMA sample preparation from historical pulps as a cost-effective means of data generation and characterisation for mineral systems where no drilling activities are planned. These pulps are often degraded or difficult to locate, however internal studies have so far shown promise in utilising sample pulp >10 years in age if stored appropriately.

There is an opportunity to define mineral domains with hard or soft boundaries directly from TIMA data, rather than estimating them within the broader nickel shell geological domains. This approach would allow for more precise refinement of variograms and search orientations tailored to each domain. This would reduce the degree of smoothing and mineral mixing and likely improve predictive accuracy.

Establishing a strong link with geometallurgical testing and TIMA results is essential to validate the assumptions and confirm performance characteristics for each mineral and mineral proportions. These assumptions can then be fed back into strategic and mine planning activities based on the data modelled in 3D.

Early exploration decision-making with regard to metallurgical outcomes is an important aspect of target ranking. Geochemical proxies can be utilised however these carry risk if targets are in unfamiliar mineralisation systems. Quantitative mineralogy allows for rapid decisions to be made with target turnover or progression.

Acid mine drainage assumptions and some aspects of mine closure planning also rely heavily on geochemical proxies. There are also opportunities to utilise quantitative mineralogy data to inform these decisions without the need to complete bespoke test work or leverage geochemical proxies.

The integration of collected data into geometallurgical algorithms, rather than relying solely on geochemical proxies is vital for improving material classification and resource estimation.

CONCLUSION

This paper has demonstrated the value of integrating quantitative mineralogical domaining into resource, mine planning and operational workflows. While chemical assays remain a widely accepted and indirect input across industry, the use of TIMA-derived mineralogical data provides a direct, diagnostic understanding of mineral systems, enabling stronger correlations to recoverable metal assessments and project optimisation assumptions.

Through routine applications across three strategic projects, TIMA data has been acquired, validated and reported into the geological database. This approach coupled with 3D modelling software has surfaced critical mineralogical nuances within the nickel systems that can materially influence key technical assumptions and downstream decisions.

The incorporation of quantitative mineralogy into both the resource and grade control models strengthens the characterisation of the orebody, enabling a spatial and predictive link through to metallurgy with less uncertainty, mine planning and broader project strategy.

ACKNOWLEDGEMENTS

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A room temperature leaching process for treating lithium-ion battery waste – advances and industrial potential

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ABSTRACT

Lithium mixed metal oxides, sourced from battery waste or black mass, can be effectively leached using 2M sulfuric acid at room temperature, with controlled addition of hydrogen peroxide as a reducing agent. This innovative approach distinguishes itself by operating at a constant solids loading of 10 per cent, eliminating the need for high temperatures, and minimising the inefficiencies associated with rapid dissolution and side reactions of peroxide observed in conventional methods. Despite its advantages, the dissolution process slows over time under lower temperatures and relatively higher solid loading, necessitating longer leach periods for near-complete extraction of valuable elements. To enhance process efficiency and facilitate industrial adaptation, strategies such as recirculation of leach liquors and residues were evaluated. Additionally, a two-step recirculating batch process was tested, allowing the reuse of both solids and leach liquor to improve combined leaching efficiency and the carbon quality of the final residue. The process demonstrated exceptional recovery rates of 96–99 per cent for Co and near-complete extraction of Mn, Ni and Li. Furthermore, the by-product leach residue graded 95 per cent total carbon, indicating the potential for resourceful utilisation of waste materials in a continuous industrial framework.

Critical mineral and commodity recovery from e-waste

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ABSTRACT

Sircel is an Australian-owned and operated green technology company solving the ever-growing e-waste crisis. Sircel has engineered a world-leading, end-to-end, large-scale recycling process, to extract source materials from electronic waste for reuse in the circular economy. Sircel has processed over 6300 t of e-waste to date with a >90 per cent commodity recovery, with significant plans to scale operations in the coming years.

The pressure to secure strategic and critical metals is driven in large part by the exponential increase in demand of technology. As a society, we regularly discard obsolete technology to consume new technology and so it stands to reason – what is the impact of circular economies on resource security?

The full suite of elements on the critical minerals list are used in electronics manufacturing – from household items to civic infrastructure – including solar and AI server farms. Thus, e-waste is a viable source of critical minerals that requires no exploration, discovery or development – we simply need to think differently about re-mining materials already liberated from the ground.

Sircel currently operates six sites along the east coast of Australia, including physical processing and hydrometallurgy sites. Our process currently recovers base, precious and platinum group metals with a multistage R&D focus on recovery of critical metals like Ge, Ga, Ta.

Sircel's commitment to divert e-waste from landfill goes beyond valuable resource recovery and encompasses the re-purposing of all outputs from our process. This holistic approach has required significant focus on development of a true circular economy, whereby we have built synergistic and/or mutually beneficial relationships with partners operating in the recycling, chemical, mining, industrial and manufacturing spaces.

The presentation will expand on the technical, social, governance and environmental challenges and opportunities to tap this significant source of critical minerals.

