AusIMM Conferences

Brisbane, Australia
21–23 September

Critical Minerals 2026



Conference Proceedings

Proudly sponsored by

LIEBHERR

Critical Minerals Conference 2026

21–23 September 2026
Brisbane, Australia

The Australasian Institute of Mining and Metallurgy
Publication Series No 3/2026

Published by:
The Australasian Institute of Mining and Metallurgy
Ground Floor, 204 Lygon Street, Carlton Victoria 3053, Australia

© The Australasian Institute of Mining and Metallurgy 2026

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form by any means without permission in writing from the publisher.

All papers published in this volume were peer reviewed before publication.

The AusIMM is not responsible as a body for the facts and opinions advanced in any of its publications.

ISBN 978-1-922395-58-0

Advisory Committee

Dr Helen Degeling
FAusIMM
Advisory Committee Chair

Dr Sibasis Acharya
FAusIMM

Dr Keith Barnard

Dr Allan Costine

Andrew Curtis
FAusIMM

Kylee Millen
MAusIMM

Professor Mark Noppe
FAusIMM(CP)

Associate Professor Hans Oskierski

Professor Seher Ata
MAusIMM

Leigh Slomp
FAusIMM(CP)

Professor Mohsen Yahyaei
MAusIMM(CP)

AusIMM

Julie Allen
General Manager, Events

Payden Rowe
Event Manager, Events

Sasha Pell
Senior Manager, Conference Growth, Events

Sharon Lim
Program Manager, Events

James Maters
Senior Manager, Events Marketing and Communications, Events

Reviewers

We would like to thank the following people for their contribution towards enhancing the quality of the papers included in this volume:

Dr Helen Degeling

Dr Sibasis Acharya

Dr Keith Barnard

Dr Allan Costine

Andrew Curtis

Kylee Millen

Professor Mark Noppe

Associate Professor Hans Oskierski

Professor Seher Ata

Leigh Slomp

Professor Mohsen Yahyaei

Foreword

On behalf of the Advisory Committee, I am delighted to present to you the Proceedings of the AusIMM's Critical Minerals Conference for 2026.

This year we returned to Brisbane following a highly successful 2025 conference in Perth. As the conference alternates annually between Australia's two major mining hubs, it is pleasing to see the Critical Minerals Conference going from strength to strength, reflecting the growing importance of critical minerals to Australia's economic, industrial and strategic future.

The response to this year's call for abstracts was outstanding. We received nearly twice as many submissions as in previous years, creating a significant challenge for the Advisory Committee as we worked through the selection process. The depth and quality of submissions made many decisions difficult, but the result is a proceedings that showcases some of the best thinking and innovation from across industry, government and research organisations.

The proceedings reflects the breadth of opportunities and challenges facing the sector. Explore topics including critical minerals markets and supply chains, sovereign capability, project financing and bankability, discovery and resource development, processing and refining technologies, rare earth elements, lithium recovery, circular economy approaches, mine waste revalorisation, environmental stewardship, First Nations partnerships, social licence, geopolitics and supply chain resilience. These provide a valuable opportunity to share knowledge, challenge ideas and build connections across the entire critical minerals value chain.

At a time when nations around the world are seeking secure, responsible and resilient supply chains for critical minerals, collaboration has never been more important. The 2026 conference provided a unique forum for industry, government, academia and the investment community to come together, exchange perspectives and help shape the future of the sector, with the proceedings as a starting point to open discussions and doorways to the potential of the future of the industry.

I would like to thank our authors for sharing their expertise, our reviewers for their diligence and commitment, and our sponsors and exhibitors for their ongoing support. I also acknowledge the dedication of the Advisory Committee and the AusIMM Events team, whose efforts have once again delivered an outstanding event.

I hope you enjoy the conference and find these proceedings a valuable resource long after the event concludes.

Yours faithfully,

Dr Helen Degeling FAusIMM
Critical Minerals Conference Advisory Committee Chair

Sponsors

Government Partner

DELIVERING FOR QUEENSLAND | Queensland Government

Platinum Sponsor

BRAVURA

Gold Sponsors

QUT

SLR

tivan
A critical minerals company

Silver Sponsors

CMCI CRC
Critical Metals for Critical Industries

MINING3

Exhibition Lounge Sponsor

CSIRO

Technical Session Sponsors

ASM
Australian Strategic Materials

SEDGMAN

Coffee Cart Sponsor

DrM

Name Badge and Lanyard Sponsor

SGS

Conference App Sponsor

umwelt

Conference Proceedings Sponsor

LIEBHERR

The new generation

PR 776 G8

LIEBHERR

Liebherr-Australia



Take a closer look at the Liebherr PR 776 G8!

The latest generation updates are designed to improve serviceability, accessibility, and maintenance efficiency across the machine.

Every update is engineered to support safer servicing, reduced downtime, and improved machine longevity in demanding mining environments.

Contents

Advances in processing, manufacturing and associated technologies

Beneficiation strategies for rare earth minerals from clay-hosted ores – a critical review 3
F Agbenyo, B Tedesse, L Dyer, K Evans, M Tade and S Owen

Froth image-based monitoring of copper flotation circuits using localised principal component models 5
C Aldrich

Supporting Australia's critical minerals strategy through applied processing research 7
K R Barnard

From batch to breakthrough – continuous magnesium metal production for a resilient critical minerals supply chain 9
A Brent, D Liu and D Freeman

Securing heavy rare earth supply beyond China – a comparative assessment of *in situ* recovery and heap leaching for ion-adsorption clay deposits 11
L Bullen

CSIRO graphite value chain capabilities 25
K Bunney and J Loh

Pilot scale critical mineral processing 27
N Chapman and A Grabsch

Mine operations management – digitally connect mine production 29
K Chhabra and S Rahangdale

Unlocking secondary resources requires a new way of thinking 31
S Couperthwaite and A B Carneiro

Impact of high sodium on separation and extraction performance in lithium brine processing 33
B Currie

Nano-bubbles effect on critical minerals flotation performance 35
M Dlame and M Safari

Recovery of manganese as a critical mineral from aqueous structures 37
D Gabeva, R Halatchev and A Halatchev

Electrolysis-based conversion for sustainable lithium refining 41
L Glynn, C Brereton, K Wilting and J Moulson

Unlocking capacity – use of process control and monitoring to increase the barge loading capacity at Metro Mining Bauxite Hills Mine 61
M Graham and R Dawe

An alternate approach – heap leach flow sheet development for ASM's Dubbo rare earth project 63
D M Hunter, D J Readett, W Dicinoski, R J Laver and D Molver

Hydrometallurgical processing of ferromanganese smelter wastes for high-purity manganese sulfate production 81
N D Ilankoon, E A Oraby and J J Eksteen

An integrated power-process-data architecture for resilient critical mineral processing 83
E Kashi

Turning pyrite to pyrrhotite for critical metal extractions – reactions during thermal decomposition 87
L Kng, O Mejías, X Ma, H Degeling, A Tong, A Randall, H Porteous and A Parbhakar-Fox

Simple yet accurate routine analysis of rare earth materials from ores through to concentrates using a single X-ray fluorescence application 89
A Komelkov, H Bhaskar, M Luce and L Grimsley

Selective flocculation-flotation of fine spodumene – recovering lithium from particles currently lost to tailings 91
D Luo, W S Ng and G V Franks

Midstream in Australia – ambition versus reality: confronting the structural constraints 93
N Mackay and S Salter

Adapting to declining ore grades – two-stage copper smelting and the role of calcium ferrite slags 95
E Mercy, X Wen, M Shevchenko and E Jak

An investigation into the current leading solid-state battery chemistry options, precursor materials and processing requirements 97
A D R Millar

From mineralogy to process insight – advanced XRD analytics for critical minerals 111
O Narygina, M Pernechele, S Makvandi, L Negrão, I Duran, Y Gomes and U König

The impact of co-occurring ions (potassium, sodium and calcium) in the recovery of lithium hydroxide from lithium liquors using electrodialysis 113
J Nsiah, K L Ang, T B Issa and A N Nikoloski

Demonstration plants allow miners to test critical minerals processing before investing in commercial production 115
D Pianta

Economic considerations in the processing of clay-hosted rare earth deposits in Australia 117
J Quinn, M Valencia Bejarano, A Manis and K Soldenhoff

Operational improvement in spodumene grinding circuits using Derrick fine screens 119
Y Reja and A Newman

Meeting rising global sulfuric acid demand and constrained fossils supply – the role of copper derived output 121
T G Ryan, S A Northey, B Mendonca Severiano and D P Giurco

Thermodynamic re-optimisation of the Ni-Fe-Cu-S-As system – supporting the processing of complex Australian ores 123
I Shakirova, D Shishin and E Jak

Selective leaching of rare earth elements from NdFeB magnet waste using salt solution 125
J Shree, W Bruckard, N Haque, V Jegatheesan and B Pramanik

Towards sustainable cobalt extraction – carbothermic reduction-assisted microwave leaching of heterogenite cobalt oxide ores 127
B Siame and I M Reaney

OpenCu – an open source framework for evaluating renewables integration in the copper value chain 129
R Singh, M H A Khan, S Saydam, I Canbulat, I MacGill and R Daiyan

Optical sorting for coarse REE pre-concentration by ink-coating and magnetic lifting 131
H Su, A Yolalmaz, R Bheemireddy, Y Wu and F Di Maio

Impact of transition metal impurities (Co, Cu, Ni, Fe) on vanadium electrolyte performance – toward direct electrolyte production from leach liquors 133
G Thompson, T B Issa, P Singh and A N Nikoloski

Upgrading rare earth from clay deposits in Western Australia – mineralogical controls via physical and thermochemical treatments 135
Q T Tran, J J Eksteen, R D Alorro and C C Beh

Beyond the flow sheet – scaling ultra-high purity alumina for semiconductor and AI infrastructure 137
R Williamson

A circular economy approach for critical mineral recovery and high-performance geopolymer production from mine tailings 139
S Yadav, W Bruckard, N Haque and B Pramanik

Sustainable and energy-efficient flow sheet optimisation for integrated recovery of niobium and tantalum oxide from carbonatite ores 141
S Zafar, V Pareek and T Bhatellia

Exploration, discovery and resource development

Novel fluorescence for spodumene imaging 145
A Baensch, C Wilske, J E Moffatt, D Beniwal, N A Spooner and E P Schartner

Crustal architecture, granites and critical minerals – machine-assisted mapping of the Yilgarn Craton, Australia 147
M Gazley, Y Lu, M Dunham, L Tannock, K Lilly, L Kendall-Langley, R Quentin de Gromard and H Smithies

Applying generative AI to geological data discovery – the GSQ digital librarian 149
M Gordon

The evolving role of precompetitive geophysics in supporting exploration success in Queensland 151
M Greenwood

From discovery to development – a beneficiation-first approach for the Jupiter clay-hosted REE deposit 153
T T Hien-Dinh, N K Bonnici and S R Owen

Distribution and controls on critical minerals at Rosebery, western Tasmania – from deposit to concentrate 165
C Jago, N Fox and A Parbhakar-Fox

Critical mineralogy – where client's needs meet real world mineral assemblages 167
C Laukamp

Systematic characterisation of Queensland's mineral deposits and their alteration footprints – insights and tools for critical mineral exploration 169
V Lisitsin, E Belousova, A Kontonikas-Charos, A Tapu and C Dhnaram

Mine waste dumps critical minerals resource characterisation framework for Zimbabwe 171
P Mugebe

Modelling scenarios for future mineral supply considering uncertain exploration outcomes and ESG risks 183
S A Northey, B Mendonca Severiano, T G Ryan and E M Dominish

Critical metal inventory of Australia's tailings and mine waste – what's next? From aspiration to delivery 185
A Parbhakar-Fox

Geochemical controls on rubidium enrichment and recovery in the Mount Edon pegmatite, Western Australia 187
A Sarmadi, R Didonna, B Rashidi, E Ramanaidou and A Razmjou

Governance and social

From approval to operation – how reform can accelerate Australia's critical minerals pipeline 209
M J Breitfuss

Beyond the E – the important role of social and governance in critical minerals 211
M Case and M Saylor

Partnerships as enablers of integrated rare earth supply chains – lessons from emerging industry models 213
A Eames

Accelerating regional development through place-based approaches – baseline studies to de-risk critical mineral projects: a Julia Creek/Richmond case study 215
B Johns

Critical minerals Queensland – First Nations economic participation 223
B Johns

Beyond social licence – First Nations partnership as critical project infrastructure 225
J Lawton

Social licence and critical minerals – comparative insights from Australian and Canadian public attitude surveys 227
K Moffat and M-O Fortin

Licensing the social licence – identifying legitimacy-based SLO issues in Victoria's critical minerals industry 229
R Noor, M Farrelly and L Lester

Deep sea tailings placement – regulatory trends, evolving environmental, social and governance practices and financing implications 245
L Rollin and K Vershinina

Digital frontiers – the impact of artificial intelligence and machine learning on Indigenous participation, economic success, sovereignty and knowledge protection 247
M Saylor and M Case

Markets and finance

An investor perspective on critical minerals opportunities 251
R Breaden

Achieving bankability in critical mineral projects – integrating market, offtake and financing considerations 255
G R Goenka

Redrawing the investment map – government intervention and the evolution of critical minerals transactions for ASX companies 261
C Schofield

Technology risk addressal in valuing assets containing novel commodity processing technologies 263
S Talan and D Omosun

Transparent market design for lithium – order books, price normalisation and quality adjusted auctions 265
L Tay, R Fenn, A Trench and A Samuel

Strategy, geopolitics and national capability

Strengthening Indo-Pacific critical mineral supply chains – opportunities for regional collaboration in the battery ecosystem 269
A Gill and D Omosun

Comparable results, credible trade – accreditation, standards and national capability in critical minerals 271
D Hobday

How government can support the acceleration of critical mineral project delivery, supported by policy, regulation and initiatives 275
P Holden, A Neil and B Johns

Australia's opportunity to add value to critical minerals through downstream pyrometallurgical processing 277
E Jak, D Shishin, P C Hayes, M Shevchenko and J Chen

From strategy to scale – why critical minerals innovation stalls between pilot and bankability 279
D Kitsos

Critical minerals and strategic alignment – Australia at an inflection point 281
N Mackay and J Townsend

Critical minerals for energy and supply network risks in the Indo-Pacific 283
B C McLellan

Demystifying the midstream bottleneck – an analytical framework for critical minerals policies 285
D M Ramizo, H Cabalu, M Harris and J Inchauspe

A regional blueprint for Australia's critical minerals future – the Mackay and Greater Whitsunday model 287
J Thompson

Digging into Australia's 'sweet spot' on critical minerals 289
D Usher, P Baker and S Taylor

Critical minerals in an age of strategic fragmentation – from resource endowment to industrial delivery 291
V Vivoda

From exploration to refining – is Australia innovating where value is created? 293
R Wulff, R Moore and N Amitay

Sustainability

Revalorising historical tin mine wastes – a sustainable source of In, Sn, Sb, W and Bi 297
S J Chingwaru, O Mejías, R Blannin, N Fox and A Parbhakar-Fox

Baseline environmental studies for the development of oil shale-hosted vanadium projects 299
M Edraki, L Rochford and C Cote

Using metal-organic frameworks to move acid mine drainage from liability to resource 313
E Jennings, M Edraki, J Hou and J Powell

Collaborative assessment of legacy materials – potential to improve environmental outcomes and unlock copper and cobalt value at Mt Oxide 315
M Longbottom and L Nicholls

Selective copper recovery from acid mine drainage using ion-exchange technologies 317
J G Outram, S J Couperthwaite and D T Alexander

Recovery of critical metals from copper tailings – a Queensland case study 319
A Parbhakar-Fox and R Magwaneng

Uncovering unconventional critical metal ore deposits in Western Tasmania, Australia 321
A Parbhakar-Fox, L Jackson, M Tayebi-Khorami and R Coleman

Integrating mine waste remediation with the material demands of the sustainable energy transition 323
L Roper, E Prangige and S Couperthwaite

Thermal pretreatment for selective recovery of rare earth elements from permanent magnet waste 325
R Tao, J Schicks, K Forsberg and M Svärd

Effect of low temperature alkaline treatment on the oxidation of end-of-life NdFeB magnets 327
R Velpoor, R Mukhlis, W Bruckard and M A Rhamdhani

Strengthening Australia's critical minerals competitiveness – LCA and supply chain data as strategic trade tools 331
P Whattoff, A Samuel and J Twohig

Assessing the sustainability of entrapped sulfate-reducing bacteria for acid mine drainage treatment – techno-economic analysis and life cycle assessment 333
X Yin, S Koay, N Gurief and A Oehmen

Author index 335

Advances in processing, manufacturing and associated technologies

Beneficiation strategies for rare earth minerals from clay-hosted ores – a critical review

F Agbenyo[1], B Tedesse[2], L Dyer[3], K Evans[4], M Tade[5] and S Owen[6]

1. PhD Candidate, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Kalgoorlie WA 6430. Email: faithyaw.agbenyo@postgrad.curtin.edu.au
2. Associate Professor, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Kalgoorlie WA 6430. Email: bogale.tadesse@curtin.edu.au
3. Associate Professor, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Kalgoorlie WA 6430. Email: laurence.dyer@curtin.edu.au
4. Professor, School of Earth and Planetary Sciences, Curtin University, Perth WA 6845. Email: k.evans@curtin.edu.au
5. Professor, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Perth WA 6845. Email: m.o.tade@curtin.edu.au
6. Exploration Manager, Critica Limited, West Perth WA 6005. Email: stuart@critica.limited

ABSTRACT

The global drive for clean energy and advanced technological development has made the Rare Earth Element (REE) supply chain a priority for many countries, including Australia. China accounts for 70 per cent of global REE mine production, creating a supply risk for the global economy and giving China a competitive advantage in price-setting. REE can be found in tailings from processing key commodities such as copper and low-grade REE deposits with total rare-earth oxides (TREO) of <1 per cent. There are 91 REE clay-hosted projects at the exploration and feasibility stages in Australia, of which only ~10 per cent are comparable to ionic-absorption clays found in Southern China, which have been well researched and have established processing methods. There is no process plant for the beneficiation of refractory or non-ionic adsorption REE clay-hosted ores. This review seeks to draw on beneficiation experiences from clay-hosted ores, such as bauxite, to develop beneficiation strategies for REE clay-hosted ores. Beneficiation flow sheets for processing REE ore explored properties such as specific density, magnetism, and hydrophobicity. However, separation performance depends on the particle size of REE and associated gangue minerals. Gravity separation methods may not apply to the beneficiation of REE from clay-hosted ores due to their relatively fine particle size, though REE -bearing minerals have high specific density. Wet high intensity magnetic separation (WHIMS) has shown impressive results by removing magnetic gangue, such as iron oxide, from saprolite, but the challenge of clay particle size remains, as desliming may be required. The chemical and physical characteristics of clay, such as ion exchange and swelling-shrinking, respectively, complicate the beneficiation of clay-hosted minerals such as Crandallite. REE-bearing minerals in the crandallite group, including crandallite, goyazite, gorceixite, and florencite, present additional mineralogical complexity because their surface chemistry closely resembles that of gangue minerals such as kaolinite, making selective separation difficult. Although flotation is the principal beneficiation technique applied to clay-hosted ores, its performance is limited by slime coating, entrainment, and entrapment, which reduce both upgrade and recovery.