Corrosion prevention of lithium-ion battery poles in NaCl solutions to develop safe and environmentally sustainable discharging process for improved recyclability

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ABSTRACT

As lithium-ion battery (LIB) production increases, the EU's recycling regulations require higher recoveries of the critical raw materials to reduce the environmental impact of mining. Recycling of waste LIBs is a challenging task as the battery cells are composed of a complex mixture of toxic and highly reactive materials, tightly glued together by a chemically stable binder and current pyrometallurgical processes only recover few valuable elements. To recover a broader range of critical raw materials from spent LIBs, mechanical and hydrometallurgical recycling methods must be employed. This requires development of a safe, environmentally sustainable, and industrially scalable discharging process to improve recycling of LIBs. Electrochemical discharge shows promise due to its simplicity, scalability, and potentially low cost, but inefficient discharge and casing corrosion, which results in production of toxic wastewater, and loss of critical raw materials remain unsolved. NaCl solution has been extensively studied as a promising discharge medium because of its low cost and efficient discharge. However, severe corrosion of the connector poles can lead to incomplete discharging and need for extensive investments in toxic wastewater treatment and gas cleaning. To reduce the corrosivity of the NaCl solution, zinc salts were added to the solution. The Zn^{2+} ions suppressed the cathodic corrosion reaction by forming $Zn(OH)_2$ particles with OH^- ions produced by the oxygen reduction on the casing surfaces, preventing oxygen from driving the corrosion reaction. Formation of metallic zinc increased the discharge efficiency. Consequently, the discharging process became less polluting and discharged LIBs safer to recycle.

Critical minerals – a very Australian overview

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ABSTRACT

The role of critical minerals in the global transition to clean energy and technological advancement is undeniable, yet the complexities surrounding their identification, tracking, and analysis remain a significant challenge. A central issue is the fragmentation of critical minerals across various Australian and New Zealand Standard Industry Classification (ANZSIC) categories. This dispersion complicates efforts to track and analyse critical minerals in a consistent and meaningful way, creating barriers to effective policy development, economic forecasting, and targeted investment.

As part of a broader effort to address these challenges, AUSMASA has proposed to the Australian Bureau of Statistics (ABS) the creation of a dedicated ANZSIC classification for critical minerals. Currently, these materials are dispersed across multiple categories—ranging from mining to manufacturing—making it difficult to capture comprehensive data on production, refining, exports, and workforce trends. Without clear categorisation, comparisons of Australia’ s performance in critical mineral sectors relative to global competitors remain imprecise, and the ability to analyse supply chain vulnerabilities is hindered.

In this presentation, we will explore the complexities surrounding the identification and tracking of critical minerals within the Australian and New Zealand Standard Industry Classification (ANZSIC) system, and the implications for policy and economic analysis. We will discuss the challenges posed by the current dispersion of critical minerals across multiple categories, which hampers the ability to accurately capture data on production, refining, and exports. A key focus will be the proposal to the Australian Bureau of Statistics for a dedicated ANZSIC category for critical minerals, highlighting how this restructuring would enable more effective monitoring, support targeted investment, and facilitate a clearer understanding of the sector’ s role in the broader economy, and findings from AUSMASA’ s forum on Critical Minerals (CMEV). The presentation will also cover the importance of critical minerals with regard to sovereign capability and domestic supply chains, including downstream application possibilities.

Analysis of lithium-bearing minerals in pegmatites – tools and traps

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ABSTRACT

The direct analysis of lithium and lithium-bearing minerals presents a significant challenge for the rapid and effective exploration of this critical commodity. As one of the lightest elements, lithium is inherently difficult to measure using technologies that have been designed and optimised over decades for the analysis of heavier elements, for example, portable X-ray fluorescence (pXRF) devices. Emerging technologies, such as laser-induced breakdown spectroscopy (LIBS), are gaining popularity. However, these techniques are relatively new, often unstandardised, and may yield spurious quantification results for unsuspecting users.

Moreover, merely characterising lithium content is insufficient, as the mineralogy that hosts the lithium is important for the extractable resource. Lithium X-ray lines in minerals are strongly controlled by the bonding and structure of the host mineral. Windowless electron dispersive spectroscopy (EDS) detectors are now commonly used to detect lithium; however, these detectors cannot resolve the difference between Si, Al and Li X-ray (K-) lines. Specialised high-resolution soft X-ray emission spectrometry (SXES) shows promise for some lithium compounds, but more general techniques are required. Techniques such as X-ray diffraction (XRD) can determine the mineralogy, however, where solid solution substitution occurs, it cannot easily resolve the lithium content, ie lithium in micas. Hyperspectral technologies face similar challenges in differentiating mica species. Combining microprobe with LIBS can quantitatively determine lithium content, however, the process remains time-consuming. When the direct analysis of lithium minerals is unavailable, indirect analysis using other elemental ratios and proxies may be used to understand lithium potential.

In this study, we analysed a suite of lithium-bearing pegmatites from Rajasthan, India, using a wide range of analytical techniques. We evaluate the strengths and limitations of these methods, highlighting the most effective tools for the rapid and accurate determination of lithium content and characterisation of lithium-bearing mineralogy.

Real-time data integration across levels 0–3: a scalable framework for critical minerals

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ABSTRACT

This paper extends the Overall Energy Effectiveness OEE 2.0 (see Vassallo and Wechsler, 2023) by applying its principles to a structured, real-world implementation in critical minerals processing.

As the mining sector transitions from bulk commodities into rare earths and battery-grade materials, system design must address increased process complexity, variable orebodies, and growing ESG and traceability requirements. Using the Iluka Eneabba project as a lens into project requirements, this paper outlines how a Purdue Model-based architecture across Levels 0–3—from field instrumentation through to control, supervision, and operations—can reduce commissioning time, improve process stability, and support long-term performance improvements.

The approach employs an Integrated Control and Safety System to unify Distributed Control (DCS), Supervisory Control and Data Acquisition (SCADA), and safety instrumentation. It includes alarm rationalisation, simulation-based commissioning, and controls capable of handling both batch and continuous modes. Moving away from traditional PLC-based control enables a unified engineering environment, built-in redundancy, and ISA-88-compliant batch execution—critical for managing variability and supporting plant-wide visibility from day one.

The paper also details a structured network design that incorporates traffic segmentation, prioritised data pathways, and inbuilt diagnostics to ensure reliability and performance. Standards such as ISA-18.2 and IEC 62682 are applied from the outset. The result is a system that seamlessly connects sensor-level data to supervisory and operational insights – offering a clear, standards-based framework for delivering reliable, high-performance outcomes in the critical minerals sector.

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Improved copper recovery from low-grade chalcopyrite ore

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ABSTRACT

MINETOMETAL is developing technology based on manipulating the ferric to ferrous iron ratio in acidic sulfate liquor to improve copper leaching from low-grade chalcopyrite ores that are not amenable to conventional concentrating and smelting. Despite many years of research copper leaching from these ores has proven very difficult with typically <50 per cent copper recovery being obtained. The technology being developed can be applied to heap leaching freshly mined ore, to existing heaps where secondary copper minerals have already been leached and to *in situ* leaching of primary sulfides.

MINETOMETAL has undertaken an experimental program where low-grade copper ore with a mix of primary and secondary copper sulfide minerals has been leached in sulfuric acid liquor with controlled ratios of ferric to ferrous iron. The test work has been carried out on ground ore (P_{80} <100 µm) using bottle rolls and the program has also examined the effects of temperature, pH and total iron content.

We have found that controlling the ferric/ferrous iron ratio enables:

- Over 99 per cent of the copper present to be the leached in <7 days with no reduction in leach rate due to passivation.
- The leaching of the chalcopyrite can be stopped by controlling the ferric/ferrous iron ratio.
- Passivated ore requires further manipulation of the ferric/ferrous iron ratio to restart the copper leaching.
- Manipulating the ferric/ferrous iron ratio allows the sulfur present to be converted to either elemental sulfur or sulfate.
- The preferred chalcopyrite leach reaction generates minimal heat and external heating is required to operate heap and/or *in situ* operations at above ambient temperature.

The work is continuing to better define the preferred operating window for the ferric/ferrous sulfuric acid system.

Selective recovery of rare earth elements from NdFeB magnet using a deep eutectic solvent

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ABSTRACT

Recycling electronic waste, such as NdFeB magnets, presents a sustainable solution to address the supply chain challenges of rare earth elements (REEs). This study aimed to:

- develop and optimise a non-corrosive, efficient deep eutectic solvent (DES)-based leaching process for NdFeB magnet waste
- selectively extract Nd from NdFeB magnets to produce a high-purity Nd oxide product.

The impact of pretreatment on leaching efficiency was thoroughly investigated. Selective REE leaching was achieved from roasted material using a 1:1 ratio of choline chloride to malonic acid DES. This DES demonstrated the highest selectivity, with 91 per cent Nd leaching, 92 per cent Pr leaching, and only 2 per cent Fe leaching at 80°C with a solid-to-liquid ratio of 1:50 over 6 hrs. The leached Nd_2O_3 was extracted from the DES via stripping with oxalic acid, followed by oxidative roasting, resulting in a purity of over 99.5 per cent, suitable for NdFeB magnet production. Furthermore, Density Functional Theory calculations revealed that the interaction between choline chloride and malonic acid leads to an energy decrease of 35.37 eV, indicating the formation of hydrogen bonds and the synthesis of the DES. This process provides a highly efficient and environmentally sustainable method for recovering REEs from magnet waste, positioning it as a promising approach for future industrial applications.

Bridging the gap between feasibility studies and operational outcomes – process risk mitigation in lithium and critical mineral concentrator projects

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ABSTRACT

Following the surge in the lithium market in 2015, there was a notable rise in the design and construction of spodumene concentrator plants in Western Australia. These facilities utilised conventional, well-established unit operations and were developed by experienced industry service providers. However, many plants failed to meet projected metallurgical performance, with numerous facilities unable to achieve targeted lithia concentrate grades and recoveries. This underperformance justifiably led to caution in approaching subsequent project development with a view there is significant inherent process risk involved.

This paper explores the impact of failing to apply critical flow sheet development principles, such as metallurgical test work definition and result interpretation, in project development phases. We investigate how these factors contributed to the disparity between expected and actual plant performance. Case studies are provided comparing expected performance with realised performance, and we quantify the economic impact of the underperformance. Additionally, this study examines how perceptions of these operational failures, particularly among stakeholders in the investment sector, influence the broader industry perspective. Leveraging insights from these learnings, the paper will provide guidelines for the flow sheet development and execution of projects within the critical minerals space.

Ultimately, the paper aims to offer insights that can guide future metallurgical test work planning, enhance process risk management, and improve execution strategies, contributing to more successful outcomes in critical mineral concentrator projects.

Red mud waste as a resource for critical minerals – a review

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ABSTRACT

Red mud, a by-product of alumina production, holds significant potential as a secondary source of critical minerals. However, improper management of red mud poses serious environmental risks, including soil and water contamination, which can lead to long-term ecological and health impacts. With the global demand for critical minerals essential for technologies like renewable energy systems and electronics continuing to rise, sustainable methods for resource recovery are increasingly important. Red mud contains valuable elements such as rare earth elements (REEs), scandium, lithium, cobalt, and vanadium. Despite this potential, the extraction and recovery of these minerals present considerable technical, economic, and environmental challenges. This review paper examines both traditional and advanced extraction methodologies, including hydrometallurgical and pyrometallurgical techniques, as well as innovative approaches like solvent extraction using ionic liquids and supercritical fluid extraction. Additionally, it critically evaluates the environmental risks of red mud mismanagement and highlights the benefits of integrating resource recovery into a circular economy framework. Addressing these challenges is essential for developing innovative, cost-effective, and environmentally friendly extraction processes that can harness red mud's resource potential while mitigating its environmental impact.