There is, however, scant published research on how to overcome the challenges. This review explores possible solutions, including wet high-intensity magnetic separation; desliming; selective flocculation; reverse flotation of gangue for preconcentration; sodium silicate and sodium hexametaphosphate for dispersion; tannin-quebracho extract for depression; mixed or novel collectors; and the use of cavitation picco-bubble column flotation to generate fine bubbles, thereby increasing the chances of collision with ultra-fine particles to improve REE upgrade and recovery. This work provides direction for developing a sustainable beneficiation flow sheet to enable Australia to fully exploit REEs from clay-hosted ores.

Froth image-based monitoring of copper flotation circuits using localised principal component models

C Aldrich[1]

1. Professor and Chair in Process Systems Engineering, Western Australian School of Mines, Curtin University, Perth WA 6845. Email: chris.aldrich@curtin.edu.au

ABSTRACT

Online monitoring of flotation froth remains variable across industrial operations, ranging from visual inspection by operators to the use of image-based measurements within process control systems. Recent advances in computer vision and multivariate statistical process monitoring provide an opportunity to develop more systematic frameworks for detecting changes in froth behaviour and distinguishing process deviations from normal changes in operating regime.

This study investigates a methodology for monitoring copper flotation systems by combining image-derived froth features with localised principal component analysis (PCA). Videographic data are collected from laboratory flotation experiments and processed to extract texton-based descriptors of froth appearance. Rather than representing all normal operation by a single global PCA model, the proposed framework partitions the normal operating space into locally homogeneous regimes and develops separate PCA monitoring models for these regions. This is intended to reduce the risk that legitimate shifts between operating conditions are incorrectly identified as process faults.

Two complementary monitoring formulations are considered. The first uses froth image features alone to characterise changes in froth state. The second combines image-derived features with process measurements, including air flow, ore feed conditions and reagent addition rates, to investigate whether deviations in froth appearance can be interpreted in the context of concurrent operating adjustments. This distinction is important because changes in process inputs may represent corrective action that maintains normal flotation behaviour rather than evidence of abnormal operation.

The work therefore focuses on the development and evaluation of a localised multivariate monitoring framework, with particular emphasis on regime-dependent behaviour, fault sensitivity and false-alarm reduction relative to global PCA monitoring. The proposed approach is intended as a basis for subsequent extension to online monitoring and decision support in industrial flotation circuits.

Supporting Australia's critical minerals strategy through applied processing research

K R Barnard[1]

1. Senior Principal Research Scientist, Critical Minerals and Hydrometallurgy, CSIRO, Waterford WA 6152. Email: keith.barnard@csiro.au

ABSTRACT

Australia's transition from a bulk commodity exporter to a globally competitive supplier of critical minerals and derived materials depends on the development and deployment of robust, scalable and environmentally responsible processing capabilities. As Australia's national science agency, CSIRO plays an important role in supporting this transition through applied research that aligns closely with the Federal Government's Critical Minerals Strategy and its focus on downstream value-adding, supply-chain resilience and sovereign capability.

This presentation provides a high-level overview of selected critical minerals processing activities currently or recently undertaken at CSIRO Mineral Resources at Waterford, Western Australia. These activities span a portfolio of projects seeking to address key processing and product-quality challenges across a range of commodities, including copper (chalcopyrite) processing, high-purity manganese production, high-purity alumina generation, graphite purification, and vanadium and titanium recovery from vanadiferous titanomagnetites. The presentation will also touch on CSIRO's involvement in precursor cathode active materials (pCAM) development through the C4P pilot plant based at Waterford, operated in collaboration with the Mineral Research Institute of Western Australia (MRIWA) and Curtin University. The C4P facility forms a key component of the Western Australian Government's proposed Critical Minerals Advanced Processing (CMAP) initiative. Collectively, these examples demonstrate how CSIRO Mineral Resources Processing cohort is supporting industry and government by aligning applied research capability with national critical minerals priorities and emerging downstream processing opportunities.

From batch to breakthrough – continuous magnesium metal production for a resilient critical minerals supply chain

A Brent[1], D Liu[2] and D Freeman[3]

1. Senior Research Technician, CSIRO Mineral Resources, Clayton Vic 3168.
   Email: andrew.brent@csiro.au
2. Senior Research Scientist, CSIRO Mineral Resources, Clayton Vic 3168.
   Email: dongmei.liu@csiro.au
3. Senior Experimental Scientist, CSIRO Manufacturing, Clayton Vic 3168.
   Email: david.freeman@csiro.au

ABSTRACT

Magnesium (Mg) metal is a strategically important material in both Australian and global critical minerals supply chains, underpinning applications in lightweight alloys, defence, transportation, and emerging energy technologies. However, global Mg metal production remains highly concentrated and largely dependent on the Pidgeon process – a batch-based vacuum thermal reduction method developed in 1940s. High energy and labour intensity, combined with short equipment lifetimes, make the process poorly suited to secure, scalable, and low-carbon magnesium production. Australia has abundant magnesium resources, so developing advanced processing technologies presents a key opportunity to strengthen sovereign production capability and diversify global supply.

Continuous vacuum technology, known as Continuous Vacuum Retort (CVR), has been developed by CSIRO and demonstrated at pilot scale as a transformative alternative for Mg metal production through the Pidgeon Process. A pilot-scale CVR facility has been designed, built and tested for continuous silicothermic reduction of MgO. Operating under stable high-temperature and deep vacuum conditions, the system enables continuous feed input, efficient metal vapour extraction, and automated residue discharge. Selective condensation using temperature-controlled condenser tubes facilitates effective separation of Mg from impurities.

The process has produced high-purity Mg metal (>98 per cent, Figure 1) operating at 1.5 kg/h, exceeding typical batch process performance. Continuous operation over 36 hrs has also been demonstrated. Analysis of residual by-products indicates they are suitable for use in cement applications, supporting improved resource efficiency.

From a supply chain perspective, transitioning to continuous processing offers significant advantages, including improved energy efficiency, enhanced equipment durability, and increased operational safety. These benefits support scalable, lower-emission production pathways critical to both Australia's ambition to develop domestic magnesium capability and the global need for more resilient and diversified supply chains. Beyond magnesium, the CVR platform shows strong potential for applications to other critical minerals/metals.

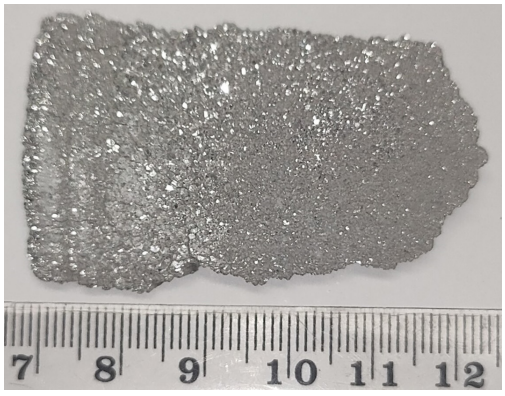


FIG 1 – Produced Mg metal.

Securing heavy rare earth supply beyond China – a comparative assessment of *in situ* recovery and heap leaching for ion-adsorption clay deposits

L Bullen[1]

1. Process Engineering Manager, Altris Engineering, Subiaco WA 6008.
   Email: lucas.bullen@altris.com.au

ABSTRACT

Ion adsorption clay (IAC) deposits accounted for approximately 35 per cent of China's total rare earth element (REE) production as of 2009. They are the dominant global source of heavy rare earth elements (HREE). Commercial *In situ* Recovery (ISR) of REE from IAC deposits has been demonstrated outside China, at MCRE Resources' Gerik Mine in Malaysia since 2023. The Gerik operation is reported to use Chinese-transferred technology and the same ammonium sulfate lixiviant as Chinese operations. A cohort of ex-China projects is now advancing through feasibility-level studies. These include a greenfield wellfield ISR development in Brazil using an alternative lixiviant, and heap leach developments in Brazil and South Australia. This paper compares these technologies on a techno-economic basis.

This paper compares REE ISR with the mature uranium ISR industry. Both use injection and recovery wellfield architecture, but the two processes diverge in host geology, lixiviant chemistry, hydrogeological containment and post-operational remediation. Uranium ISR targets confined and permeable sandstone aquifers. It uses strong oxidising acid or alkaline lixiviants, within regulatory frameworks that require aquifer restoration toward pre-mining groundwater quality. Reagent consumption ranges from approximately 8–80 kg acid per kg U depending on host geology, with wellfield solution recycle rates running at above 90 per cent. REE ISR instead operates through mild cation exchange within unconfined, near-surface saprolite profiles, using dilute salt solutions at materially lower reagent intensity. These saprolite deposits are shallower and lower-pressure. They present a distinct risk and regulatory paradigm, for which limited ex-China commercial precedent currently exists.

Lixiviant selection is a critical environmental and permitting differentiator. Ammonium sulfate, the predominant Chinese reagent, carries a documented legacy of ammonia-nitrogen contamination. It is also an established driver of clay swelling and slope instability. Magnesium sulfate, the reagent selected for the Ema Project (Brazilian Critical Minerals, Amazonas, Brazil), presents a significantly lower nitrogen-contamination risk.

Heap leach is compared here to ISR, as several commercial REE development companies have selected this extraction technique. In 2011 China domestically banned heap leaching of ion-adsorption clay on environmental grounds, shifting extraction towards ISR. Serra Verde's Pela Ema operation (Brazil) and Australian Rare Earths Limited Koppamurra Project (South Australia) are two examples of REE heap leaching currently in development outside of China. This paper weighs heap leach's lower capital intensity and simpler process control against its conventional surface mining and materials-handling exposure, relative to ISR.

Capital intensity and operating cost benchmarking is presented using a normalised flow sheet boundary framework at the mixed rare earth carbonate (MREC) product gate. Bankable Feasibility Study (BFS)-level estimates for the Brazilian Critical Minerals Ema Project are compared alongside published feasibility data for several comparable REE projects: Meteoric Resources' Caldeira, Australian Rare Earths' Koppamurra, Mkango Resources' Songwe Hill, Hastings Technology Metals' Yangibana, Pensana's Longonjo, and Defense Metals' Wicheeda (Defense Metals Corp, 2025; Hastings Technology Metals Limited, 2026; Mkango Resources Ltd, 2026; Meteoric Resources NL, 2026).

Declaration: The author is employed by Altris Engineering, which holds a commercial engineering services relationship with Brazilian Critical Minerals Limited (BCM) on the Ema Project, including delivery of the Bankable Feasibility Study (BFS) referenced throughout this paper. This relationship

is declared in the interests of transparency. All third-party project data is drawn from public disclosures and is referenced accordingly.

INTRODUCTION

Rare earth elements (REE), in particular the magnet rare earths neodymium, praseodymium, dysprosium and terbium, sit at the centre of strategic mineral policy in the United States, the European Union, Japan, Australia and other economies seeking to reduce dependence on Chinese-controlled supply chains. China's 2022 mineral imports of US$623 billion made it by far the world's largest minerals importer (Landry, 2025). Its restrictions introduced during 2024 and 2025 on gallium, germanium, antimony and select rare earth exports have sharpened concern over the security of downstream magnet and defence supply chains (Baskaran and Schwartz, 2024a, 2024b). This geopolitical backdrop is the principal driver behind the current cohort of ex-China Ionic Adsorption Clay (IAC) projects now advancing through feasibility studies in Brazil and Australia. Several of these projects are the subject of this comparison.

IAC deposits form through deep lateritic weathering of a REE-enriched host rock. This produces clay-rich saprolite profiles, in which rare earth ions are weakly adsorbed onto clay mineral surfaces. This weak bonding is the IAC deposit type's defining commercial advantage. REE can be desorbed by simple cation exchange with a dilute salt solution at ambient temperature and pressure. No comminution, flotation or high-temperature digestion circuit is required, unlike for hard rock REE ores. The same weak bonding explains the deposit type's outsized importance for heavy rare earths: ionic clays are comparatively enriched in dysprosium and terbium relative to most hard rock deposits.

Several extraction pathways are in active feasibility-level development for ex-China IAC resources. Wellfield *in situ* recovery (ISR) injects and recovers lixiviant through a network of wells or trenches, without mining the clay. The term used throughout this paper, ISR, follows the convention in the United States and Australian uranium industries, where it denotes recovery of a dissolved metal from an undisturbed, *in situ* resource. *In situ* leaching (ISL) is the equivalent term preferred in other jurisdictions, including much of the uranium literature, where ISL and ISR are used interchangeably to describe the same wellfield injection/recovery architecture. The heap leach method processes ore that is mined and then leaches *ex situ* on an engineered pad. Hard rock and tank-leach REE developments are examined here as capital-intensity benchmarks and not process analogues.

This paper's objective is to assess the relative technical, environmental, economic and regulatory merits of wellfield ISR and heap leaching for ex-China ion-adsorption clay rare earth projects. It uses the mature uranium ISR industry as a technical analogue for REE ISR's containment, reagent and remediation challenges, and draws on recently disclosed feasibility-level project data to identify the principal uncertainties that will determine which pathway, and which technology variant, proves commercially viable outside China.

ION ADSORPTION CLAY DEPOSITS AND THE EX-CHINA DEVELOPMENT COHORT

IAC deposits accounted for approximately 35 per cent of China's rare earth production by 2009. At the time of the last comprehensive academic assessment, they also hosted more than 80 per cent of the world's medium and heavy rare earth elements (Yang *et al,* 2013), reflecting their disproportionate importance as the principal global source of HREEs. Both figures are consistently repeated in the subsequent literature.

Though the single-study estimates are now dated, China's 2024 mine production quotas are the most recent official data available. China allocates approximately 7 per cent of the 270 000 t national rare earth mining quota to the ion-adsorption clay category (19 150 t), with the remainder assigned to light rare earth deposits (US Geological Survey, 2025). This discrepancy has at least three possible explanations. First, China's production mix may have genuinely shifted, as light rare earth output expanded to meet magnet demand. Second, tonnage share and value share may simply differ, since ion-adsorption clay's heavy rare earth content is disproportionately valuable per tonne. Third, this category may remain under-represented in official quotas, due to historically difficult-to-regulate illegal mining (Yang *et al,* 2013). The relative contribution of these factors cannot be

determined by publicly available information and therefore both figures are reported here rather than asserting a single current share.

Commercial ion-adsorption clay extraction in southern China (Jiangxi, Guangdong, Fujian and Guangxi provinces) began in 1970. It was historically carried out via mountaintop conventional mining followed by tank or heap leaching, typically using ammonium sulfate. *In situ* leaching was developed in China in the mid-1980s. The first commercial ISR plant began operation in 1997. The two extraction methods then operated in parallel for over a decade. In June 2011, the Chinese central government banned surface mining and tank or heap leaching of ion-adsorption clay outright, making *in situ* leaching the sole permitted extraction method (Yang *et al,* 2013). This highlights that China's *in situ* leaching practice, and the ISR-specific environmental problems documented here predate the 2011 ban by well over a decade. The ban converted an already-operating parallel technique into the sole permitted method.

The ban followed documented and quantified environmental damage from the surface mining and heap leaching method specifically, rather than a general environmental concern. Producing 1 t of rare earth oxide by tank or heap leach was estimated to remove 300 m^2 of vegetation and topsoil. It also disposed of up to 2000 t of tailings into adjacent valleys and streams and generated 1000 t of wastewater containing high concentrations of ammonium sulfate and heavy metals (Yang *et al,* 2013).

In the Ganzhou region of Jiangxi Province alone, this practice left 302 abandoned mines and 191 million tonnes (Mt) of tailings. Destroyed forest area increased from 23 km^2 to 153 km^2 between 2000 and 2010. Estimated reclamation costs were approximately US$5.8 billion, against a regional rare earth industry earning only around US$300 million in annual profit over the preceding decade (Yang *et al,* 2013).

MCRE Resources Sdn Bhd's Gerik Mine, in Kenering, Hulu Perak, Malaysia, has operated an ex-China wellfield ISR operation since 2022 (MCRE Resources Sdn Bhd, 2023). MCRE uses ammonium sulfate lixiviant and a combination of injection and collection wells to produce a mixed rare earth carbonate product. In the six months to January 2026, Gerik produced approximately 3800 t of rare earth carbonate, from only two of nine planned mining parcels (Rare Earth Exchanges, 2026).

MCRE's ownership is Malaysian, not Chinese. Southern Alliance Mining Ltd (SAM, SGX: QNS) holds a 40 per cent interest via its wholly owned subsidiary SAM Advance Minerals, following completion of the acquisition in September 2025 (Oaklins, 2025; NextInsight, 2026; Southern Alliance Mining Ltd, 2026). The remaining approximately 60 per cent is held by Malaysian individuals and entities. No Chinese entity holds a publicly disclosed equity stake.

MCRE's China exposure is commercial rather than an ownership relationship: its rare earth carbonate output is exported to China for downstream separation (Rare Earth Exchanges, 2026). The company is also reported to hold its ionic clay ISR technology under licence from China Rare Earth Group, the state-owned entity formed in December 2021 through the merger of the rare earth divisions of Chinalco, China Minmetals and Ganzhou Rare Earth Group, though this specific licensing arrangement, and the offtake and Shanghai Metals Market pricing terms described in some industry commentary, could not be independently confirmed against a primary source and are presented below as reported rather than verified (South China Morning Post, 2021).

MCRE nonetheless demonstrates that ex-China commercial ISR production is achievable, using Chinese-origin ISR technology and the ammonium sulfate lixiviant, under what is reported to be a technology-licensing and offtake structure rather than Chinese ownership. It does not, however, establish a precedent for an independently developed, non-Chinese-technology ISR operation.

Serra Verde's Pela Ema operation in Brazil, commercially operated since January 2024, is a separate and later precedent. It is an independently developed, *ex situ* (mined) heap leach operation, not an ISR one. Serra Verde's standing as the first independently developed, commercial-scale ex-China ionic clay producer remains an important distinction for this paper (Serra Verde, 2024–2026).

A cohort of projects are advancing the ISR and heap leach pathways concurrently toward final investment decisions (FID). The Ema Project (Brazilian Critical Minerals Limited, 'BCM') is located

in the Apuí region of Amazonas State, northern Brazil. It is the most advanced wellfield ISR development outside China. BCM completed a three-month field-scale ISR trial. In June 2026 BCM released a Bankable Feasibility Study (BFS) with an AACE Class 3 (±15 per cent) capital cost accuracy (Brazilian Critical Minerals Limited, 2026).

The Koppamurra Project (Australian Rare Earths Limited, 'AR3', South Australia/Victoria border) is an advanced ex-China ionic clay heap leach development. AR3 released a Pre-Feasibility Study (PFS) with a maiden Ore Reserve in June 2026 (Australian Rare Earths Limited, 2026). These two projects, together with MCRE's operating ex-China ISR precedent and Serra Verde's operating heap leach precedent, form the technical basis of the ISR-versus-heap-leach comparison in this paper.