Minas Gerais, Brazil – the global hub for critical minerals value chain

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ABSTRACT

As the global economy accelerates, its shift towards clean energy, securing reliable sources of critical minerals, has become a top priority. Geopolitical tensions, trade disputes, and the strategic repositioning of major economies intensify the urgency to diversify supply chains. In this scenario, Minas Gerais emerges as a key player in the global critical minerals landscape, offering stability, sustainability, and scalability for investors.

A historic mining powerhouse – its name literally means General Mines – Minas Gerais is home to more than 50 per cent of the periodic table, including lithium, graphite, rare earth elements, niobium, silicon, manganese, and titanium, as well as essential agrominerals to guarantee food security, such as potassium and phosphate. The state's commitment to adding value to these resources led to the launch of Lithium Valley Brazil in 2023 at Nasdaq Stock Market, positioning Minas as one of the world's most promising lithium hubs. Since then, multiple Memorandums of Understanding (MOUs) have been signed with international companies, generating employment and economic growth.

Building on this success, Minas Gerais has expanded its strategy beyond lithium to other critical minerals, reinforcing its role as a global hub for the critical minerals value chain. The state offers an investor-friendly legal framework, a well-developed infrastructure network, a highly skilled workforce, and a 100 per cent renewable, cost-competitive energy matrix. In 2024, a roadshow in Australia resulted in new agreements with four Australian companies committed to strengthening Minas' role in the global supply chain.

Looking ahead, Minas Gerais commits to going beyond extraction, fostering a sophisticated ecosystem of mineral processing, engineering services, and financial solutions. With a streamlined regulatory framework, reduced bureaucracy, and a transparent licensing process, the state ensures predictability and efficiency for investors. Mining in Minas Gerais positions itself not only as an economic driver but also as a catalyst for technological advancement, innovation, and sustainable local development.

Methods for the characterisation of high-purity alumina

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ABSTRACT

High-purity alumina (HPA) plays a key role in the global energy transition, being an essential material in many high-end technologies. HPA is a purified form of synthetic aluminium oxide (corundum) characterised by a concentration ≥99.99 per cent of α-Al_2O_3 that finds applications in LED lights, sapphire glass production, catalysts, thermal insulators, and lithium-ion batteries.

With a clear trend toward higher purity materials being used in both sapphire and batteries, one of the major challenges to benchmark HPA quality resides in the sensitivity required to quantify, in a precise and reproducible way, the very low concentrations of trace element impurities (≤ppms) in such a refractory and chemically stable material. There are several inorganic analytical techniques commercially available, such as inductively coupled plasma – mass spectrometry (ICP-MS), inductively coupled plasma – optical emission spectroscopy (ICP-OES), or glow discharge – mass spectrometry (GD-MS) offering a range of options, costs, and sample preparation methods that can be applied to determine trace contaminants in HPA. To support Australian industry, the CSIRO is undertaking a comprehensive evaluation of analytical techniques and methods used to benchmark HPA. The results highlight the need for standardised methods and materials to verify that HPA purity specification is being met.

A second stream of research focuses on the advanced characterisation of HPA and some of its precursor feedstocks (eg aluminium salt and clays). The study integrates a range of state-of-the-art multiscale approaches to investigate micro-to-nanostructures, phase transitions during calcination, and the chemistry-crystallographic relationship within single crystals of α-Al_2O_3 providing a new understanding of the fundamentals of HPA materials.

This work has been supported by the Australian Critical Mineral Research and Development Hub whose activities are funded by the Australian Government.

Metso alkaline leach processes for lithium chemicals production

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ABSTRACT

Global energy transition from fossil energy sources towards electrification will increase the demand for lithium mining during the next decades due to its use for batteries in electric vehicles and in energy storage. Lithium extraction from minerals, primarily hard rock spodumene will be increasingly important as well. Reducing environmental impacts while maintaining cost competitiveness is crucial for operators in the production of battery-grade lithium compounds.

This presentation is discussing key advancements in Metso's alkaline leaching technologies for spodumene and a variety of other lithium minerals. The Metso alkaline lithium extraction processes have an advantage of providing a direct route to lithium carbonate production from mineral feedstocks as a very attractive, low-cost alternative.

The patented hydrometallurgical lithium process has been demonstrated in pilot scale and the first reference plants are under construction for lithium hydroxide monohydrate production. The case example of Sibanye-Stillwater's Keliber lithium project is presented to support the commercialisation of the processing concept.

Metso has developed and commercialised the alkaline/soda leaching process for lithium extraction from hard rock spodumene. Additionally, a novel hydrometallurgical concept for processing non-spodumene lithium feedstocks, building on the existing Metso alkaline/soda leaching process. The alkaline leaching realises a sulfate-free, more sustainable, and efficient lithium extraction process. The alkaline leach process has certain benefits such as selectivity for lithium dissolving only limited amounts of impurities and consequently, less downstream purification stages are required. Since the processes do not require sulfuric acid for leaching nor sodium chemicals for conversion the process does not produce sodium sulfate as a byproduct. In particular, the lithium carbonate production options are based on industry standard route downstream of the main alkaline lithium extraction step. The process through bicarbonation → decarbonation by recycled carbon dioxide, allows lithium solubilisation and mineral residue separation. Total plant lithium recoveries are typically resulting in high levels around ~90 per cent and the production of lithium carbonate or hydroxide products are fulfilling the battery grade specifications.