URANIUM ISR – A TECHNICAL ANALOGUE

In situ leaching/*in situ* recovery (ISL/ISR) is well established in the uranium industry. It accounted for 56 per cent of world uranium production in 2022, up from 16 per cent in 2000. The largest operations are in Kazakhstan, Uzbekistan, the United States and Australia (Li and Yao, 2024; World Nuclear Association, 2026). Uranium ISR is the closest available commercial analogue to REE ISR, sharing an injection/recovery wellfield architecture, though the two processes diverge in ways that matter for project design, permitting and risk.

Host geology and containment

Uranium ISR targets confined or semi-confined, laterally continuous, permeable sandstone aquifers, typically at depths of tens to hundreds of metres. An overlying and underlying confining low-permeability layer also referred to as an aquitard, provides the primary hydraulic containment for the injected lixiviant. Wellfield design and permitting in the United States and Australia both rely on this confinement, to show that lixiviant migration can be controlled and monitored.

REE ISR, by contrast, typically operates within unconfined, near-surface saprolite profiles, perched at shallow depth (commonly less than 50 m), above an impermeable bedrock surface. There is no overlying confined aquifer for the Ema project. Underlying containment at the Ema Project utilises hillslope hydrogeology and downgradient horizontal recovery wells, positioned to intercept solution flow, coupled with a low permeability bedrock at near surface depths (<15 m deep). This is a materially different containment paradigm, with correspondingly different monitoring and permitting requirements, and limited ex-China regulatory precedent.

Lixiviant chemistry and reagent intensity

Uranium ISR lixiviants are oxidising. They use either acid, typically dilute sulfuric acid with an oxidant, or alkaline, sodium or ammonium bicarbonate-carbonate with oxygen or hydrogen peroxide chemistry. The lixiviant choice depends primarily on host-rock carbonate content. Alkaline leaching is preferred where carbonate content exceeds approximately 2 per cent of the host rock mass, to avoid excessive acid consumption from gangue neutralisation, and dominates in most United States operations. Acid leaching dominates in Kazakhstan and Australia, typically achieving higher recoveries of 70–90 per cent, compared with 60–70 per cent for alkaline leaching.

Reported acid consumption is strongly geology-dependent. Acid consumption runs at approximately 7.7 kg acid per kg U at Beverley, South Australia, compared with a general range of 40–80 kg acid per kg U across Kazakh operations (World Nuclear Association, 2026). By comparison REE ISR uses a non-oxidising and dilute magnesium sulfate solution at Ema or a dilute ammonium sulfate at MCRE. This works through cation exchange rather than mineral dissolution.

Ema's BFS reports a lixiviant consumption of approximately 20 649 t/a $MgSO_4$, against average annual production of 5500 t TREO (total rare earth oxide), which is a reagent-to-product mass ratio of ~ 3.8:1. This ratio is not directly convertible to a kg-reagent-per-kg-product basis comparable with the uranium figures above, as the two processes consume reagent against different metrics: ore-contained metal for uranium ISR, recovered TREO for REE ISR. The ratio is presented here to enable future like-for-like benchmarking, as more REE ISR operating data becomes available.

Wellfield solution recycle and water management

Commercial uranium ISR operations report wellfield solution recycle rates of the order of 99 per cent, with only a small bleed stream (approximately 0.5–1 per cent of circulating solution) drawn off continuously to maintain the hydraulic gradient that keeps lixiviant contained within the wellfield. Cameco's Smith Ranch-Highland operation in Wyoming recirculates carbonate-leach groundwater with re-added CO_2/O_2, bleeding approximately 1 per cent of circulating solution (Li and Yao, 2024; US NRC licensing documentation).

The Ema Project's process design adopts the same closed-loop philosophy: barren liquor is returned to storage, reconditioned with magnesium sulfate and sulfuric acid as required, and reused as lixiviant, with raw water make-up included only to replace process losses. It should be noted that the Ema BFS does not yet disclose a quantitative wellfield solution recycle percentage equivalent to the uranium industry's ~99 per cent benchmark. As this data becomes available it should be assessed relative to published uranium industry recycle rates.

Post-operational remediation

Uranium ISR licensing in the United States and Australia requires restoration of affected groundwater toward pre-mining baseline quality (or an approved alternate concentration limit) following production, with restoration performance and time frames a recurring source of regulatory and technical difficulty industry-wide (Li and Yao, 2024). REE ISR at Ema is designed around wellfield flushing with clean water to dilute residual lixiviant prior to decommissioning, followed by wellfield rehabilitation. It should be noted that using magnesium sulfate as the lixiviant, it is expected the residual levels of interest will be sulfate targets, rather than specific elements such as nitrogen or phosphorous.

No ex-China regulatory framework yet specifies quantitative post-closure water quality restoration criteria equivalent to those governing uranium ISR, however. This remains true even accounting for MCRE's operating Gerik Mine: MCRE has not yet reached closure, so its post-closure restoration performance, and Malaysia's regulatory requirements for it, remain untested in practice. This is a regulatory paradigm gap, not a resolved question, and is one of the clearest respects in which REE ISR cannot yet claim the same post-operational precedent as its uranium analogue.

HEAP LEACH – AN ALTERNATIVE PATHWAY

Heap leach is included in this comparison as a third pathway, alongside wellfield ISR and the uranium ISR analogue. Heap leach has an operating ex-China commercial precedent, Serra Verde and is the pathway selected by several other ex-China IAC developers, including Koppamurra in Australia. The choice between them impacts capital intensity, surface disturbance, water management and permitting pathway.

Process description and rationale for inclusion

In heap leaching, mined clay is agglomerated, stacked on an engineered and lined pad, then irrigated with lixiviant. The lixiviant percolates through the heap and reports to a collection system at its base. This is functionally the *ex situ* equivalent of ISR's wellfield injection/recovery cycle, using the same broad category of dilute salt or dilute acid lixiviants. At Koppamurra, AR3's PFS (June 2026) specifies a dilute sulfuric acid and magnesium sulfate lixiviant, applied to a heap of approximately 4 m height, following agglomeration and drum-scrubber pre-treatment of shallow open pit-mined ore, with off-site calcination to a mixed rare earth oxide (MREO) product. Heap leach test work at Koppamurra has achieved magnet REE recoveries of up to approximately 76 per cent in some column tests. The pathway is currently being validated at larger scale, through an ANSTO pilot programme using 4 m columns (2026) and an earlier bulk heap leach trial (2025).

Comparative advantages

Heap leach carries a materially lower capital intensity in some published comparisons. AR3's Koppamurra PFS reports an initial capital cost of A$178M for 3 Mt/a throughput. China's own multi-decade domestic experience with the technique, prior to its 2011 ban, demonstrates its process simplicity and rapid deployability.

The ore is mined and stacked under engineered and contained conditions, rather than leached in the undisturbed subsurface. This gives heap leach tighter operational control over lixiviant application rates and recovery, while avoiding the hydrogeological containment uncertainty inherent to ISR's reliance on natural subsurface flow paths. Serra Verde's Pela Ema operation demonstrates that this control can be translated into sustained commercial-scale operation, with a Phase 1 nameplate target of approximately 6400–6500 t/a TREO by end-2027, and cumulative development spend exceeding US$1.1 billion to reach commercial production.

Comparative disadvantages and why ISR was selected at Ema

Heap leach requires open pit mining, ore haulage, agglomeration, and an engineered and lined leach pad. This introduces ground disturbance, vegetation clearance and rehabilitation requirements. These are the same category of surface impacts that led directly to China's 2011 domestic ban on tank and heap leaching of ion-adsorption clay (Yang *et al,* 2013). ISR is specifically designed to avoid them.

BCM's own rationale for selecting ISR at Ema is explicit on this point. The BFS states that ISR avoids the need for extensive ground disturbance associated with open cut mining, reducing environmental impact and closure legacy, and that this lower-disturbance profile was a primary driver of the technology selection. Heap leach economics are also more exposed to strip ratio, haulage distance and rehabilitation cost than ISR. None of these apply to a wellfield development in the same way.

Heap leach and ISR are not a hierarchy of 'better' and 'worse' technology: they represent a genuine trade-off. Heap leach offers faster deployment, tighter process control at the expense of greater surface disturbance and the mining-related environmental and social impacts that motivated China's own shift away from the technique. ISR offers a lower-disturbance development footprint but introduces greater hydrogeological and containment uncertainty.

Yang *et al* (2013), whose data underpins China's 2011 ban, conclude that blanket enforcement of *in situ* leaching, irrespective of a mine's specific hydrogeological and geotechnical characteristics, is itself a risk. They recommend that mining technique be selected on a site-by-site basis, not mandated uniformly. That conclusion, drawn from the only jurisdiction with an operating history of both pathways at meaningful scale, is directly relevant to how ex-China developers and regulators should weigh the ISR-versus-heap-leach choice today.

LIXIVIANT SELECTION AS AN ENVIRONMENTAL AND PERMITTING DIFFERENTIATOR

Ammonium sulfate and the Chinese precedent

Ammonium sulfate (AMSUL) is the predominant lixiviant used in Chinese commercial ISR and, historically, tank or heap leach operations. It is favoured for its high desorption efficiency with ionic clay minerals and supply availability relative to the Chinese ISR locations. Its established drawback is a documented legacy of ammonia-nitrogen contamination of soil and groundwater surrounding Chinese operations, alongside elevated impurity content in the pregnant leach solution (Xu *et al*, 2023; cited in CSIRO, 2024). Yang *et al* (2013) report ammonium concentrations of 3500–4000 mg per litre in groundwater near Chinese *in situ* leach sites, together with pH increases of 11–18 per cent in surface and groundwater near the Longnan and Xunwu operations in the Ganzhou region.

AMSUL use is also linked in the published literature to swelling of clay minerals in the orebody. Yang *et al* (2013) attribute more than 100 landslides in the Ganzhou region to *in situ* leaching practices employing this reagent, at material human cost and loss of resources. This is the strongest environmental argument available to ex-China developers proposing an alternative reagent. It is a well-documented differentiator, supported by the operating record of *in situ* leaching projects in China rather than by comparisons with heap leach operations alone.

Magnesium sulfate and its reduced risk profile

Magnesium sulfate ($MgSO_4$) is the lixiviant selected for the Ema Project. It is also used in combination with dilute sulfuric acid at Koppamurra. Relative to ammonium sulfate, $MgSO_4$ avoids the ammonia-nitrogen contamination pathway entirely, since it introduces no nitrogen species to the leach circuit. This is a material environmental advantage, however it would be inaccurate to characterise $MgSO_4$ as risk-free.

Published test work by Chen *et al* (2020) specifically examined swelling of clay minerals during weathered-crust elution-deposited REE ore leaching using magnesium salts. They found that magnesium-salt leaching is not immune to the same clay-swelling mechanism implicated in ammonium sulfate-related slope instability. This finding is relevant to Ema's hillslope-hosted wellfield design, where slope stability under sustained lixiviant irrigation is a geotechnical consideration.

The Ema Project precipitation reagent, magnesium bicarbonate ($Mg(HCO_3)_2$), is produced on-site from magnesium oxide and captured carbon dioxide. The BFS includes a new US$19M CO_2 capture and storage system, specifically to reduce reagent trucking costs and reagent supply risk at this remote Amazonian site. The inclusion of a CCS is an efficient design response to a genuine remote-site logistics constraint. But it also means that Ema's favourable reagent cost position (US$2.13/kg TREO, 34 per cent of total operating cost) is contingent on the CCS system performing as designed. A comparable alternative precipitation route based on trucked sodium carbonate or sodium bicarbonate, would avoid this dependency. However, it would come at materially higher delivered reagent cost, with its own sodium-accumulation and bleed-stream management penalty in a closed-loop circuit.

It is notable that MCRE, the only currently operating ex-China commercial ISR precedent continues to use ammonium sulfate rather than magnesium sulfate. Ema's and Koppamurra's choice of $MgSO_4$ is accordingly a deliberate departure from the one proven ex-China ISR operating precedent, and neither project can yet point to an ex-China commercial track record for the alternative reagent it has selected.

CAPITAL INTENSITY AND OPERATING COST BENCHMARKING

Cross-project capital and operating cost comparison in the REE sector is confounded by inconsistent flow sheet boundaries, inconsistent product definitions (MREC product mass versus contained TREO versus contained NdPr), and variation in study phase and maturity, from scoping study through to BFS/DFS.

Methodology

Nine projects are benchmarked in Tables 1 and 2: the five ex-China ion-adsorption or comparable clay-hosted developments that motivate this paper's technology comparison (Ema, Gerik, Caldeira, Koppamurra, Pela Ema), plus four hard rock or flotation-based REE developments (Songwe Hill, Yangibana, Longonjo, Wicheeda) included solely as capital-intensity benchmarks, consistent with the scope defined earlier. Selection was limited to projects with a publicly disclosed feasibility-level study (Scoping, PFS, DFS or BFS) or, for Gerik and Pela Ema, disclosed operating or development-stage figures, as of August 2026.

TABLE 1

Capital intensity benchmarking, normalised to nearest disclosed product gate.

Project	Pathway / product gate	Study phase	Initial CAPEX	NPV8 (post-tax) / IRR
Ema (BCM, Brazil)	Wellfield ISR → MREC	BFS, Jun 2026	US$74M (Stage 1) + US$27M (Stage 2) (US$359M incl. sustaining)	US$1.47B / 105%
Gerik (MCRE, Malaysia)	Wellfield ISR (AMSUL, Chinese technology licence and offtake) → rare earth carbonate	Operating, no public feasibility study	>RM100M (~US$21 to 22M)	Not disclosed.
Caldeira (Meteoric, Brazil)	Open pit + tank leach (AMSUL). MREC product. Not ISR	DFS, Jul 2026	US$498M	US$847M / 24% †
Koppamurra (AR3, Australia)	Heap leach → MREO	PFS, Jun 2026	A$178M (~US$123M)	A$858M (~US$593M) / 99%
Pela Ema (Serra Verde, Brazil)	Heap leach. MREC product. Commercial since Jan 2024	Operating, no public study	>US$1.1B cumulative to commercial production †	Not disclosed
Songwe Hill (Mkango, Malawi)	Hard rock (carbonatite) → MREC	DFS, Mar 2026	US$325.5M (US$417.0M incl. sustaining/reclamation)	US$339.5M / 24.3%
Yangibana Stage 1 (Hastings, Australia)	Hard rock → flotation concentrate (27% TREO, not MREC)	Updated DFS, Jul 2026	A$333M (~US$230M, 100% JV) / A$133M (~US$92M, Hastings 40%)	A$649M (~US$449M) / 34%
Longonjo (Pensana, Angola)	Hard rock → MREC. Under construction	BFS/EPCM, Apr 2025 to Jul 2026	US$216.5M (Apr-25) → US$250M (construction budget, mid-2026) †	NPV/IRR not reconfirmed in the 2025 to 2026 update, only 2022-study figures available
Wicheeda (Defense Metals, Canada)	Hard rock → non-standard MREC (La/Ce removed)	PFS, Feb 2025	US$1.4B (US$1.53B incl. sustaining)	US$992M (after-tax) / 18.9%

† Serra Verde's figure is a cumulative development spend rather than a study-derived capital estimate, as no public feasibility study has been released, treat as indicative of scale only. Pensana's 2026 construction budget represents an approximate 16% increase over the April 2025 EPCM figure and could not be cross-verified against a formal updated study document at the time of writing (Pensana PLC, 2025). Caldeira's DFS reports both spot and forecast pricing scenarios. The spot-price NPV8 and IRR are shown for consistency with the single-scenario estimates used elsewhere in this table (forecast-price case: US$2.721M NPV8 post-tax / 47% IRR).

TABLE 2

Unit operating cost and technical performance benchmarking.

Project	C1 opex (US$/kg TREO unless noted)	Recovery	Lixiviant / reagent	Water / environmental note
Ema (ISR)	8.84 (AISC 13.02), reagents 2.13/kg TREO, 34% of OPEX	IAC→MREC 55% (LOM), PLS→MREC 94.4%	$MgSO_4$, ~20 649 t/a	Closed-loop recycle design; % recycle not disclosed
Gerik (ISR)	Not publicly disclosed	Not publicly disclosed	Ammonium sulfate	Closed-loop design claimed (no discharge)
Caldeira (tank leach, not ISR)	11.68 LOM avg (AISC 16.74)	54% TREO (LOM); 71% MREO	Ammonium sulfate, 90% recycled	~85% water recovery; zero-liquid-discharge design
Koppamurra (heap leach)	34.14 (AISC 38.32)	68% TREO/MREO (resource → product), up to 76% in column tests	Dilute H_2SO_4 + $MgSO_4$	Lined heap, not yet at commercial scale

Project	C1 opex (US$/kg TREO unless noted)	Recovery	Lixiviant / reagent	Water / environmental note
Songwe Hill (hard rock)	22.3 first 5 yr / 26.1 LOM avg	Flotation 74.1%, NdPr hydromet 85.3%, Ce rejected (20.9%)	HCl leach, caustic conversion	Conventional tailings/flotation circuit
Yangibana Stage 1 (hard rock)	A$162/t ROM (~US$20.75/kg TREO in concentrate)	85% (flotation, target)	Flotation reagents only	Concentrate only, no on-site hydromet
Wicheeda (hard rock, non-standard MREC)	37.42/kg NdPrO equivalent	Flotation 76.7% LOM avg, hydromet 93.4%	Acid bake + SX	La/Ce removed, 6× mass reduction versus standard MREC
Uranium ISR (WNA benchmark)	Not comparable basis (per kg U)	60 to 90% (alkaline versus acid)	7.7 to 80 kg acid/kg U (geology-dependent)	approximately 99% wellfield solution recycle, approximately 0.5 to 1% bleed

Each project's study date and stage are shown in Table 1. No inflation or escalation adjustment has been applied, as all sources fall within an approximately 17-month window (18 February 2025 to 31 July 2026). Cost-estimate accuracy also varies systematically by stage (approximately ±30–50 per cent for Scoping-level, ±20–25 per cent for PFS, ±10–15 per cent for DFS/BFS), and Table 1 and Table 2 figures should be read against this confidence range rather than as directly comparable point estimates.

Figures are reported in the currency of original disclosure. Where a project reports in Australian dollars (Koppamurra, Yangibana), a US dollar equivalent is shown in Table 1 alongside the native figure, converted at the spot A$/US$ exchange rate on the study's announcement date (A$1 = US$0.6908 on 25 June 2026 for Koppamurra; A$1 = US$0.6919 on 13 July 2026 for Yangibana). This conversion is provided for cross-comparison only. The native-currency figure remains each project's primary disclosure.

Operating cost is reported as C1 cash cost per kilogram of TREO in Table 2, the most consistently disclosed metric across the benchmark set. AISC is shown in parentheses where disclosed, for context only, since it additionally incorporates sustaining capital and royalty costs not itemised by every source, and the two bases should not be combined. US$/kg TREO figures are taken directly from, or calculated from, each study's disclosed annual operating cost divided by annual payable or produced TREO. Where a project discloses cost on a different product basis (Yangibana's flotation concentrate; Wicheeda's non-standard MREC with La/Ce removed), this is noted explicitly in Table 2 rather than converted to an equivalent TREO basis, as the metallurgical conversion factor is not disclosed with sufficient precision to support one.

Each project's flow sheet boundary and product gate is stated in Tables 1 and 2 rather than normalised to a common gate. Most projects are benchmarked at the MREC gate, with Caldeira, Yangibana and Wicheeda benchmarked at earlier or non-standard gates as noted, since normalising to a common MREC-equivalent basis would require assumed downstream costs and recoveries not publicly disclosed for several projects in the set.

Initial capital figures in Table 1 were checked directly against each project's source study or announcement: all nine disclosed initial-capex figures are confirmed as pre-production or Stage 1 estimates that exclude sustaining capital, so the headline capex column is on a consistent basis. A separate sustaining capital figure is disclosed for four projects and is shown alongside the initial figure in Table 1 where a comparable lump-sum basis exists: Ema (US$258M over a 20-year LOM), Songwe Hill (US$91.5M sustaining and reclamation, within its US$417.0M combined figure), and Wicheeda (US$133M over the LOM). Longonjo discloses an average US$5.7M/a from Year 6, not combined into a lump sum here as remaining mine life is not disclosed. The remaining five projects either do not separately quantify sustaining capital in public disclosure (Caldeira, Koppamurra, Yangibana), or have no capital breakdown to draw one from at all (Gerik, an operating mine with no

public feasibility study; Pela Ema, a cumulative actual-spend figure rather than a forward study estimate).

Recovery percentages in Table 2 are reported against each project's own disclosed denominator (*in situ* ore-to-product for Ema, resource-to-product for Koppamurra, ore-to-flotation-concentrate for the hard rock projects) rather than normalised to a single basis, since a common denominator cannot be reconstructed from public disclosure without introducing further unstated assumptions. This is a deliberate choice: it is intended to make the inconsistency visible to the reader rather than obscure it behind a false equivalence.

Benchmarking results

Table 1 summarises capital intensity across the benchmark set. Table 2 summarises unit operating cost and technical performance. Several items, marked †, reflect superseded or unverifiable figures and are included for transparency rather than as current guidance.

Ema's disclosed 55 per cent overall MREO recovery sits at the lower end of the 70–90 per cent ore-to-solution recovery range reported for Chinese commercial ISR operations in the peer-reviewed literature (Burcher-Jones *et al,* 2018; Wang *et al*, 2022; cited in CSIRO, 2024). This gap may reflect a more conservative LOM-average basis, incorporating ramp-up, staged wellfield development and lower-grade Inferred-category material, rather than a shortfall in leaching performance.

OPERATIONAL RISKS AND LIMITATIONS

Operational risks and limitations of the ISR pathway require explicit discussion of the technical limitations, recovery challenges, scale-up risks and hydrogeological uncertainties that accompany a technology who's specific lixiviant and design have no independently developed ex-China commercial precedent. The BFS itself is a useful source for this discussion and its stated key assumptions amount to a candid public risk register.

Hydrogeological uncertainty

The BFS's economic case rests on two assumptions: that field trial results and available hydrogeological data are representative of all production areas within the project, and that solution recovery, recycle rates and losses remain within ranges adopted at the earlier Scoping Study stage. In practice, this means wellfield performance across the full 189 km^2 tenement, of which only 45 per cent has been explored, has been extrapolated from a single three-month field trial and associated numerical groundwater modelling. It has not been validated across the multiple, geologically variable pods that will ultimately be developed over the 20-year mine life.

This extrapolation is a source of technical risk. Whether field-trial recovery and solution-loss behaviour will hold across the full wellfield programme should be treated as an open question, pending further field validation.

Metallurgical and process scale-up risk

Ema's process recovery figures of 95 per cent impurity-removal recovery and >99 per cent MREC precipitation recovery at bulk scale, are underpinned by ANSTO column and bulk test work. The BFS explicitly assumes that process plant recoveries, reagent consumptions and product quality demonstrated in test work are achievable at commercial scale. This is a common and reasonable basis for a BFS, though the broader ex-China ionic clay cohort illustrates how large the gap between test work and commercial operation can be.

Aclara's Chilean tank-leach pilot processed only 120 t of clay to produce 107 kg of concentrate over three months. AR3's earliest Koppamurra test work processed 800 kg of clay via ANSTO's laboratory equipment, which is several orders of magnitude below the throughput stated in either company's subsequent feasibility studies. Ema's design throughput of 3188 dry t/a TREO for the Stage 1 plant represents a similarly large scale-up from column-scale test work.

Peninsula Energy's experience at its Lance uranium ISR project is a directly relevant cautionary precedent here for lixiviant consumption assumptions carried from column test work into a full-scale

REE ISR mass balance. Field-scale acid consumption during a demonstration conducted from 2020 to 2022 trended higher than laboratory-modelled 2018 feasibility study projections.

Recovery variability and resource maturity

Understanding site-specific geological and geotechnical conditions is critical to maximising REE extraction and implementing an appropriate wellfield design. Yang *et al* (2013) report that Chinese *in situ* leaching operations conducted without adequate site-specific geological and geotechnical survey have achieved recovery as low as 5 per cent. This underscores that ISR recovery is highly dependent on survey quality and site characterisation, not a fixed property of the lixiviant chemistry alone.

Approximately 16 per cent of Ema's produced MREC over the life-of-mine is sourced from Inferred Mineral Resource category material. This introduces geological confidence risk into the production schedule that underpins the reported unit operating costs. The disclosed 55 per cent LOM-average MREO recovery relative to the wider literature range of 70–90 per cent, should also be read in this context. A portion of the gap may reflect genuine ramp-up and lower-grade-pod effects rather than a fixed metallurgical ceiling though this has not yet been demonstrated. It should be noted that the LOM-average MREO recovery as reported is consistent with a BFS phase study.

Permitting, climatic and infrastructure risk

ISR permitting, licensing, land access and approvals are an unknown risk, with limited western analogues and a lack of established commercial precedent. The Ema Project BFS assumes that required permits, licences, land access and approvals can be obtained within the assumed development schedule, and that seasonal Amazon rainfall can be managed through operational and engineering controls. Both are reasonable planning assumptions, yet neither was secured at BFS release.

Serra Verde's 2026 experience demonstrates that these are not abstract risks, even for a technology, heap leach, with a longer ex-China operating history than ISR. Goiás's state environmental agency found water-quality exceedances, drainage deficiencies and over 300 hectares of unauthorised clearing at that operating, commercial-scale ex-China ionic clay site, following a joint inspection with Brazil's federal environmental agency (Agência Pública, 2026). This should temper any assumption that ISR's lower-disturbance design necessarily translates into lower regulatory risk in practice.

Remote-site infrastructure dependency is a related risk specific to Ema. The project's favourable reagent cost position depends on a CO_2 capture and storage system, and on diesel-fired power generation whose fuel logistics are subject to the same remote Amazonian supply chain constraints already identified as the dominant driver of delivered CO_2 cost.

DISCUSSION

The comparisons developed in this paper support four conclusions.

1. REE ISR and uranium ISR share an architectural resemblance. They diverge sufficiently in geology, containment and remediation obligation that uranium ISR regulatory and technical precedent can inform but cannot substitute for ex-China REE ISR-specific study. The absence of a defined post-closure water quality restoration standard for REE ISR is the clearest illustration of this gap.
2. Heap leach and wellfield ISR represent a genuine engineering trade-off, not a strictly dominant technology choice. The tighter process control required for heap leach is a real advantage. BCM's selection of ISR at Ema reflects a considered environmental-footprint rationale, not an absence of alternatives.
3. Ex-China commercial ISR production has been demonstrated at MCRE's Gerik Mine, but that precedent relies on Chinese-transferred technology and the ammonium sulfate lixiviant this paper identifies as the greater environmental risk. Ema's proposed departure from that precedent, an independently developed technology using an alternative lixiviant, therefore remains commercially untested at scale, even though the underlying ISR architecture now has an operating ex-China reference point.

4. Ema's BFS-level capital intensity and operating cost position, US$74M initial capex, US$8.84/kg TREO C1 opex, is genuinely favourable relative to every hard rock comparison in Table 1, and favourable relative to the one comparable Brazilian tank-leach project, Caldeira. This favourable position is contingent on a set of hydrogeological, metallurgical and infrastructure assumptions that have not yet been tested at commercial scale for an independently developed, non-Chinese-technology ISR operation.

The narrower absence of an independently developed, non-Chinese-technology ex-China REE ISR precedent is, in the author's view, the single most important qualifier to attach to any capital intensity or operating cost comparison in this paper, including the author's own project.

Public disclosure would help close this gap: quantitative wellfield solution recycle rates, recovery-by-resource-category data, and post-closure water quality monitoring criteria, from Ema, MCRE, and from any subsequent ex-China REE ISR developer. This would materially strengthen the evidentiary basis for the comparisons this paper has attempted to make which are currently considered on the best currently available public data.

CONCLUSIONS

Ex-China commercial ISR production of ion-adsorption clay already exists at MCRE's Gerik Mine in Malaysia, but it rests on Chinese technology transfer and ammonium sulfate lixiviant as the primary environmental risk. Wellfield *in situ* recovery of rare earth elements from ionic adsorption clay deposits is technically distinct from, but usefully informed by, the mature uranium ISR industry. This is particularly true for lixiviant reagent intensity, wellfield solution recycle practice, and post-operational remediation obligations.

Heap leach remains a technical credible, commercially demonstrated (via Serra Verde) alternative pathway, with process-control advantages that must be weighed against greater surface disturbance. Magnesium sulfate offers a materially lower nitrogen-contamination risk than the ammonium sulfate reagent used at MCRE and in Chinese commercial operations, though published test work confirms that it is not free of clay-swelling risk. This limitation should be carried forward into subsequent geotechnical work at Ema and at any other magnesium-salt ISR development.

The Ema Project's BFS-level capital intensity and operating cost position compares favourably against the wider ex-China REE comparison set benchmarked in this paper. That comparison, and the broader case for an independently developed, non-Chinese-technology ex-China REE ISR industry, remains contingent on hydrogeological, metallurgical scale-up, and permitting assumptions. These can only be fully resolved through continued field validation and, ultimately, commercial operation of such a project outside China.

ACKNOWLEDGEMENTS

The author thanks Brazilian Critical Minerals Limited for permission to reference publicly disclosed Ema Project Bankable Feasibility Study data. Altris Engineering's commercial relationship with BCM, including delivery of the Ema BFS, is declared at the outset of this paper. All comparable project data is drawn from public company disclosures, which are referenced in full below.

REFERENCES

Agência Pública, 2026. Terras raras: Serra Verde impacta córregos em Goiás, diz análise de órgão ambiental (translation: Rare earths: Serra Verde impacts streams in Goiás, according to environmental agency analysis), 4 May 2026. Available from: <https://apublica.org/2026/05/terras-raras-serra-verde-impacta-corregos-diz-orgao-ambiental/>

Australian Rare Earths Limited, 2026. Koppamurra Pre-Feasibility Study and Maiden Ore Reserve, ASX announcement, Australian Rare Earths Limited (AR3), 25 June 2026. Available from: <https://www.listcorp.com/asx/ar3/australian-rare-earths-limited/news/koppamurra-pre-feasibility-study-3369049.html>

Baskaran, G and Schwartz, M, 2024a. China Imposes its Most Stringent Critical Minerals Export Controls Yet, Center for Strategic and International Studies, Washington DC. Available from: <https://www.csis.org/analysis/china-imposes-its-most-stringent-critical-minerals-export-restrictions-yet-amidst>

Baskaran, G and Schwartz, M, 2024b. The Consequences of China's New Rare Earths Export Restrictions, Center for Strategic and International Studies, Washington DC. Available from: <https://www.csis.org/analysis/consequences-chinas-new-rare-earths-export-restrictions>

Brazilian Critical Minerals Limited (BCM), 2026. Ema Rare Earth Project Bankable Feasibility Study, ASX announcement, 30 June 2026. Available from: <https://braziliancriticalminerals.com/>

Burcher-Jones, C, Mkhize, S, Becker, M, Ram, R and Petersen, J, 2018. Study of the Deportment of REEs in Ion Adsorption Clays Towards the Development of an In Situ Leaching Strategy, University of Cape Town.

Chen, Z, Zhang, Z, Liu, D, Chi, X, Chen, W and Chi, R, 2020. Swelling of clay minerals during the leaching process of weathered crust elution-deposited rare earth ores by magnesium salts, *Powder Technology*, 367:889–900. https://doi.org/10.1016/j.powtec.2020.04.008

CSIRO, 2024. Supplementary report: rare earths, From minerals to materials: assessment of Australia's critical mineral mid-stream processing capabilities, CSIRO, Canberra.

Defense Metals Corp, 2025. Wicheeda Rare Earth Element Project Pre-Feasibility Study, news release, 18 February 2025. Available from: <https://www.prnewswire.com/news-releases/defense-metals---robust-economics-from-wicheeda-rare-earth-deposit-pfs-302378645.html>

Hastings Technology Metals Limited, 2026. Yangibana Stage 1 Updated Definitive Feasibility Study, ASX announcement, 13 July 2026. Available from: <https://www.miningweekly.com/article/updated-dfs-confirms-robust-economics-early-production-start-for-hastings-yangibana-rare-earths-project-2026-07-13>; 2022 DFS baseline available from: <https://announcements.asx.com.au/asxpdf/20220221/pdf/45655xc8x5wkj9.pdf>

Landry, D, 2025. Chinese mining investment globally: who, where and how?, *Resources Policy*, 111:105780. https://doi.org/10.1016/j.resourpol.2025.105780

Li, G and Yao, J, 2024. A Review of In Situ Leaching (ISL) for Uranium Mining, *Mining*, 4:120–148. https://doi.org/10.3390/mining4010009

MCRE Resources Sdn Bhd, 2023. Our Project. Available from: <https://mcreresources.com/>

Meteoric Resources NL, 2026. Caldeira Project Definitive Feasibility Study, ASX announcement, 31 July 2026.

Mkango Resources Ltd, 2026. Songwe Hill Updated Definitive Feasibility Study, news release, 19 March 2026. Available from: <https://mkango.ca/site/assets/files/5123/20260319_mkango_-_final_embargoed_press_release_v16_19_03_2026_1_1.pdf>

NextInsight, 2026. Southern Alliance Mining: This Company Turns to Rare Earth Mining in Malaysia for A Gush of Profit, 30 April 2026. Available from: <https://www.nextinsight.net/story-archive-mainmenu-60/949-2026/16681-southern-alliance-mining-this-company-turns-to-rare-earth-mining-in-malaysia-for-a-gush-of-profit>

Oaklins, 2025. Southern Alliance Mining acquisition of 40% stake in MCRE Resources, deal record. Available from: <https://www.oaklins.com/sg/en/deals/111348/>

Pensana PLC, 2025. Longonjo EPCM Contract Award and Updated Ore Reserve Estimate, 2025. Available from: <https://pensana.co.uk/wp-content/uploads/2025/04/EPCM-and-updated-Ore-Reserve-estimate-1.pdf>

Rare Earth Exchanges, 2026. Malaysia's Rare Earth Moment: SAM's Revenue Surge Signals a New Ionic Clay Challenger Outside China, 14 March 2026. Available from: <https://rareearthexchanges.com/news/malaysias-rare-earth-moment-sams-revenue-surge-signals-a-new-ionic-clay-challenger-outside-china/>

Serra Verde, 2024–2026. Company operations disclosures and third-party reporting on Pela Ema commercial production, 2024–2026. Available from: <https://www.serraverde.com/operations/>

South China Morning Post, 2021. China forms rare earths giant to protect its dominance in global output as market share falls, 23 December 2021. Available from: <https://www.scmp.com/business/commodities/article/3160794/china-forms-rare-earths-giant-bid-protect-its-global-dominance>

Southern Alliance Mining Ltd, 2026. Investor Presentation, March 2026. Available from: <https://investor.southernalliancemining.com/newsroom/>

US Geological Survey, 2025. Mineral Commodity Summaries 2025: Yttrium, Reston, VA. Available from: <https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-yttrium.pdf>

Wang, G, Xu, J, Ran, L, Zhu, R, Ling, B, Liang, X, Kang, S, Wang, Y, Wei, J and Ma, L, 2022. A green and efficient technology to recover rare earth elements from weathering crusts, *Nature Sustainability*, 6(1):81–92. https://doi.org/10.1038/s41893-022-00989-3

World Nuclear Association, 2026. In-Situ Leach Mining of Uranium, updated 20 January 2026. Available from: <https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium>

Xu, Z, Li, G, Yang, H, Sha, A, He, Z, Tang, Y, Wu, M and Qu, J, 2023. Development Review on Leaching Technology and Leaching Agents of Weathered Crust Elution-Deposited Rare Earth Ores, *Minerals*, 13(9):1223. https://doi.org/10.3390/min13091223

Yang, X J, Lin, A, Li, X-L, Wu, Y, Zhou, W and Chen, Z, 2013. China's ion-adsorption rare earth resources, mining consequences and preservation, *Environmental Development*, 8:131–136. https://doi.org/10.1016/j.envdev.2013.03.006

CSIRO graphite value chain capabilities

K Bunney[1] and J Loh[2]

1. Senior Research Scientist, CSIRO, Waterford WA 6152. Email: karl.bunney@csiro.au
2. Group Leader, CSIRO, Waterford WA 6152. Email: joanne.loh@csiro.au

ABSTRACT

Minerals and materials used in critical applications have more stringent physical and chemical requirements than standard bulk commodities. Graphite is on the critical minerals list of Australia, as well as geopolitically-aligned countries such as the UK, the USA, India, Japan, Korea and the EU due to its ubiquitous use as the anode in lithium-ion batteries. The value chain from graphite ore to battery anode is complex, with anode materials requiring high purities (>99.95 per cent), specific morphologies, and narrow particle size distributions. CSIRO, Australia's national science agency, has advanced scientific capabilities spanning the breadth of that chain; from ore characterisation to spheronisation, purification, and electrochemical cell testing. These links in the value chain contribute toward the supply of an electrifying critical mineral.

Pilot scale critical mineral processing

N Chapman[1] and A Grabsch[2]

1. Team Leader, CSIRO Minerals Resources, Bentley WA 6102. Email: nicole.chapman@csiro.au
2. Senior Experimental Scientist, CSIRO Minerals Resources, Bentley WA 6102. Email: alton.grabsch@csiro.au

ABSTRACT

CSIRO Minerals Resources supports the Critical Minerals sector through the development of advanced processes and flow sheets for refining and generating value-added products from partner feedstocks. These work programs typically begin with bench-scale testing to validate and optimise the proposed process, followed by piloting to demonstrate scalability and operability. CSIRO has a strong history of operating pilot plant projects, with throughputs ranging from tens to thousands of kilograms, with supporting capability in various unit processes that include leaching, solid:liquid separation, purification and downstream processing to generate high purity value-added products. Examples of recent pilot scale operations include:

- Nickel laterite leaching with nitric acid to produce MHP.
- Processing of a titanium vanadium ore to generate saleable products of titanium, vanadium and magnetite.
- Nickel purification to create battery grade nickel sulfate.
- Solvent extraction purification process to produce battery grade manganese.
- Graphite purification to produce battery grade material.
- A pCAM production pilot plant to support the development of Australian pCAM manufacturing.