The case example of Keliber lithium project is based on several deposits and future mine sites and the concentrator plant in Kaustinen area and the lithium refinery in Kokkola, Finland. The entire process chain is under construction from the spodumene ore mining to the production of battery-grade lithium hydroxide. The lithium refinery in this project is based on the Metso's Soda pressure leaching technology, which will help minimise negative environmental effects of production and allowing for side stream optimisations. Key considerations and learning experiences of the refinery project are presented concerning the project planning, permitting, and construction. Keliber Lithium Refinery is cold commissioning, ongoing in H2 2025 and scheduled for hot commissioning which will follow during H1 2026 utilising their own spodumene concentrate.

Transition metal based cathode for electrochemical recovery of lithium from aqueous brine

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ABSTRACT

The global push towards clean energy transition has positioned lithium (Li) as a critical mineral enabling decarbonisation. Lithium mining from unconventional reserves such as aqueous brine is becoming crucial as hard rock mining falls short of meeting demand and sustainability targets. However, its recovery from low concentrated brines presents significant challenges. Conventional Li extraction methods based on adsorption, solvent extraction, membrane separation face limitations such as membrane fouling, regeneration issues, and are inefficient in dilute aqueous Li reserves. Recently developed electrochemical intercalation/deintercalation approach has shown promise through highly Li selective electrodes, but previously studied materials ($LiMn_2O_4$, $LiFePO_4$, $LiCoO_2$) suffer from stability issues, require prior electrode delithiation, and often rely on other critical minerals like Mn and Co.

This study investigates tungsten trioxide (WO_3) nanoparticles synthesized via flame spray pyrolysis (FSP) as a novel, cost-effective material for lithium extraction from synthetic brine (~1057 ppm). WO_3 characterised by powder X-ray diffraction (PXRD) and transmission electron microscopy (TEM), confirmed the monoclinic phase with 14 nm of average particle size. Highest Li extraction efficiency (4.07 per cent) was achieved at -1.35 V versus Reversible Hydrogen Electrode (RHE), with inductively coupled plasma – optical emission spectroscopy (ICP-OES) analysis confirming Li recovery 1.2 mg g^{-1} by FSP WO_3.

Post reaction X-ray photoelectron spectroscopy (XPS) of the electrode surface revealed partial reduction of tungsten from W^{6+} to W^{5+}, supporting the formation of lithiated bronze-like Li_xWO_3 during intercalation. Further, *in situ* W L_3-edge X-ray absorption near edge structure (XANES) analysis demonstrated energy shifts toward lower energies at negative potentials (-1.35 V, -0.75 V) versus RHE, confirming W^{6+} reduction to W^{5+} Li intercalation, while restoration of original oxidation state at positive potentials (+1.65 V, +1.85 V versus RHE), confirmed Li deintercalation. Further coating of WO_3 nanoparticles with reduced graphene oxide (rGO) prevented W dissolution and enhanced charge transfer kinetics. This work establishes FSP WO_3 as an efficient material for lithium extraction from dilute aqueous brines while elucidating the underlying intercalation/deintercalation mechanisms. Further, Li selectivity tests showed Brucite $Mg(OH)_2$ as a major precipitate along with Li recovery. Thus, WO_3 can be used as a potential cathode material used for brines with high Mg/Li ratio such as Atacama brine (Chile) offering a scalable and sustainable route for brine-based Li extraction.

Navigating the geopolitics and economics of critical minerals in a fractured global supply chain

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ABSTRACT

The global supply chain for critical minerals is increasingly defined by geopolitical tensions, economic volatility and policy uncertainty. While deposits and processing facilities are geographically concentrated, demand is widely dispersed across clean energy, transport and advanced technology sectors. As nations seek to secure supplies through strategic stockpiling, trade restrictions and friend-shoring, the industry faces mounting challenges in maintaining resilient and sustainable supply chains.

The return of Donald Trump to the US presidency could further disrupt global mineral markets, with potential shifts in industrial policy, trade agreements and international alliances. A renewed emphasis on resource nationalism, onshoring and bilateral trade deals may reshape global supply chains, creating both risks and opportunities for Australian producers. As a major supplier of critical minerals, Australia must navigate increasing pressure to align with US supply chain strategies while managing its own economic and geopolitical interests in the Indo-Pacific. The potential for escalating trade tensions with China adds further complexity, underscoring the need for diversified markets and investment in downstream processing.

This presentation will explore the economic and geopolitical forces shaping critical minerals markets, including the impact of policy shifts, resource nationalism and emerging alliances in the sector. It will assess the implications of price volatility, investment risks and the growing importance of circular economy approaches in ensuring long-term supply security. By examining these factors through the lens of geopolitics, mineral economics and strategic resource management, this presentation aims to provide industry stakeholders with insights into navigating risks and capitalising on emerging opportunities in an increasingly uncertain global landscape.

A national-scale assessment of clay-hosted rare earth element mineral system potential in Australia

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ABSTRACT

The transition to net zero emissions is driving increased demand for critical minerals, including rare earth elements (REE). Rare earth elements and the technologies they enable, such as permanent magnets used in electric vehicles and wind turbines, are important across a range of sectors including defence, space, transport, computing and telecommunications. Clay-hosted REE represent a significant source of REE globally, having received significant attention due to the potentially distinct processing advantages.

Given their global strategic importance, Geoscience Australia is undertaking a national-scale mineral potential assessment for clay-hosted REE mineral systems to evaluate their potential in Australia. This work is part of the 'Accelerating Development of Australia's Rare Earth Resources (ADARER)' project under the Australian Critical Minerals Research and Development Hub. Rather than aiming to identify individual deposits, the focus of the mineral potential assessment is to delineate prospective regions or districts that possess favourable geological criteria for the development and preservation of a clay-hosted REE mineral system.