These examples will highlight the need for pilot scale operations to demonstrate the feasibility of laboratory scale processes and de-risk at increased scale. For example, during the scale up of the nickel purification process several process issues emerged that were not identified during laboratory development. The team identified the causes, implemented operational changes, and resolved these issues during pilot plant operation. In one example, these process solutions were scaled up and incorporated into to a commercial production plant in Australia.

These pilot plants demonstrate CSIRO's capability to bridge the gap between laboratory research and commercial deployment. By identifying and resolving scale-up challenges, the operation of pilot plants helps de-risk new technologies, validate process robustness, and support the successful transition to full-scale operation for Australian and International partners.

Mine operations management – digitally connect mine production

K Chhabra[1] and S Rahangdale[2]

1. Industry Consultant Manager, Dassault Systèmes, Australia. Email: kriti.chhabra@3ds.com
2. Industry Consultant, Dassault Systèmes, Singapore. Email: sagar.rahangdale@3ds.com

ABSTRACT

Mining operations generate large volumes of production data; however, fragmented source systems, spreadsheet-based calculations and delayed material-movement capture can limit operational visibility and prolong reconciliation cycles. This paper presents the architecture, integration methodology and operational outcomes of implementing a Mine Operations Management (MOM) Material Tracking and Reconciliation solution at a large-scale, multi-commodity critical-minerals operation.

The solution was implemented as an operational system of record connecting data sources not limited to such as from survey, resource models, tactical schedules through APIs/database interfaces/file-based interfaces. It consolidated shift-level mining, material-movement, stockpile and mill-feed data within a unified operational data model. The implementation covered more than 35 stockpiles and applied standardised business rules for movement validation, stockpile mass balancing and mass-weighted multi-commodity grade calculations. Automated controls identified missing movements/duplicate records/out-of-range values/material-balance exceptions, while traceable adjustment and approval workflows supported reconciliation governance.

The reconciliation methodology calculated expected closing inventory from opening balances, receipts, transfers and consumption, with differences compared against (survey measurements/ source-system totals/approved production records). The solution was validated through parallel testing/historical-data replay/user-acceptance testing over 12 weeks using variance threshold as the acceptance criterion.

The case study demonstrates how a governed operational data model, standardised reconciliation logic and integration with existing mine systems can improve the timeliness, consistency and traceability of Mine to Mill production information. It also establishes a reliable data foundation for future advanced analytics, while distinguishing those future capabilities from the functionality validated in the current implementation.

COMMERCIAL IMPACT STATEMENT

Supervisors gained access to near-real-time stockpile levels, movement histories and production indicators across more than 35 stockpiles. A governed operational data model and traceable adjustment process improved consistency between departments, strengthened auditability and enabled earlier identification of production exceptions.

Unlocking secondary resources requires a new way of thinking

S Couperthwaite[1] and A B Carneiro[2]

1. Professor, Queensland University of Technology, Brisbane Qld 4001.
   Email: sara.couperthwaite@qut.edu.au
2. Research Fellow, Queensland University of Technology, Brisbane Qld 4001.
   Email: andreia.borgescarneiro@qut.edu.au

ABSTRACT

Renewable energy technologies and the global transition to net-zero emissions are driving unprecedented demand for critical minerals while simultaneously exposing vulnerabilities in global supply chains and domestic processing capabilities. Mine wastes represent a significant secondary resource, however, their low-grades, complex mineralogy and spatial variability present substantial technical and economic barriers to commercial-scale recovery. Analysis of 77 samples collected from a single mine waste dump demonstrates the considerable mineralogical and elemental heterogeneity that can exist within these secondary resources. Unlocking their value therefore requires a departure from conventional processing approaches developed for primary ores. Instead, flow sheets must be purpose-designed for heterogeneous secondary resources, targeting not only metal recovery but also the purity, consistency and material specifications required for critical mineral products. These processes must also be designed for the future operating environment of the minerals industry, where reagent availability, particularly sulfuric acid supply, may become increasingly constrained.

This work explores hydrochloric acid (HCl) as an alternative hydrometallurgical platform for recovering critical minerals from complex mine waste rocks. HCl offers several potential advantages, including chloride complexation to enhance metal extraction, opportunities for selective downstream purification, avoidance of sulfate-rich secondary wastes, and the potential to recover and recycle acid within a more circular process. These attributes are increasingly relevant as sulfuric acid supply faces growing pressure from competing industrial demand and changes to traditional sulfur supply associated with decarbonisation. Comparative leaching of two complex mine waste materials also demonstrated substantially higher recovery from a mine waste rock using HCl relative to H_2SO_4. For one mine waste rock sample, HCl achieved approximately 98 per cent Cu, 87 per cent Co and 72 per cent Mn recovery, while only 16 per cent Mn was achieved for H_2SO_4 with negligible amounts of Cu and Co recovered.

The opportunity, however, extends beyond extraction efficiency. Future critical-mineral projects must integrate reagent circularity, supply-chain resilience, environmental performance and sovereign capability into process design. Reprocessing mine wastes can simultaneously recover strategic resources, reduce long-term environmental liabilities and improve resource efficiency. Critical minerals are not bulk commodities, and their value cannot be assessed by tonnes and conventional economics alone. Unlocking secondary resources therefore requires a broader definition of value, one that recognises economic, environmental and strategic outcomes alongside metal recovery.

Impact of high sodium on separation and extraction performance in lithium brine processing

B Currie[1]

1. Principal, Betallurgy Consulting, Brisbane Qld 4000. Email: info@betallurgy.com

ABSTRACT

High-sodium brines, characteristic of many salar-hosted, geothermal, and oilfield lithium resources, impose fundamental limitations on conventional adsorption and membrane-based separation processes, as well as on electrodialysis (ED) and bipolar electrodialysis (BMED) systems. This work evaluates the mechanisms by which elevated sodium concentrations can reduce separation efficiency, increase operating costs, and constrain process design across direct lithium extraction (DLE) flow sheets. Elevated Na/Li ratios are also economically significant because they lower lithium yield per unit of brine processed, increase both energy and reagent demand, and complicate downstream purification, all of which materially worsen the cost of producing each tonne of high-purity lithium product.

In electrodialysis, sodium exerts a dominant influence on ion transport behaviour because its concentration is typically far greater than that of lithium. Migration through a cation-exchange membrane becomes competitive, as Na^+, with its different charge density, is preferentially carried by the electric current. This effect is compounded by the limited ion-specific permselectivity of standard membranes, which are highly effective at charge discrimination but exhibit only weak differentiation between similar monovalent cations such as Li^+ and Na^+. Consequently, lithium recovery efficiency declines, particularly in brines with high Na/Li ratios, where sodium effectively dictates flux rates.

Although high ionic strength can initially reduce solution resistance, overall energy consumption per unit of lithium recovered increases. This is driven by inefficient current utilisation, where much of the energy is spent transporting sodium towards the membrane interface rather than selectively recovering lithium. Scenarios with high Na/Li ratios therefore translate into greater electricity consumption, lower throughput, and the need for additional treatment stages to achieve a saleable product.

The challenges are further amplified in BMED systems, where high concentrations of sodium salts favour NaCl splitting and NaOH co-production rather than the desired generation of lithium hydroxide. This leads to mixed NaOH/LiOH streams, dilution of product value, and increased downstream purification complexity. Current efficiency losses are significant, as electrical input is consumed by non-target salt-splitting reactions rather than lithium-specific product formation. In economic terms, this raises the cost of separation, adds polishing and crystallisation requirements, and weakens the commercial advantage of BMED when Na/Li ratios are high.

Beyond ED and BMED, high sodium also impacts upstream and parallel membrane processes. Nanofiltration exhibits poor rejection of monovalent ions, limiting its effectiveness for Li/Na fractionation, while reverse osmosis performance is compromised by elevated osmotic pressures. While sodium itself is not a scaling species, its presence correlates with high total dissolved solids and the co-occurrence of divalent ions such as Ca^{2+}, Mg^{2+}, and SO_4^{2-}, which contribute to membrane fouling, scaling, and increased maintenance requirements. These effects further add to life cycle costs and can reduce plant availability.

In hybrid systems, high sodium can suppress lithium adsorption kinetics and compete for active sites, depending on sorbent selectivity. These limitations necessitate process adaptation. Viable strategies include the deployment of lithium-selective sorbents, the development of monovalent-selective or lithium-specific media, and the adoption of hybrid flow sheets where ED or BMED is applied for bulk salt management rather than primary lithium recovery. Pre-treatment to reduce competing ions and optimise brine chemistry is critical to maintaining system performance and improving economic viability.

Actual cases of sodium's impact on projects are usually framed as brine-chemistry or scale-up problems rather than as explicit 'Na/Li ratio failures'. Public sources show that high-salinity, sodium-

rich brines make DLE harder to commercialise, push up costs, and delay ramp-up, while project documents and technical reviews emphasise the Na/Li ratio as a key performance metric.

Global data were analysed across 67 research prospects, spanning nearly three orders of magnitude in Na/Li mass ratio, ranging from ~24 (Groß Schönebeck, Germany — a Rotliegend-hosted geothermal brine) to ~16 647 (Anadarko Basin, USA — a halite-dissolution oilfield brine). The findings indicate that geological provenance (lithology category) and basin type (enrichment/evaporation category) are the two main factors determining which domains are dominated by sodium interference and structurally disadvantaged for recovery.

Caucharí-Olaroz, Argentina, is a useful benchmark for cases where Na/Li is not itself the limiting factor. The operation initially ran below nameplate capacity before moving closer to full capacity, illustrating how brine projects often face commissioning and ramp-up challenges even when the chemistry is workable. Lake Resources' Kachi project in Argentina was delayed by six years, with cost expectations rising sharply, consistent with the broader challenge of making sodium-rich brines economic at scale. Salar de Uyuni's development in Bolivia has been described as a very large but chemically challenging salar, where DLE was intended to manage brine-chemistry complexity.

While several lithium brine projects have shown that sodium-rich chemistry can undermine project economics, in practice the issue is usually not sodium alone but the combined effects of difficult brine chemistry, lower lithium selectivity, fouling risk, and added purification costs, which together raise operating expenditure and slow ramp-up.

Overall, high sodium shifts the function of lithium processing flow sheets from straightforward selective separation technology to supporting unit operations focused on acid/base generation or salinity control. Recognition of the economic and technical penalties associated with high Na/Li ratios is essential for realistic technology selection, process optimisation, and economic evaluation of next-generation lithium brine developments.

Nano-bubbles effect on critical minerals flotation performance

M Dlame[1] and M Safari[2]

1. Senior Engineer, Flotation, Minerals Processing Division, Mintek, South Africa.
   Email: musad@mintek.co.za
2. Head, Flotation, Minerals Processing Division, Mintek, South Africa.
   Email: mehdis@mintek.co.za

ABSTRACT

Addressing the persistent challenge of fine particle flotation has been the subject of extensive research, focusing on various methodologies across different commodities at laboratory scales. While some progress has been made with proposed solutions, many remain impractical for large-scale commercial implementation due to technical complexities and economic constraints. One promising approach gaining momentum involves the use of nano-bubbles (NB) and pico-bubbles (PB), especially those generated through hydrodynamic cavitation techniques, to enhance fine particle flotation. Despite demonstrating improvements in fine particle flotation, previous studies have largely overlooked the influence of cavitation intensity on flotation performance, a factor crucial for managing operating costs. This study aimed to investigate the impact of hydrodynamic cavitation intensity on the froth flotation performance of Cu-Ni ore. Comparative analyses were performed at consistent time intervals rather than identical residence times through the cavitation device. The results revealed that below the cavitation threshold, the cavitation device functioned primarily as a static mixer. However, higher cavitation intensity significantly improved Cu-Ni recoveries at various recirculation time intervals. Both lower and intermediate intensity levels above the threshold achieved superior recoveries to the base case, albeit slightly below the highest intensity scenario.

Recovery of manganese as a critical mineral from aqueous structures

D Gabeva[1], R Halatchev[2] and A Halatchev[3]

1. Managing Director, AusGEMCO Pty Ltd, Brisbane Qld 4078. Email: deliana@ausgemco.com
2. Director Mining, AusGEMCO Pty Ltd, Brisbane Qld 4078. Email: ross@ausgemco.com
3. Secretary, AusGEMCO Pty Ltd, Brisbane Qld 4078. Email: angel@ausgemco.com

EXTENDED ABSTRACT

In this paper, we present an *in situ* recovery approach for manganese at lower costs from aqueous structures, with less environmental harm and energy use than conventional mining methods. The approach incorporates preliminary prediction of the manganese resources and reserves in the pre-feasibility and feasibility stages of the project. The paper touches upon some new concepts that may lead to the expansion of successful *in situ* projects of manganese and other critical minerals recovery, such as lithium, wolfram, copper, etc.

The focus of this study is on the numerical modelling predictions of manganese (Mn) recovery. A case study is provided based on a system containing injection/production and observation wells, and a 3D porous matrix of the reservoir. The Trial Site is located in an aquifer formed in the river terrace (Figure 1).

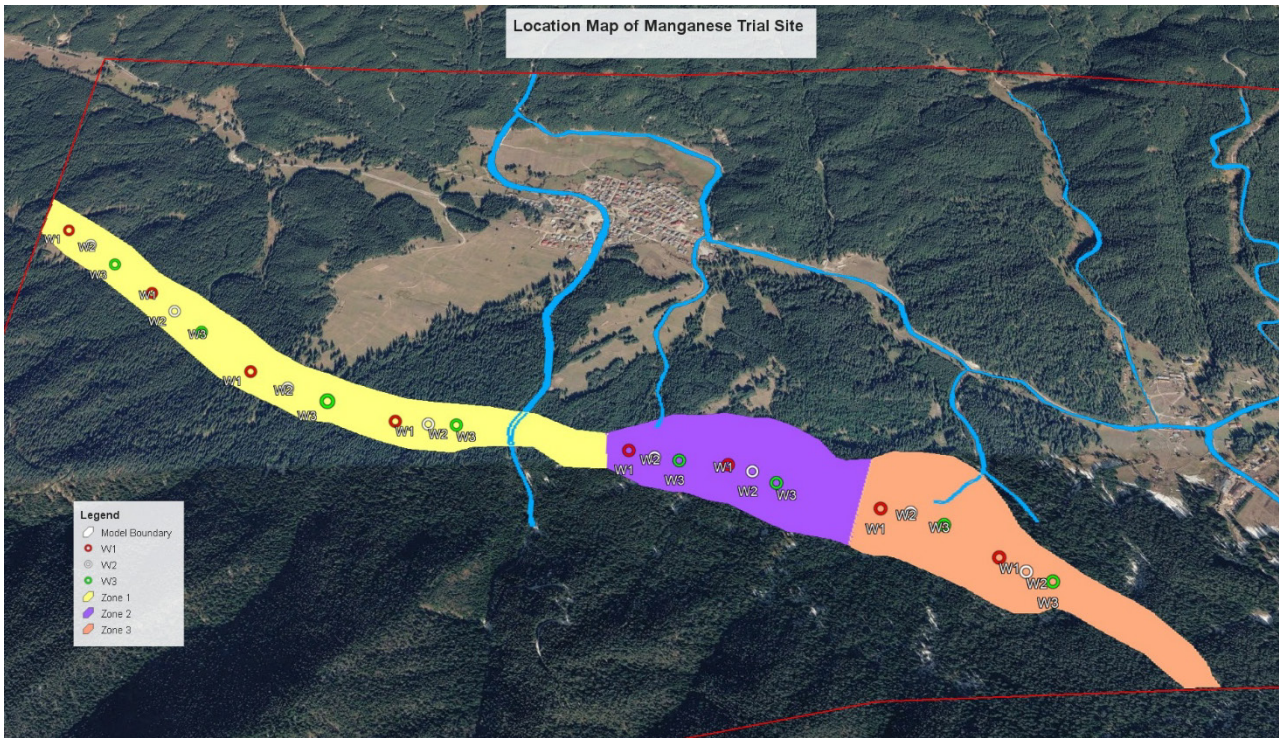


FIG 1 – Location map.

The experiment is carried out with an Extraction-Injection Well Doublet as shown in Figure 2, where W1 is the injection well; W2 is the monitoring borehole, and W3 is the extraction well. The monitoring borehole is located approximately in the middle between the injection and extraction wells. The extraction and injection wells form a dipole pair, and they are hydraulically connected and operate at the same flow rate.

The geological and lithological profile is illustrated in Figure 3 which depicts the geological units forming the structure of the Manganese Trial Site area. The basement is presented by Palaeozoic granites, weathered in its upper part and strong in depth. Regionally, the Palaeozoic granites are overlaid by sandstone. Granites are the lower aquitard underlying the sandstone unit. The sandstone is considered to form a single aquifer unit. The manganese orebody is located in the middle of the sandstone unit. The sandy-gravel sediments overlay the sandstone unit.

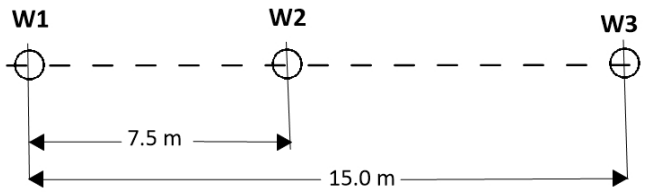


FIG 2 – A plan view of the Well Doublet experiment.

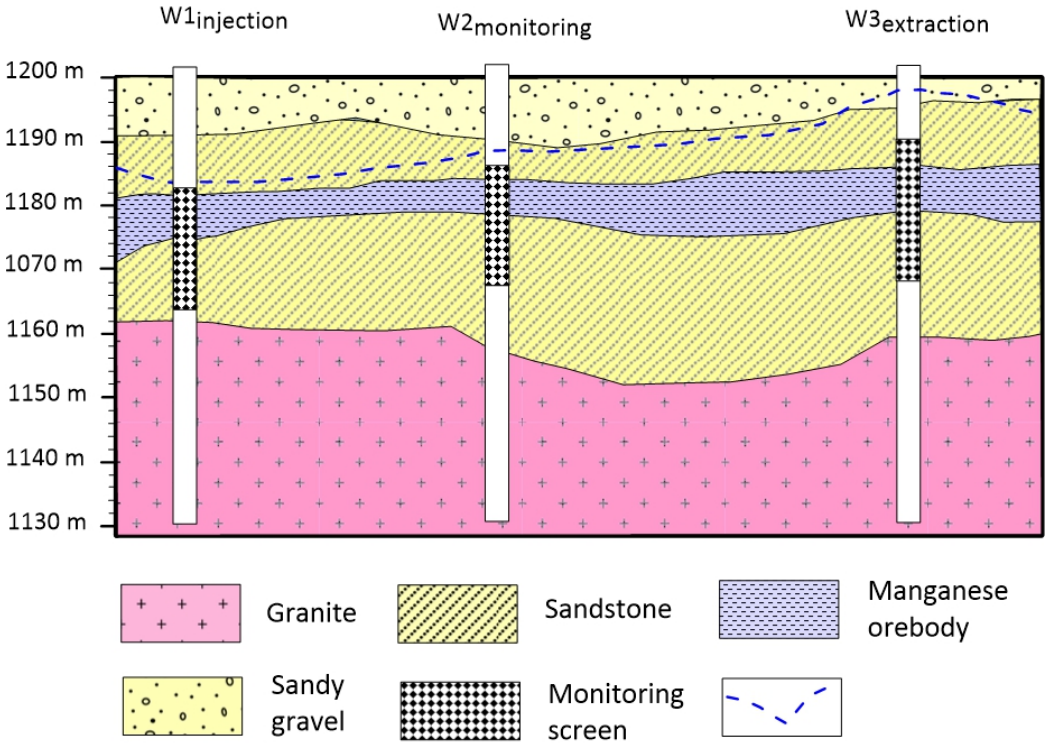


FIG 3 – Schematic presentation of the experiment cross-section.

The primary groundwater-bearing unit (aquifer) is the sandstone. The average thickness of the sandstone aquifer is 32 m. The average hydraulic conductivity of the sandstone aquifer hosting the Mn deposit is 0.36 m/h.

The static resources of the aquifer comprising the manganese orebody represent the total volume of water contained in the aquifer pore space. The dynamic resources of the aquifer covering the manganese orebody represent the groundwater flow that flows through the aquifer and is drained from the river.

Four numerical models are developed to predict the Mn mass transport and maximum manganese extraction: a simple dispersion model (SDM), a convective diffusion model (CDM), a dispersion elimination model (DEM), and a dispersion diffusion model (DDM). The numerical models represent the best tools for prediction of brine composition, freshwater intrusions and well field design. The major advantage of the numerical models is their capability to estimate the heterogeneous geologic setting, simulate density-driven flow, and define the optimal production schedule under different scenarios (Braun *et al,* 2016).

The output results of the model's execution are shown in Table 1. After comparing the results with the SSD criterion and the Correlation Coefficient, it can be found that the DDM model most adequately describes the migration process of manganese.

TABLE 1

Migration parameters of mass transport for Manganese Extraction-Injection Well Doublet.

Model	n_s	γ	D	B_d	PG	PE	SSD	R
	-	h^{-1}	m^2/h	$h^{-½}$	-	-	h	-
Simple Dispersion Model (SDM)	0.00300	0.00000	1.28506	0.00000	0.00000	2.10108	1.04536e-003	0.99591
Convective Diffusion Model (CDM)	2.05401	0.00000	0.00000	0.04121	0.00000	0.00000	9.34055e-006	0.99996
Dispersion Elimination Model (DEM)	1.08328	0.98381	1.29509	0.00000	1.08989	2.08480	9.27012e-006	0.99996
Dispersion Diffusion Model (DDM)	2.13130	0.00000	1.91868	0.03782	0.00000	1.40722	0.00000	1.00000

The definition of the parameters in Table 1 is as follows:

- n_s parameter characterising the sorption capacity of the medium in relation to a specific component (manganese)
- γ parameter characterising the irreversible elimination of a substance from the filtration solution due to radioactive or hydrolytic decay processes
- D parameter that connects the molecular diffusion coefficient in a porous medium and the filtration rate
- B_d complex parameter characterising the intensity of diffusion removal of a substance from the filtration solution from the aquitard
- PG elimination criterion
- PE dispersion criterion
- SSD sum of the squares of the deviations
- R correlation coefficient

Taking into account the hydrogeologic character and properties of the brine-hosted Mn deposit, as well as the well field design parameters, the volume of brine that can be extracted from such a deposit is simulated using a numerical groundwater flow and mass transport model.

The estimation of the Mn resource and recovery is performed in accordance with the JORC Code requirements (JORC, 2012, 2026). It is based on the performance of eight Extraction-Injection Well Doublets for a period of time of ten days. The sandstone aquifer hosted Mn deposit is heterogeneous, and it is divided into three zones with specific hydraulic conductivity and dimensions. The estimation of the resource for each zone is achieved by using the parameters: aquifer zone volume, effective porosity, and manganese concentration. The JORC classification for measured, indicated and inferred resources is developed based on the hydrogeological numerical model.

The results obtained show that the developed approach enables conversion of the resource into reserves, supporting the economic extraction of manganese. The final results are provided in the poster presentation of the Critical Minerals Conference.

REFERENCES

Braun, T, Cortegoso, P, Pereira, C and Ugorets, V, 2016. Interpretation and application of hydrogeological concepts to commercial-scale brine extraction projects, in *Proceedings of the 5th International Congress on Water Management in Mining,* pp 1–10 (Gecamin: Santiago).

JORC, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code) [online]. Available from: <http://www.jorc.org> (The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia).

The JORC Code Update – March 2026. https://www.jorc.org/code-update.

Electrolysis-based conversion for sustainable lithium refining

L Glynn[1], C Brereton[2], K Wilting[3] and J Moulson[4]

1. Technical Manager Europe, NORAM Electrolysis Systems Inc, Vancouver BC V6C 1S4, Canada. Email: lglynn@nesi.tech
2. CTO, NORAM Electrolysis Systems Inc, Vancouver BC V6C 1S4, Canada. Email: cbrereton@nesi.tech
3. Process Engineer, NORAM Electrolysis Systems Inc, Vancouver BC V6C 1S4, Canada. Email: kwilting@nesi.tech
4. President and CEO, NORAM Electrolysis Systems Inc, Vancouver BC V6C 1S4, Canada. Email: jmoulson@nesi.tech

ABSTRACT

Conventional lithium refining from hard rock sources, such as spodumene, is chemically intensive and produces significant waste. The commonly used process requires large quantities of sulfuric acid, soda ash, lime and caustic soda, while generating substantial volumes of low-value sodium sulfate effluent, which is increasingly challenging and costly to manage and dispose of. As global demand for lithium continues to grow, especially for applications in electric vehicles and energy storage, there is a need for more sustainable yet economically viable refining alternatives.

Electrolysis-based lithium refining for hard rock sources offers a solution that effectively addresses the key challenges of incumbent processes. In this approach, the process begins with the same sulfuric acid sulfation step as in conventional refining to produce a lithium sulfate intermediate. However, instead of proceeding to the reagent-heavy chemical conversion step, which typically involves large amounts of soda ash or caustic soda, the lithium sulfate solution is instead directed to an electrolysis step. This step directly converts the lithium sulfate solution to an ultra-pure lithium hydroxide solution, which can be further processed into battery-grade lithium hydroxide or carbonate. Importantly, this step eliminates the co-generation of sodium sulfate waste.

In addition to reducing the amount of chemicals consumed, electrolysis generates sulfuric acid as a byproduct. The sulfuric acid can be recycled back into upstream acid roasting and leaching operations, further decreasing the consumption of external reagents and offering a more sustainable, circular solution for lithium refining.

This paper will primarily focus on the flow sheet integration, technological maturity and economics of electrolysis for the production of battery-grade lithium products from hard rock sources, benchmarking against conventional and other emerging technologies. It will describe two different electrolysis approaches, two and three compartment cells, either of which may be the more appropriate depending upon other technologies being used in the plant.

INTRODUCTION

The rapid global transition toward electrification and renewable energy systems has significantly increased the demand for lithium, a critical raw material for lithium-ion batteries used in electric vehicles, grid-scale energy storage, and portable electronic devices. Global lithium consumption is expected to continue rising over the coming decades as governments and industries pursue ambitious decarbonisation targets. While the expansion of lithium mining has received considerable attention, the downstream refining of lithium concentrates into battery-grade chemicals remains a major technological and environmental challenge. Conventional refining routes are energy-intensive, consume large quantities of chemical reagents, and generate substantial waste streams, undermining the sustainability of the lithium value chain.

Hard rock lithium deposits, primarily composed of spodumene ($LiAlSi_2O_6$), represent one of the most important sources of lithium supply worldwide. Spodumene must undergo a series of physical, thermal, and chemical processing stages before high-purity lithium chemicals suitable for battery applications can be produced. Although these processes are well established commercially, conventional flow sheets call for significant reagent consumption and generate large quantities of sodium sulfate waste. Disposal of this sodium sulfate is increasingly problematic.

The increasing emphasis on sustainable manufacturing has stimulated interest in alternative lithium refining technologies that reduce environmental impacts while maintaining high lithium recovery and product purity. Among these emerging approaches, electrolysis-based conversion has attracted growing attention as a promising pathway for lithium refining. While electrolysis can be adopted for refining lithium from a wide range of sources – hard rock ores, brines, end-of-life lithium-ion batteries etc, this paper focuses on the application of electrolysis technologies in processing of hard rock lithium feedstocks.

CONVENTIONAL LITHIUM REFINING AND THE ROLE OF ELECTROLYSIS

Australia is the leading producer of hard rock lithium, contributing a significant portion of the global supply through large-scale open pit mining operations. Hard rock extraction involves mining, crushing, and concentration of spodumene ore, followed by thermal conversion and chemical processing to produce lithium hydroxide or carbonate. Although generally more energy-intensive and costly than brine extraction, hard rock operations offer faster project development timelines, greater production flexibility, and geographic diversification – key factors that have driven their rapid growth in recent years.

Spodumene concentrate produced in Australia, typically containing around 6 per cent lithium oxide (Li_2O), is traditionally shipped to Chinese refineries for further processing and conversion into battery-grade lithium chemicals such as lithium hydroxide and lithium carbonate, with limited success onshoring downstream refining operations within Australia. These refineries typically convert the spodumene concentrate to lithium carbonate through a chemically intensive process which generates significant waste.

Figure 1 presents a process flow sheet for conventional spodumene refining, incorporating both carbonate and hydroxide production. Following calcination at around 1000°C to transform the α-spodumene into the more reactive β-phase, the material is then roasted with sulfuric acid, producing lithium sulfate. This is then leached, filtered, and purified to remove impurities such as iron, magnesium, and calcium. For lithium carbonate production, the purified lithium sulfate solution is reacted with sodium carbonate, precipitating lithium carbonate and generating a sodium sulfate by-product. To produce lithium hydroxide, which is preferred for high-nickel cathode battery chemistries, the lithium carbonate can undergo further conversion through reaction with calcium hydroxide (lime), producing lithium hydroxide and calcium carbonate as a by-product. Alternatively, as also shown in Figure 1, lithium hydroxide can be produced directly by reacting purified lithium sulfate with sodium hydroxide, eliminating the carbonate intermediate, but also producing sodium sulfate as a by-product.

Although well established, conventional lithium hydroxide production routes are characterised by intensive reagent requirements and the generation of substantial quantities of secondary products, which can complicate waste management and reduce overall process sustainability. Other emerging production routes, including alkaline leaching processes, also typically have reagent consumption and produce substantial amounts of waste. Electrochemical approaches have consequently attracted interest as alternative technologies capable of enabling lithium hydroxide production with reduced chemical inputs and fewer waste streams.

Electrolysis can be integrated into spodumene concentrate refining downstream of acid roasting and leaching, where lithium is present in solution as lithium sulfate. At this stage, electrochemical processes can be employed to convert the lithium sulfate solution into lithium hydroxide while simultaneously regenerating sulfuric acid for reuse in the roasting and refining circuits. This integration has the potential to reduce reagent consumption, minimise waste generation, and simplify downstream processing, offering both economic and environmental benefits compared with conventional chemical conversion routes.

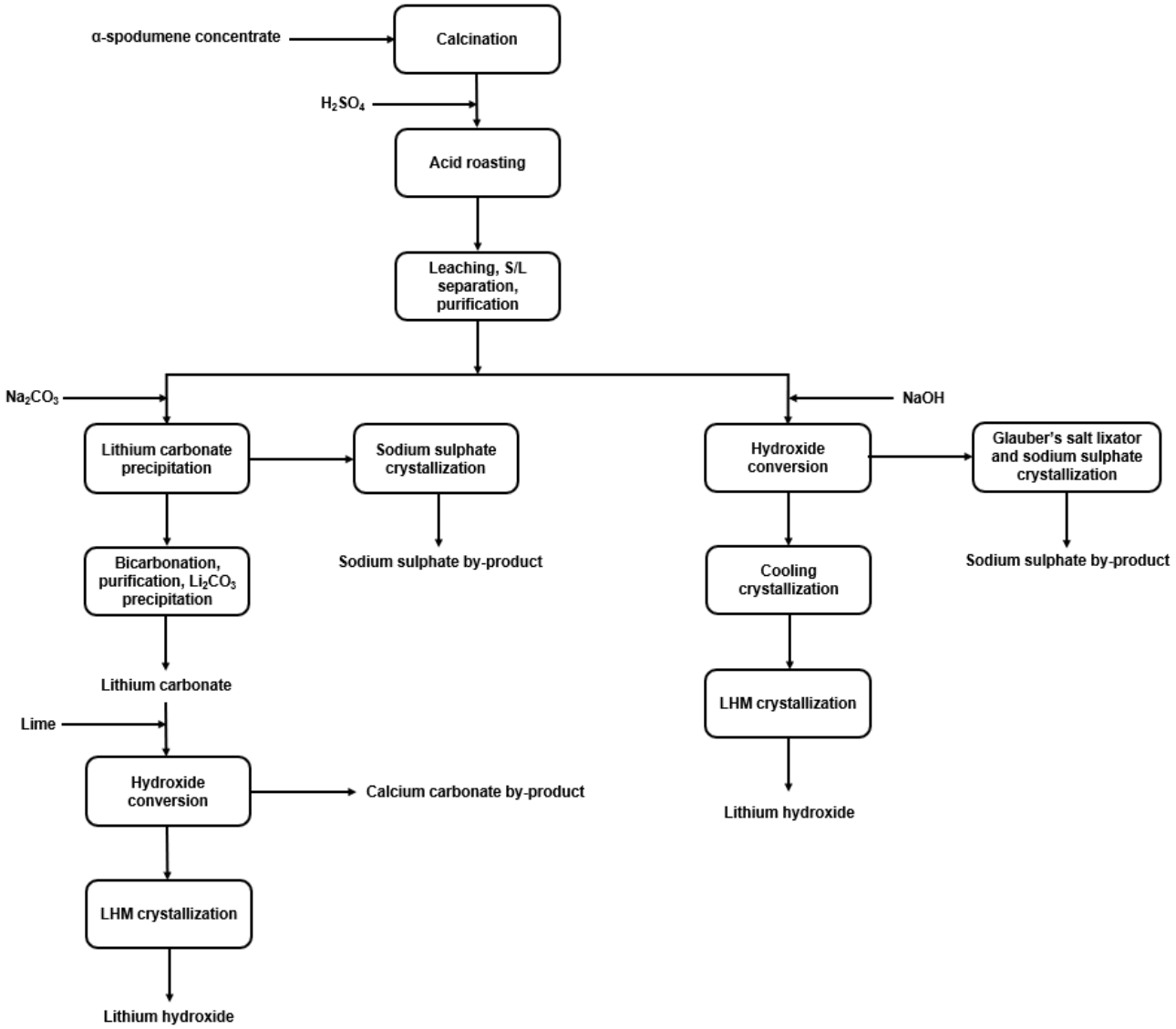


FIG 1 – Conventional spodumene refining flow sheet for carbonate and hydroxide production.

ELECTROLYSIS-BASED LITHIUM REFINING PROCESS OVERVIEW

One of the major ways in which electrolysis can be incorporated into lithium refining is salt splitting. This is the conversion of neutral salts into acids and bases. It is valuable when both acids and bases are used as part of a refining process and become combined as a neutral salt which needs to be disposed of. Salt splitting avoids the disposal, and the purchase of new reagents.

Salt electrolysers may come in many forms but among the most common are 'two-compartment' and 'three-compartment' systems. These differ primarily in the composition of the acid which is produced. The two-compartment electrolyser produces an acid which still contains significant lithium sulfate. The three-compartment electrolyser produces an almost pure acid. Both types of electrolysers can be incorporated into spodumene refining flow sheets and examples of their incorporation are shown in Figures 2 and 3, respectively.

Figures 2 and 3 follow the conventional spodumene refining process up to the production of a partially purified lithium sulfate solution. For electrolysis, however, additional purification of this solution may be required compared with conventional processing. The electrolysers contain ion exchange membranes and electrodes with mixed metal oxide coatings which are subject to fouling, and feed solution purity is critical to long-term performance. Purity influences current efficiency, cell voltage, and the lifetimes of membranes and electrodes. Impurities such as alkaline earth metals (eg magnesium and calcium), silica, iron, aluminium and organic species must therefore be reduced to lower concentrations than would be required in conventional processing to promote long

membrane and electrode life. The required purity can be achieved through established brine pretreatment approaches adopted by the chlor-alkali and similar industries, employing steps such as precipitation reactions, filtration, and ion exchange. Although these are used already to some degree as part of conventional spodumene refining, additional purification steps are needed ahead of electrolysis. One benefit of this is that improved upstream purification produces a high-purity lithium hydroxide solution that requires little downstream purification. In contrast, conventional chemical conversion routes typically require more extensive downstream purification to achieve battery-grade lithium products.

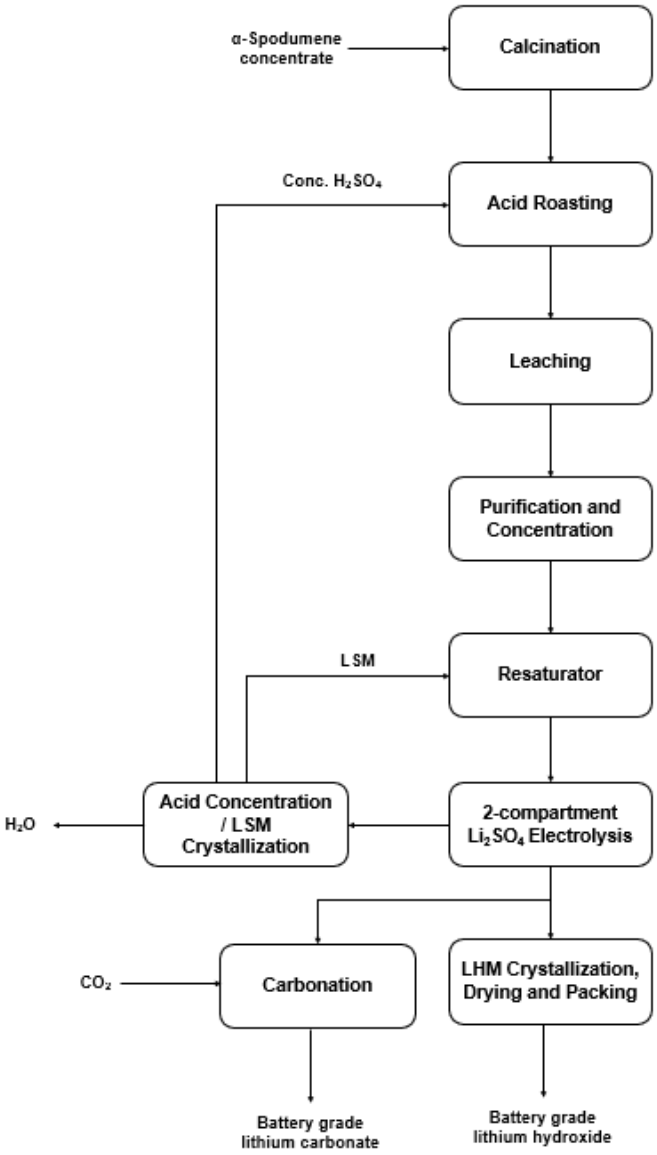


FIG 2 – Two-compartment electrolysis flow sheet.