This study demonstrates how national-scale pre-competitive geoscience data sets can be integrated using a hybrid knowledge- and data-driven methodology that combines a robust statistical analysis with mineral systems expertise to predictively map areas with a higher geological potential for the presence of clay-hosted REE mineral systems. Statistical evaluation of the relationship between different mappable criteria that represent spatial proxies for mineral system processes has been undertaken to test previously published hypotheses on the formation of clay-hosted REE mineral systems. The mineral potential assessment predicts the location of known clay-hosted REE deposits and identifies additional areas of high prospectivity in regions with no previously identified deposits in Australia while effectively reducing the exploration search space.

Advancing lithium exploration with laser-induced breakdown spectroscopy (LIBS) – a rapid and cost-effective approach

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ABSTRACT

Lithium (Li) is a critical element for the global green energy transition, and the growing demand necessitates the discovery of new, economically viable Li resources. Beyond traditional assay results, a comprehensive understanding of deposit characteristics—including grade, size, mineral deportment, grain size, and mineral associations—is essential to advance a prospect to a mineable resource. However, these parameters are often derived from small sample suites analysed using laboratory-based scanning instruments (eg SEM, XRF) that do not directly measure Li. Such limited and high-cost data sets are then used to inform ore processing strategies, introducing considerable risk to resource development.

Recent advancements in mobile laser-induced breakdown spectroscopy (LIBS) offer transformative potential for lithium exploration. LIBS enables rapid, high-resolution chemical mapping of drill core, including direct measurement of Li, using containerised, mine-deployable instruments. For example, LIBS can scan a 2 cm-wide strip at 250 μm resolution in approximately 5 mins per metre, making it a powerful tool for generating mine-scale mineralogical models in near real-time.

In this study, we demonstrate the application of LIBS for characterising lithium-bearing minerals such as cookeite, spodumene, lepidolite, and Li-rich muscovite. Our results show that LIBS can effectively detect and quantify Li, perform grain size and textural analysis, generate *in situ* lithium and mineral phase maps, and reveal Li enrichment processes. The ability to rapidly acquire low-cost, spatially resolved geochemical data under ambient conditions makes LIBS particularly well-suited for field-based exploration, prospect evaluation, and quality control in lithium mining operations.

LIBS has the potential to revolutionise lithium exploration by providing a fast, efficient, and cost-effective alternative to traditional geochemical and mineralogical techniques—bridging the gap between lab-based analysis and real-world decision-making in the critical minerals sector.

Beyond the baseline – ESG priorities to support capability uplift across the Queensland critical minerals industry

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ABSTRACT

The Partnership Project led by the Queensland Government and AusIMM aims to develop an industry-led approach to support industry and stakeholder collaboration and lift environmental, social and governance (ESG) Capability Queensland Critical Minerals Industry (QCMI).

The evidence base included three-phase research process, comprising 472 survey responses, 38 targeted interviews, and four regional workshops. The objective was to establish an ESG capability baseline, identify priority ESG themes, recognise challenges and enablers, and inform the design of practical, targeted ESG capability uplift strategies.

Utilising a maturity framework, the assessment reveals that current ESG capability across the QCMI is perceived between Basic and Good. ICMM Maturity Framework 2022 modified in consultation with the ESG Advisory Panel and in consideration of Australian Sustainable Finance Institute, 2024.

Explorers were perceived to have lower capability, reflecting limited progress or integration of ESG practices, while mining operators with larger, more mature companies generally demonstrate stronger ESG systems and awareness. Approximately 70 per cent of respondents desire ESG capability to be Good or Leading by 2030, with aspirations even higher in regional areas such as Richmond, Julia Creek, Mount Isa, and Cape Flattery.

Among the 16 ESG themes assessed, the highest perceived capability were workplace and public health, safety and security, labour rights and human rights, and stakeholder engagement. Conversely, the lowest-rated ESG themes include circular economy, traceability, and decarbonisation.

The top ESG themes identified for capability uplift are community impact, benefit and investment, environmental impact, ecosystems and biodiversity, mining transition and post-mine land use, circular economy, climate adaptation and resilience, and decarbonisation.

Findings from the four regional workshops—Julia Creek, Mount Isa, Mackay, and Cairns/FNQ—highlight a strong regional appetite for ESG leadership grounded in local values and practical outcomes. Across all zones, community impact, benefit and investment emerged as the highest priority theme, reinforcing a call for tangible and lasting outcomes for host communities.

To address the gaps and build a more capable, and future-ready QCMI, several capability uplift strategies will be developed.

Opportunities and threats for critical minerals exploitation in Australia – an analysis using patent data

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ABSTRACT

As Australia looks to secure its supply of critical minerals in an ever-changing geopolitical environment, ensuring investment into our resources by companies that will provide Australians with access to our critical minerals is essential. To understand how well Australia is placed to exploit its own critical minerals, we need to understand who is investing into developing critical minerals-related technologies in Australia. It is also important to identify the opportunities and threats that exist within our onshore supply chain. In this presentation, we focus on the level of investment in nickel and cobalt technologies.

We use patent data to provide us with an indication of the state of development of technology related to critical minerals in Australia. From this, we identify emerging trends in critical minerals in Australia and identify the gaps in our supply chain. This helps us to understand the areas that require further investment for Australia to ensure a reliable supply chain into the future.