Figures 2 and 3 show the principal differences between the flow sheets based on two and three compartment electrolysis. The two-compartment electrolysis produces a sulfuric acid – lithium sulfate mixture, and there are normally additional separation steps needed before the acid can be recycled for use. This is the price of a simpler electrolysis system. In both systems the electrolyser is fed with brine which is close to saturation. In the two-compartment flow sheet, before entering electrolysis a weaker purified lithium sulfate solution is fortified with recycled lithium sulfate monohydrate from a depleted anolyte lithium sulfate monohydrate (LSM) crystalliser. The brine, close to saturation in lithium sulfate, then enters the anolyte circuit of the two-compartment electrolyser. With the three-compartment electrolyser the acid – salt separation occurs in the electrolyser itself, and this separation and recycle loop are unnecessary. The cell configurations are illustrated in Figures 4 and 5.

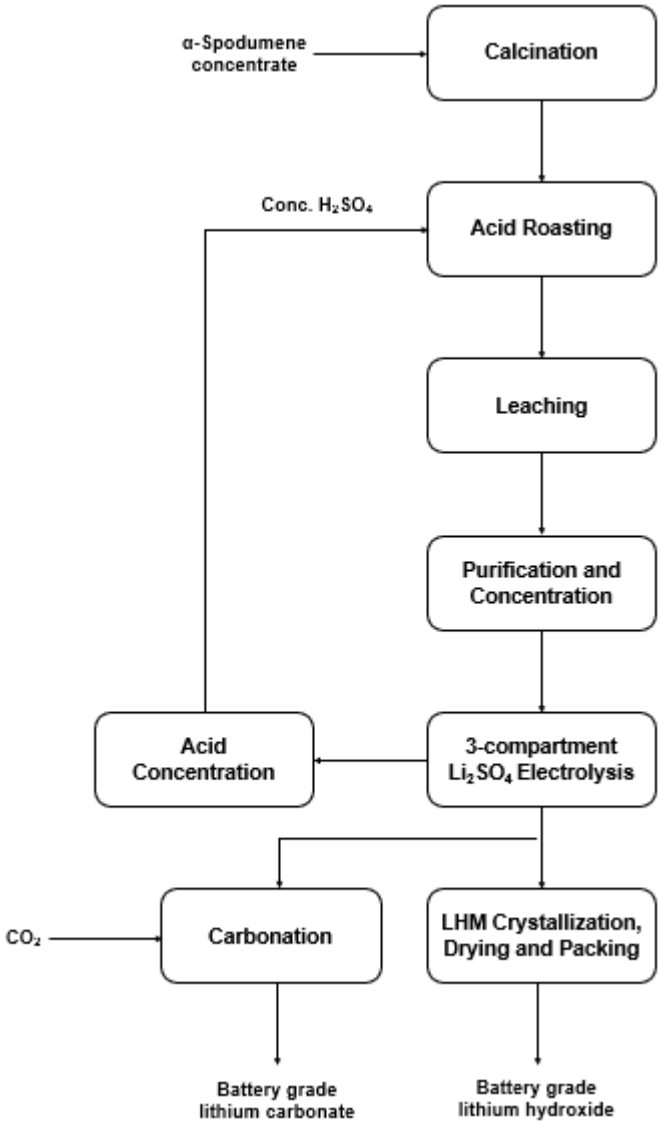


FIG 3 – Three-compartment electrolysis flow sheet.

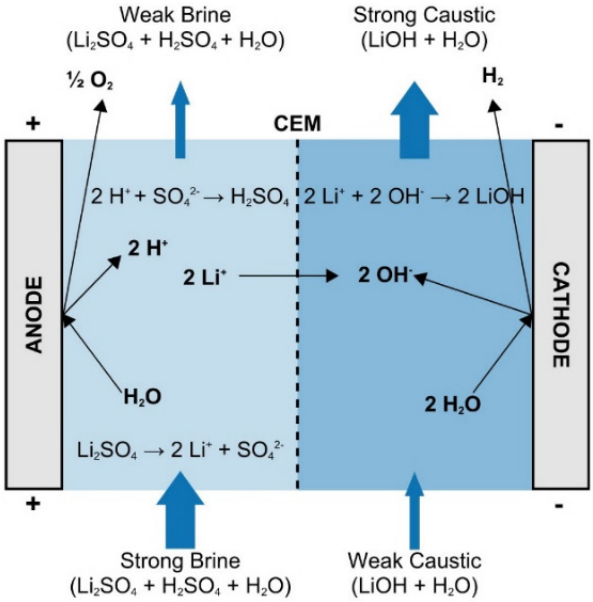


FIG 4 – Two-compartment lithium sulfate electrolysis.

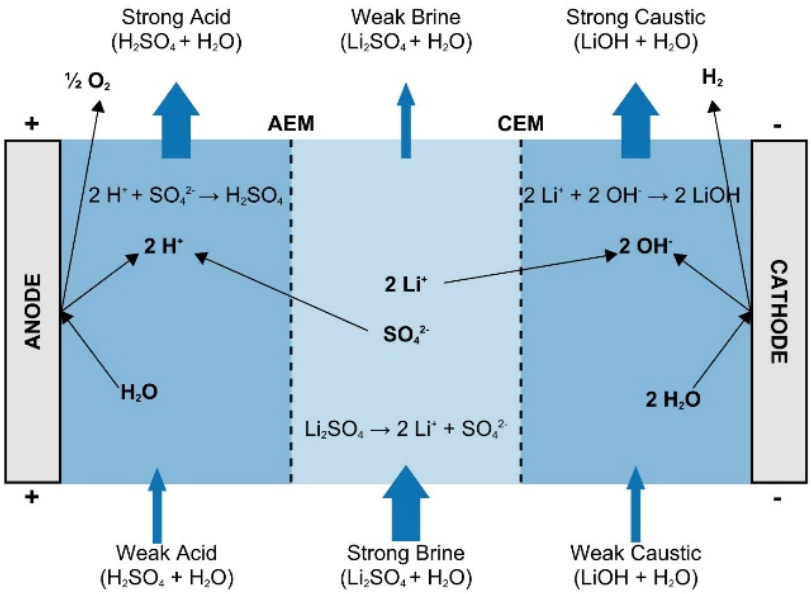


FIG 5 – Three-compartment lithium sulfate electrolysis.

Although the cell designs differ between two and three compartment cells, the overall chemical reaction is the same in both configurations and is described by:

$$Li_2SO_4 + 3\,H_2O \rightarrow 2\,LiOH + H_2SO_4 + H_2 + ½\,O_2$$

The electrochemical reactions are the reduction of water at the cathode and the oxidation of water at the anode. Excluding the non-reactive lithium and sulfate species, the half-cell reactions are:

At the cathode: $$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$$

At the anode: $$H_2O \rightarrow ½\,O_2 + 2\,H^+ + 2\,e^-$$

Both cell configurations generate a high purity lithium hydroxide solution, up to approximately 7 wt per cent, suitable for crystallisation to produce battery grade lithium hydroxide, or for carbonation to produce battery grade lithium carbonate. Current efficiency is a strong function of caustic concentration, making the selection of the optimum operating concentration a critical design consideration. While lower caustic concentrations generally improve current efficiency, the resulting increase in downstream evaporation requirements can offset these gains, necessitating optimisation at the broader integrated process level.

In the three-compartment cell, the feed brine is introduced to the central compartment and is separated from the anolyte and catholyte compartments by an anion exchange membrane (AEM) and a cation exchange membrane (CEM) respectively. The presence of the AEM separates the lithium containing feed from the acid product, allowing production of a pure sulfuric acid within the cell, up to 10 wt per cent with current AEM technology. Operation at higher acid concentrations results in a significant reduction in current efficiency which typically outweighs the reduced cost of evaporation. In some cases, it may be preferable to operate at eg 5 wt per cent acid to exploit the improved current efficiency at lower acid strength. While the acid can be used directly in certain applications, concentration is often required when it is intended for recycle into upstream process operations or for sale into commercial markets.

By comparison, the three-compartment cell is not intended to, and does not produce a low lithium acid; the anolyte product is a mixture of sulfuric acid and lithium sulfate (lithium bisulfate). It is normal to describe the operation of the anode side of a two-compartment salt splitting cell by the ‘conversion,’ which is defined as the fraction of the sulfate in the product associated with acid, compared to the fraction still in the lithium form. Depending on the cell design and expected current efficiency, a significant conversion, or ‘depletion’ is possible, up to approximately 50 per cent.

There are many applications where the acidic lithium sulfate product from two-compartment electrolysis can be recycled to upstream processes without the need for additional processing.

Examples are stripping of solvent extraction streams, ion exchange and DLE media regenerations (**D**irect **L**ithium **E**xtraction), and simple neutralisations. However, for many flow sheets, lithium will need to be rejected from the solution and the acid concentration increased. This is typically the case for integrating electrolysis into spodumene concentrate processing, where there is a requirement for concentrated acid for efficient operation of the acid roasting stage. In these cases, two-compartment electrolysis can be coupled with evaporation to remove water and crystallisation to reject lithium, which can be recycled to the electrolysis feed. Through a combination of evaporative and crystallisation techniques, a 95 wt per cent acid can be obtained, and the lithium can be recycled upstream of electrolysis. It is recycled as a mixture which is primarily lithium sulfate monohydrate but may contain some lithium bisulfate.

BENEFITS OF ELECTROLYSIS-BASED LITHIUM REFINING

One of the key advantages of electrochemical conversion to lithium hydroxide is that it eliminates the generation of sodium sulfate as a by-product. In conventional spodumene refining, approximately two tonnes of sodium sulfate (dry anhydrous basis) are produced for every tonne of lithium hydroxide monohydrate. Sodium sulfate has limited commercial value, with demand largely confined to mature markets such as detergents, paper pulping, and glass manufacturing. These markets are relatively small and already well supplied. This challenge is likely to persist, as significant quantities of sodium sulfate are also generated elsewhere in the battery materials value chain, particularly during precursor cathode active material (pCAM) production and black mass recycling.

Sodium sulfate is challenging to manage because to its high solubility, which allows it to leach into groundwater and disrupt local ecosystems if not properly contained. Improper disposal can lead to soil salinisation and harm aquatic life, raising serious environmental concerns. Regulations regarding sulfate emissions are becoming increasingly stringent, which results in higher costs associated with treatment and disposal of sodium sulfate effluent. In some cases, inadequate sodium sulfate management has delayed project development. For example, in 2024, a Finnish court halted the commissioning of BASF's battery materials plant in Harjavalta after its environmental permit was challenged over plans to discharge treated wastewater containing sodium sulfate into a nearby river (Blois, 2024).

Electrochemical lithium conversion also has the potential to produce higher-purity battery-grade lithium hydroxide than conventional chemical conversion routes without the need for significant product purification. In the conventional spodumene refining process, impurities can be introduced through the addition of reagents such as soda ash, lime, and sodium hydroxide, while incomplete removal of sodium, calcium, sulfate, and other residual ions during conversion often necessitates multiple purification and washing steps to meet battery-grade specifications. In contrast, the stringent feed purification required to protect ion-exchange membranes and electrodes for electrolysis also results in an exceptionally pure lithium hydroxide solution post-electrolysis. As discussed above, trace impurities such as calcium, magnesium, iron, aluminium, and other anions and multivalent cations must be removed upstream to prevent membrane and electrode fouling and corrosion. Consequently, the lithium hydroxide solution exiting the electrolyser contains very low concentrations of impurities, reducing the burden on downstream purification. Battery-grade lithium hydroxide can typically be produced following only two stages of crystallisation, compared with the multiple purification, washing, and recrystallisation steps often required in conventional chemical conversion processes. An example product specification for electrolysis derived lithium hydroxide monohydrate (LHM) is shown in Table 1.

The lithium hydroxide product is benchmarked against the GB/T 26008–2020 D1 battery-grade lithium hydroxide monohydrate standard (Standardization Administration of China, 2020). This is one of the most widely referenced public specifications for battery-grade LHM, particularly within the Chinese lithium-ion battery supply chain and provides a recognised benchmark for evaluating product quality and impurity levels. D1 grade is the highest grade specified by the standard.

TABLE 1

Comparison of electrolysis-derived LHM specification with GB/T 26008–2020 D1.

Product	GB/T 26008–2020 D1 battery-grade LHM	Electrolysis-derived LHM (example)
LiOH, wt%	56.5	57.5
Ca, mg/kg	< 20	< 1
Na, mg/kg	< 50	< 20
K, mg/kg	< 30	< 10
Mg, mg/kg	< 10	< 1
Fe, mg/kg	< 7	< 5
Al, mg/kg	-	< 1
CO_3^{2-}, wt%	< 0.4	< 0.1
Cl, mg/kg	< 20	< 10
SO_4^{2-}, mg/kg	< 80	< 50
Cr, mg/kg	-	< 1
Cu, mg/kg	< 1	< 1
Ni, mg/kg	-	< 1
Si, mg/kg	< 50	< 10
Zn, mg/kg	-	< 1

Electrolysis also offers significant advantages for improving the sustainability of lithium production by reducing reliance on chemical reagents and enhancing process circularity. Where conventional extraction and refining methods require large quantities of acids, alkalis, or precipitation agents and rely on a sequence of thermodynamically favourable reactions, electrochemical processes use electricity to drive reactions which are thermodynamically unfavourable. This substantially decreases the consumption of external reagents, reducing the environmental and cost burdens associated with reagent production, purification, packaging, transportation, storage, and handling, while also minimising the generation of reagent-derived waste streams. Furthermore, electrolysis enables the regeneration and reuse of electrolytes and process streams, facilitating closed-loop operation and improving resource efficiency. As electricity from renewable sources becomes increasingly available, lithium electrolysis also presents an opportunity to decarbonise lithium production while reducing dependence on finite chemical inputs.

This approach aligns with the zero-carbon lithium production strategy being developed by Vulcan Energy Resources through its Lionheart Project in Germany, where electrochemical processing forms a key element of an integrated lithium and renewable energy production strategy. By combining direct lithium extraction, renewable geothermal energy, and electrochemical conversion, the project aims to minimise the carbon intensity associated with lithium production and demonstrate a more resource-efficient pathway for battery-grade lithium production.

Furthermore, as discussed in a later section, electrolysis-based lithium refining represents a potentially cost-competitive approach, with the potential to reduce both capital and operating expenditure relative to conventional refining processes and other emerging technologies.

APPLICATION OF ELECTROLYSIS-BASED LITHIUM REFINING – A CASE STUDY

In 2017, Nemaska Lithium commissioned its Phase 1 Plant (P1P) in Shawinigan, Quebec, to produce lithium hydroxide from spodumene concentrate. The lithium conversion process was centred on a

two-compartment electrolysis system employing NESI's NORSCAND® electrolyser and was designed for continuous operation at a nominal production capacity of 500 t/a (tonnes per annum) of LHM expandable to 800 t/a. The plant was built around a platform of commercial electrochemical cells to give absolute confidence that there would be no additional scale-up risk on proceeding to commercial operation.

Spodumene concentration by flotation and calcining of the concentrate to produce spodumene was conducted off-site. The overall plant flow sheet at the Shawinigan site comprised the following key unit operations:

- acid bake pug mixer and kiln
- leach reactor
- primary, secondary, and tertiary impurity removal
- ion exchange
- electrolysis
- crude and pure LHM crystalliser
- LHM dryer.

The acid regeneration and recycle circuit represented the only significant component of the overall flow sheet that was not included in the P1P demonstration plant. Instead, spent anolyte from electrolysis was recycled back to the primary impurity removal stage where it was neutralised. However extensive laboratory and pilot scale test work was conducted, in collaboration with experienced technology suppliers, to validate the acid concentration stages.

The P1P plant operated for a number of years and successfully processed a range of feedstocks, including synthetic brine, spodumene concentrate and recycled lithium sulfate salts, to produce battery grade lithium hydroxide product. The demonstration plant achieved its primary objectives of repeatedly producing battery-grade lithium hydroxide to customer specifications, qualifying the products with potential customers, and generating operational learnings to optimise the process and inform the design of the commercial-scale facility.

NESI have since deployed similar scale demonstration plants using the NORSCAND® electrolyser for both lithium sulfate and lithium chloride electrolysis at client sites globally. These systems have been implemented across diverse lithium value chain applications, including hard rock operations, brine processing, midstream refining, and end-of-life battery recycling facilities. For its own development programs, NESI operates two demonstration plants using commercial electrolysers at its Richmond, British Columbia headquarters, including the recently commissioned Lithium Electrolysis Validation Plant. These commercial scale units couple with multiple laboratory-scale skidded units and prototypes dedicated to long-term performance testing, process optimisation, and technology validation. Figures 6 and 7 show example lithium electrolysis plants deployed at Nemaska Lithium and Vulcan Energy respectively. Following successful demonstration of the technology, NESI has also been awarded a contract by Vulcan Energy for the deployment of a commercial-scale lithium electrolysis plant at its Zero Carbon Lithium™ Project in Germany. This represents a significant step in the commercialisation of lithium electrolysis technology.



FIG 6 – Nemaska Lithium's P1P Electrochemical Plant, Shawinigan PQ.



FIG 7 – Vulcan Energy's Central Lithium Electrolysis Optimisation Plant (CLEOP), Industriepark Höchst, Frankfurt.

ECONOMIC ASSESSMENT

The economic viability of lithium refining technologies is governed by both technology-specific process costs and the overall economics of the integrated refinery. Accordingly, this section presents information at both levels.

Cellhouse costs – two- versus three-compartment electrolysis

Table 2 presents the estimated capital and operating costs for representative lithium sulfate cellhouses employing two- and three-compartment electrochemical cell configurations.

TABLE 2

Two- versus three-compartment cellhouse Capex and Opex comparison.

Parameter	3-Compartment	2-Compartment
Capacity / t/a LHM	25 000	
Current density / A/m^2	2000	4000
Cellhouse LiOH concentration / wt% LiOH	4.6	4.6
Anolyte/acid product concentration	5 wt% H_2SO_4	20% depletion[1]
Anode/membrane service interval / years	6	4
Relative Cell area	1.6	1
Electrolysis specific energy consumption / kWh/kg LHM	5.4	4.6
Total installed cellhouse capital intensity / US$/t/a LHM	3400	2000
Total cellhouse operating costs / US$/t LHM[2,3]	700	520
• Utilities, raw materials and consumables	50	30
• Power	520	370
• Cell maintenance costs	90	80
• Labour	40	40

1. Approximately 20 wt per cent Li_2SO_4, 4.5 wt per cent H_2SO_4; 2. Based on a power cost of 0.08 $/kw.hr; 3. Excluded from this estimate are costs which can be ascribed any upstream concentration/purification, and any product concentration outside of the cellhouse.