Using patent data, we can explore and identify who the major investors are in the critical minerals sector and where the major investors are based. This can provide an indication as to whether certain companies or countries are looking to monopolise certain parts of the Australian critical minerals supply chain. This allows us to identify potential threats to our supply chain. We can also look at those parts of the supply chain that are less technologically advanced to show us where the major opportunities lie.

Finally, as companies look to add value to critical minerals, strategic partnerships between major players will become more crucial. We map the activity of competitors, which can help to identify potential research or commercialisation partners.

The quantitative measurement of lithium in hard rock ores using nuclear magnetic resonance

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ABSTRACT

The real-time, quantitative analysis of ores to determine their elemental composition is crucial for applications such as ore-sorting and grade control. For hard rock mining, implementations of ore sorting prior to concentration are limited by the ability of measurement techniques to be reliably implemented on large conveyor belts. X-ray and optical based measurements, such as laser induced breakdown spectroscopy and infra-red reflectance are limited to the analysis of the surfaces of samples which render them unable to measure through the bulk of the ore. This introduces significant sampling errors which can affect the ability of the method to facilitate ore sorting and grade control.

Nuclear magnetic resonance (NMR) is a radio-frequency spectroscopy that can directly detect certain nuclei within an ore sample for the purpose of grade quantification. The operating frequency of the NMR measurement is typically less than 30 MHz for industrial applications which allows for the full penetration of the ore allowing for a bulk analysis all the way up to the scale encountered on primary conveyor belts. NMR utilises non-ionising radiation making it safe and free from significant regulatory oversight for implementation at the mine site.

This work presents laboratory results on the NMR analysis of a number of lithium pegmatite ores. A commercial sample of high-grade spodumene was also analysed. The NMR results were compared to quantitative X-ray diffraction (XRD) analysis which showed excellent correlation. Initial results from a scaled-up prototype, large enough to reside on a small conveyor belt, show that reasonable measurement times for the quantification of spodumene can be obtained demonstrating the feasibility of the method for ore-sorting and grade control at the bulk scale.

Clean and efficient tungsten extraction via direct solvent extraction in alkaline medium

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ABSTRACT

Tungsten is ranked by Australia, British Geological Surveys, US Department of Defence and the European Commission as a 'critical' mineral due to its economic importance, supply risk and inability to be substituted. However, the vast majority of tungsten mining and processing occurs in China. Australia ranks second for world economic resources of tungsten although current production is modest with only WO_3 concentrate being sold from two operating mines (Hughes, 2020). As the Chinese government has implemented export controls on ammonium paratungstate (APT $[(NH_4)_{10}(H_2W_{12}O_{42})\cdot 4H_2O$ or $5(NH_4)_2O\cdot 12WO_3\cdot 5H_2O]$), tungsten oxide and high-purity tungsten alloys from 4 February 2025, a substantial opportunity exists for downstream hydrometallurgical processing of tungsten in Australia by converting scheelite and/or wolframite ores to APT. In the present work, the current technologies and existing problems of tungsten hydrometallurgy have been summarised and compared. To overcome drawbacks of current processes, a new process for APT production from caustic leach solutions of scheelite and/or wolframite based on direct solvent extraction (DSX) is presented in Figure 1. The principle, flow sheet and characteristics are introduced in detail. The results indicated that the new technology had wide applicability to the treatment of alkaline leach solutions arising from different tungsten ores generated via either autoclave soda leaching or caustic soda leaching. After leaching, tungsten was selectively extracted from P/As/Si impurities in the DSX process without pH adjustment or dilution of caustic leach solution to make the sodium tungstate-rich solution (Na_2WO_4) readily transform to ammonium tungstate solution ($(NH_4)_2WO_4$). The raffinate solution can be returned to the leaching step directly (for scheelite leaching) or after conversion to a caustic soda-rich solution with lime (for wolframite leaching), realising the recycling of alkali and water. Compared to traditional processes, the new process exhibits significant advantages of high recovery of WO_3 (>98.5 per cent), low release of wastewater and low consumption of chemicals resulting in an estimated 40 per cent decrease in operational cost.

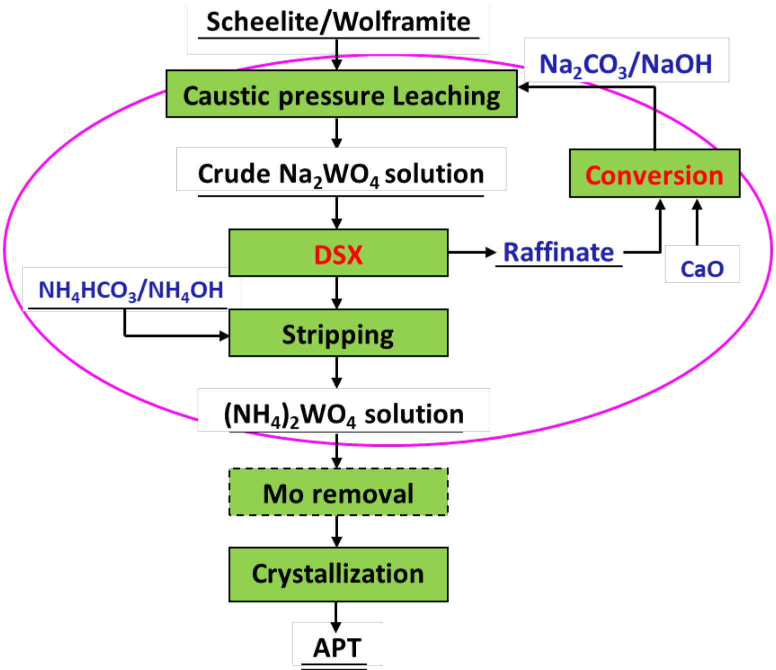

FIG 1 – Clean and efficient process of W extraction via DSX in alkaline medium.

REFERENCE

Hughes, A, 2023. Tungsten, Australian Resource Reviews, Geoscience Australia, Canberra. Available from: <https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/tungsten>

A circular system for metals and critical raw materials

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ABSTRACT

There is a lot of talk by sustainability and circular economy professionals regarding systems thinking. What does this mean or look like in practical terms? This presentation outlines a circular system from mining through to the development of a secondary raw materials industry for end-of-use-cycle metals and critical raw materials.

At present, only a few mining companies show interest or involvement in the secondary markets for metals and critical raw materials. This is understandable, given the distinct nature of these two businesses and industry sectors. However, in the near future, there will be a compelling need for increased collaboration, which promises significant benefits for all involved.

The presentation will be divided into the following three sections.

Part one – the circular economy: resource management

Many people view the circular economy as an advanced form of recycling. However, for this project and the broader mining industry, the circular economy will be introduced as a powerful resource management tool, a role for which it is uniquely suited.

Part two – a secondary raw materials industry for metals and critical raw materials

The logical progression from the circular economy definition of resource management will be to present substantial evidence for a secondary raw materials sector to sit alongside the virgin extractive resources industry.

One method available to manage metal and critical raw materials resources is through the implementation of materials passports. Materials passports (MPs) and digital product passports (DPPs) are tools designed to enhance transparency, sustainability, and circularity in supply chains, but they differ in scope, application, and functionality (Table 1).

TABLE 1

The difference between a materials passport and a digital product passport.

Feature	Materials passport	Digital product passport
Scope	Material composition	Full product life cycle
Main use	Reuse, repair, repurpose, remanufacture and recycling	Compliance, traceability
Common sectors	Construction, transportation, manufacturing and machinery and energy, and electronics	Consumer products, batteries, electronics
Regulatory link	Voluntary	Mandatory (eg European Union's Ecodesign for Sustainable Products Regulation (ESPR))
Data focus	Material properties, supply chain, carbon footprint, disassembly and circular Rs*	

* <https://www.circulareconomyasia.org/the-circular-rs>

Please note: The above-mentioned differences are supported by the author, as not everyone working in this area is in agreement.

Currently, most of the focus is on supply chain traceability, which is vital; however, it still does not address the weaknesses within the overall system. For example, some countries export end-of-use-cycle metals and products to Asia for reprocessing under conditions that may not comply with generally recognised environmentally compliant operations, which are often linked to health and safety practices. Alternatively, environmental laws may not be robust enough or may not be effectively enforced.

Circular Economy Asia believes that the metals, critical raw materials, and mining industries, as a whole, can contribute significantly more and proposes greater engagement across the entire supply chain.

Part three – a collaborative solution

The presentation will underscore the importance of a circular system for metals, with a particular focus on critical raw materials. This system will encompass recycling, waste utilisation, social performance, governance, standards, and global finance, highlighting its urgency and importance.

It will also include the execution and stages of the project, as well as how it can be managed. In addition, the market is demanding not just traceability but also major improvements across the environmental, social and governance (ESG) spectrum for investment.

Finally, we conclude with some remarks on politics. Not the geopolitics of critical raw materials, instead, the opening up of soft political engagement for both the mining industry and the Australian government within the Asian region and beyond.

The structure of the author's argument will follow the Minto Pyramid Principle as it provides a clear, concise framework for presenting a complex idea in 15 mins (Figure 1).

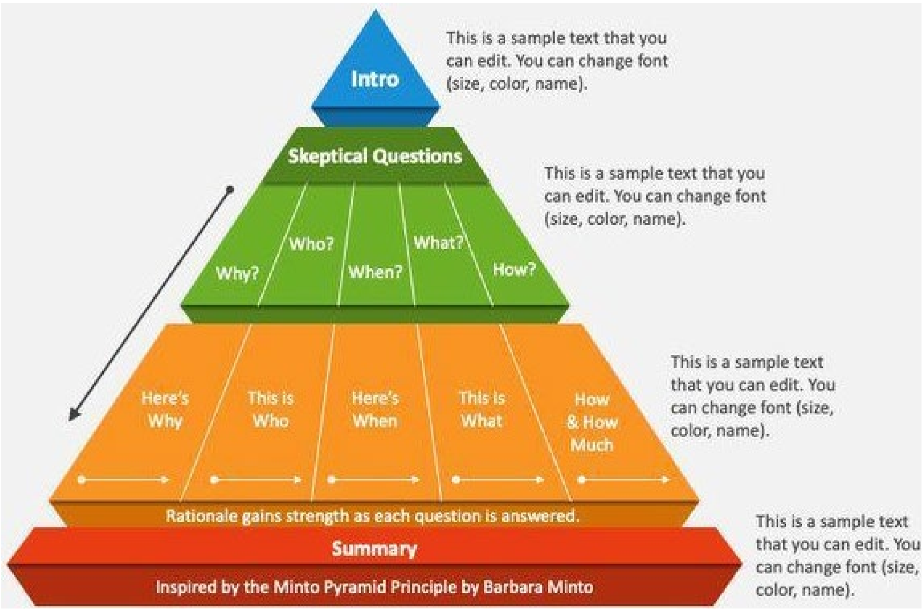

FIG 1 – Minto Pyramid Principle.

The Minto Pyramid is a way to organise presentations, communication and thinking in an 'executive-friendly' way, by starting with the answer and key idea; grouping and summarising recommendations and supporting arguments; and logically ordering supporting ideas.

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