When comparing the capital cost of two- and three-compartment electrolysis cellhouses, the principal cost drivers are the required installed cell area, and to a lesser extent, cell complexity and balance-of-plant requirements. Three-compartment electrolysers typically operate at lower current densities than two-compartment designs. The addition of the anion exchange membrane restricts practical operation to current densities in the range 2000–3000 A/m^2, or the power consumption typically becomes excessive. There is a trade-off between cell voltage, current efficiency, and cell area that must be studied for a given case. By comparison, current densities of up to approximately 4500 A/m^2 can be achieved in the two-compartment cell. In this example, the current density of the two-compartment cellhouse is 2500 A/m^2 compared with 4000 A/m^2 in the three-compartment cellhouse, with comparable current efficiencies. The three-compartment cellhouse requires approximately 1.6 times the cell area for the two-compartment cellhouse to achieve the same production capacity, which has significant impact on the cellhouse Capex. The decreased Capex for the two-compartment system must be weighed against what may be increased cost for integration into the wider facility. The two-compartment electrolyser produces an anolyte containing significant concentrations of lithium sulfate mixed with the sulfuric acid. Recovery of a saleable or reusable acid product may require a more complex acid concentration system incorporating crystallisation and solids handling operations to separate lithium sulfate from the acid. This introduces additional process equipment, including evaporative crystallisers, solid-liquid separation, solids handling and storage systems, and associated utilities and controls.

As expected, operating costs for electrolysis-based lithium refining, in both cell configurations, are dominated by electricity consumption, which is primarily governed by cell voltage, current efficiency, and current density. Maintenance represents the second largest contributor to Opex, reflecting the need for periodic refurbishment and replacement of electrodes and membranes required to sustain electrolyser performance over time.

When comparing the two configurations, the three-compartment system exhibits higher power consumption, driven by increased cell voltage associated with the additional compartment and membrane. Maintenance costs are also slightly higher in the three-compartment configuration, as the lower allowable operating load results in a requirement for greater installed cell area, and

therefore a larger inventory of anodes and membranes subject to routine, albeit less frequent, replacement.

It should be noted that the costing presented here is illustrative only. Variations in operating parameters, such as product concentration, current density, and plant operating load, can significantly influence cellhouse sizing and, consequently, both capital and operating expenditure. In many cases, these effects involve trade-offs between Capex and Opex. For example, increasing the operating current density reduces the electrode area required to achieve a given production capacity, thereby lowering cellhouse Capex. However, higher current densities are associated with increased cell voltages, resulting in greater electricity consumption and higher Opex. Changes in the current density have relatively little impact on the wider facility design, as the overall production capacity and product concentrations remain unchanged. Consequently, the effects are largely confined to the size of the cellhouse and its associated capital and operating costs.

In contrast to the change in current density, for which the consequences are largely limited to the cellhouse, changes to other operating conditions – such as product concentrations – can have much broader implications for the overall facility. For example, within the cellhouse, operating at a lower catholyte concentration generally improves current efficiency, reducing the required cell area and lowering Capex. The improved current efficiency also typically outweighs the modest increase in cell voltage, leading to a reduction in cellhouse Opex. However, the resulting more dilute lithium hydroxide solution increases the duty of the downstream evaporation circuit, as additional water must be removed to produce the final lithium hydroxide monohydrate product. This increases both the capital and operating costs of the evaporation system. These interactions highlight that the economic performance of electrochemical lithium refining must be assessed at the overall refinery level, where trade-offs between individual process units determine the overall project economics.

Table 3 illustrates the relative impact of changes to key operating parameters on cellhouse and up- and downstream operation Capex and Opex. The arrows indicate the expected direction of change in cost when the corresponding parameter is increased. An upward arrow (↑) indicates an increase in Capex or Opex, a downward arrow (↓) indicates a decrease, and a horizontal arrow (→) indicates little or no significant change. Double arrows (↑↑ or ↓↓) indicate a relatively greater magnitude of change than a single arrow (↑ or ↓). The arrows provide a qualitative indication only and are not intended to represent quantitative changes.

TABLE 3

Capex and Opex sensitivity to key operating parameters.

Parameter (impact of *increasing* parameter)	**Cellhouse**		**Rest of facility ex. cellhouse**	
	Capex	**Opex**	**Capex**	**Opex**
Current density	↓↓	↑	→	→
Catholyte concentration	↑	↑	↓	↓
Anolyte concentration (2-compartment)	↑	↑	↓	↓
Anolyte depletion (3-compartment)	↑↑	↑	↓	↓

Electrolysis benchmarked against alternative technologies

Due to the integration opportunities offered by electrolysis-based lithium refining, meaningful benchmarking against alternative technologies should consider overall facility-level costs rather than electrolysis in isolation. The economics of electrolysis-based refining can be seen through a comparative assessment of capital and operating expenditure across selected spodumene refining projects in North America and Europe. This is summarised in Table 4.

TABLE 4

Capital intensity and Opex comparison for spodumene refining projects.

Project (source)	Flow sheet	Plant capacity t/a LHM	Capital intensity US$/t/a LHM	Opex USD/t LHM
Nemaska Lithium, Becancour, 2019 DFS, ±15% (Nemaska Lithium, 2019)	Electrolysis	37 000	22 000	2300
RockTech Lithium, Guben Converter, 2023 FEL3, ±10% (RockTech Lithium, 2023)	Conventional	24 000	31 700	5300
RockTech Lithium, Red Rock Converter, 2024 Scoping Study (RockTech Lithium, 2024)	Conventional	36 364	32 100	4600
Frontier Lithium, PAK Project, 2023 PFS (Frontier Lithium, 2023)	Conventional	20 000	21 600	3600
Piedmont Lithium, Kings Mountain, 2020 PFS, ±25% (Piedmont Lithium, 2020)	Conventional	20 000	25 200	3200
Sibanye Stillwater, Keliber, 2023 FS, ±25% (Sibanye Stillwater, 2023)	Alkaline leach	15 000	26 300	3800
Piedmont Lithium, Tennessee, 2023 DFS, ±15% (Piedmont Lithium, 2023)	Alkaline leach	30 000	26 400	2700
Piedmont Lithium, Carolina, 2021 BFS, ±15% (Piedmont Lithium, 2021)	Alkaline leach	30 000	21 700	2400
Avalon Advanced Materials, Thunder Bay, 2024 PEA (Avalon Advanced Materials, 2024)	Alkaline leach	30 000	29 500	2900

The three main processing technologies and their associated principal unit operations are:

1. Electrolysis: Calcination - acid roast - leaching - purification - electrolysis - crystallisation.
2. Conventional: Calcination - acid roast - leaching - purification - causticisation - crystallisation.
3. Alkaline Leach: Calcination - pressure leach - conversion leach - purification - crystallisation.

Projects have been selected which take a spodumene concentrate feed and produce a lithium hydroxide product. The basis for the Capex and Opex figures encompasses the full flow sheet from spodumene concentrate through to LHM. Figures are taken from published engineering studies, with the cost estimate accuracy given where available. Only studies with a stated cost accuracy of ±25 per cent or better have been considered. Costs have been adjusted to a 2025 USD basis using Chemical Engineering Plant Cost Indices (CEPCI).

Across the selected projects, the average capital intensity for the electrolysis, conventional and alkaline leach flow sheets are USD21 900, USD27 600 and USD25 900 per tonne LHM respectively. The average operating costs for the three flow sheets are USD2200, USD4100 and USD2900 per tonne LHM respectively.

When comparing the overall electrolysis flow sheet capital intensity with the cellhouse figures presented in Table 2, it is clear that the cellhouse accounts for a relatively small fraction of the overall capital expenditure. The remaining capital requirement is distributed across the upstream and downstream processing stages, including spodumene calcination, leaching, impurity removal and purification, product crystallisation, acid concentration, and associated utilities and infrastructure.

Some of the projects evaluated provide a detailed breakdown of operating costs. One of the key observations, which is consistent with the general chemistry, is that reagent costs are significantly lower for the electrolysis flow sheet than for both conventional and alkaline leach processes.

For the alkaline leach process, the main reagents are sodium carbonate and calcium hydroxide. Of the three projects including an Opex breakdown, the annual reagent costs were consistent at approximately USD1100/t LHM and are the largest single contributor to operating costs.

For the conventional flow sheet, the major reagents are sulfuric acid for the acid roast and leaching stages, and sodium hydroxide for causticization. Annual reagent costs average approximately USD1600/t LHM and, again, are the largest single contributor to operating costs.

While sulfuric acid is still required for the acid roast/leach stage, the electrolysis flow sheet benefits from recovery and recycling of acid generated in the electrolysis stage, reducing the amount of externally sourced sulfuric acid required. Incorporating electrolysis also eliminates the need for sodium hydroxide, with no reagent required for the electrochemical conversion of lithium sulfate to hydroxide. For the Nemaska project, reagent costs totalled only USD200/t LHM. The closed-loop nature of electrolysis flow sheets and reduced reagent consumption also reduces the carbon footprint associated with producing, transporting and handling large quantities of raw materials.

For the electrolysis-based flow sheet, energy consumption unsurprisingly represents the largest contributor to Opex. For the Nemaska project, power costs account for approximately 20 per cent of total Opex, with nearly 70 per cent of this energy requirement associated with the electrolysis operation.

Energy and reagent costs vary significantly by region and can clearly influence the relative competitiveness of different refining technologies. Electrolysis-based refining is expected to be most economically attractive in regions with access to low-cost renewable electricity and where conventional refining routes are penalised by high reagent and waste disposal costs. Nonetheless, the economic balance would only be expected to shift in favour of conventional routes under conditions of unusually high electricity costs combined with exceptionally low reagent costs.

THE ROLE OF SODIUM SULFATE ELECTROLYSIS IN HARD ROCK REFINING

While lithium sulfate electrolysis represents a fundamentally different refining route for spodumene concentrates, sodium sulfate electrolysis provides an attractive complementary technology for existing hard rock lithium operations that continue to employ conventional conversion processes. Rather than replacing the established process flow sheet, sodium sulfate electrolysis can be integrated as a chemical recovery and reagent regeneration step, improving overall process circularity while reducing dependence on externally supplied reagents.

In conventional spodumene refining flow sheets, sodium sulfate is generated principally during lithium conversion, where lithium sulfate leach solution is reacted with soda ash or caustic soda to produce lithium carbonate or lithium hydroxide. In both cases, sodium sulfate is formed as the primary by-product of these reactions. These sodium sulfate-bearing streams are typically managed through crystallisation and disposal or diverted to low-value external markets, despite containing recoverable sodium and sulfate values. Integration of sodium sulfate electrolysis allows these streams to be recycled as an internal process feedstock for regeneration of sulfuric acid and sodium hydroxide, closing the sodium and sulfur reagent loops (alkali and acid) within the refinery.

Similar to lithium sulfate electrolysis, sodium sulfate electrolysis can take place in two- or three-compartment electrolysers, illustrated in Figures 8 and 9.

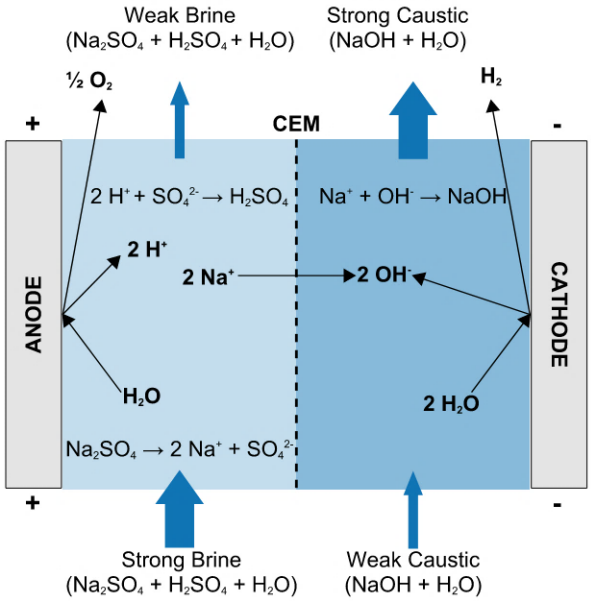


FIG 8 – Two-compartment sodium sulfate electrolysis.

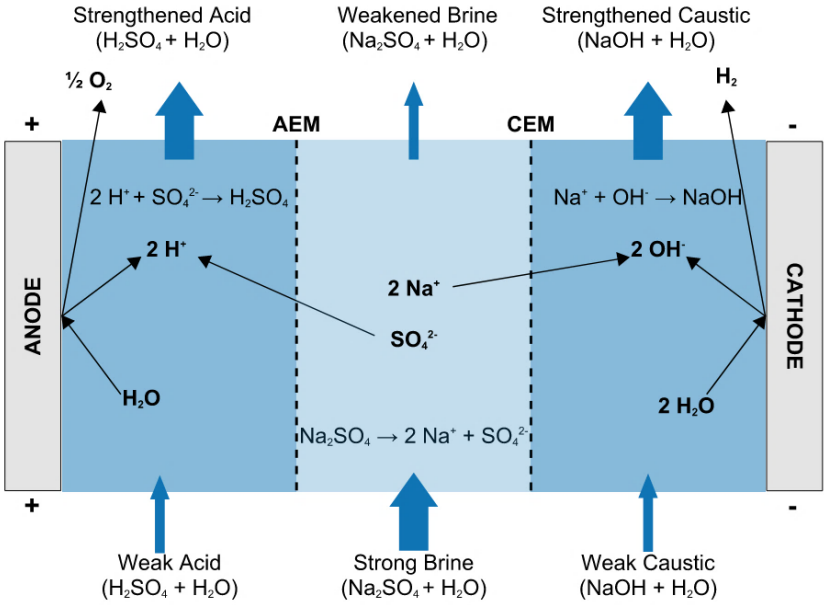


FIG 9 – Three-compartment sodium sulfate electrolysis.

Three-compartment electrolysis produces high purity sodium hydroxide and sulfuric acid. Product concentrations from the cellhouse are typically optimised for the requirements of the recycle or downstream process. While sodium hydroxide concentrations of up to approximately 32 wt per cent can be achieved, comparable to conventional chlor-alkali production, current limitations in anion exchange membrane performance restrict the sulfuric acid product concentration to typically less than 10 wt per cent. As described above, for spodumene refining applications, recycled sulfuric may be required at concentrations greater than 93 wt per cent for reuse in the acid roast or leach circuit. Conventional acid concentration technologies, including mechanical vapour recompression (MVR) (up to ~ 25 wt per cent acid), multi-effect evaporation (up to ~ 65 wt per cent acid), and sulfuric acid recovery and concentration (SARC) systems (up to ~95 wt per cent acid), can be applied sequentially to achieve the required recycle concentration. NESI is also developing integrated electrolysis flow sheets that incorporate alternative water-rejection technologies to reduce the energy intensity and operating costs associated with sulfuric acid concentration.

Like two-compartment lithium sulfate electrolysis, the absence of an anion exchange membrane in two-compartment sodium sulfate electrolysis results in the generation of a mixed sulfuric acid-sodium

sulfate product from the anolyte circuit. Where the acid produced is either too dilute or contains excessive sodium sulfate, downstream evaporation and crystallisation can be employed to remove water and concentrate the acid to the required concentration, and separate sodium sulfate for recycle within the process. Understanding the limits of the two-compartment cell technology, and how it can be coupled with downstream concentration and sodium rejection, is key to selecting the most appropriate process configuration. Irrespective of the evaporative crystallisation package employed, concentrated acid solutions produced from the two-compartment anolyte product will retain sodium sulfate at low percentage levels ie 2wt per cent sodium sulfate in a 60 wt per cent sulfuric acid solution. Where this residual sodium content is acceptable for the intended recycle or downstream application, two-compartment electrolysis can provide a technically attractive and potentially lower-cost alternative.

To illustrate the downstream anolyte processing for two-compartment electrolysis, and compare with lithium sulfate electrolysis, ternary phase diagrams for the lithium sulfate – sulfuric acid – water and sodium sulfate – sulfuric acid – water systems are presented in Figures 10 and 11 respectively. The contrasting phase behaviour of these two systems has a fundamental impact on the design of the recycle flow sheet.

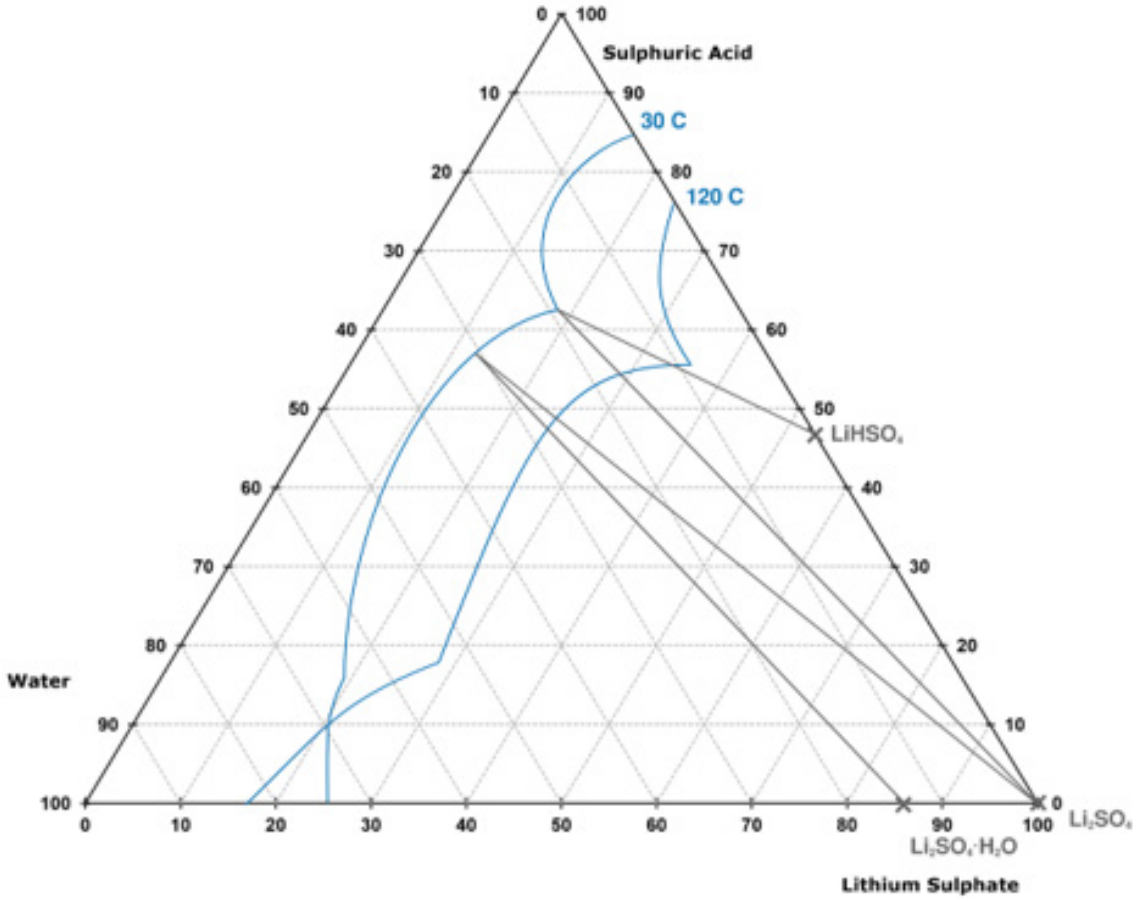


FIG 10 – Ternary phase diagram for the lithium sulfate – sulfuric acid – water system.

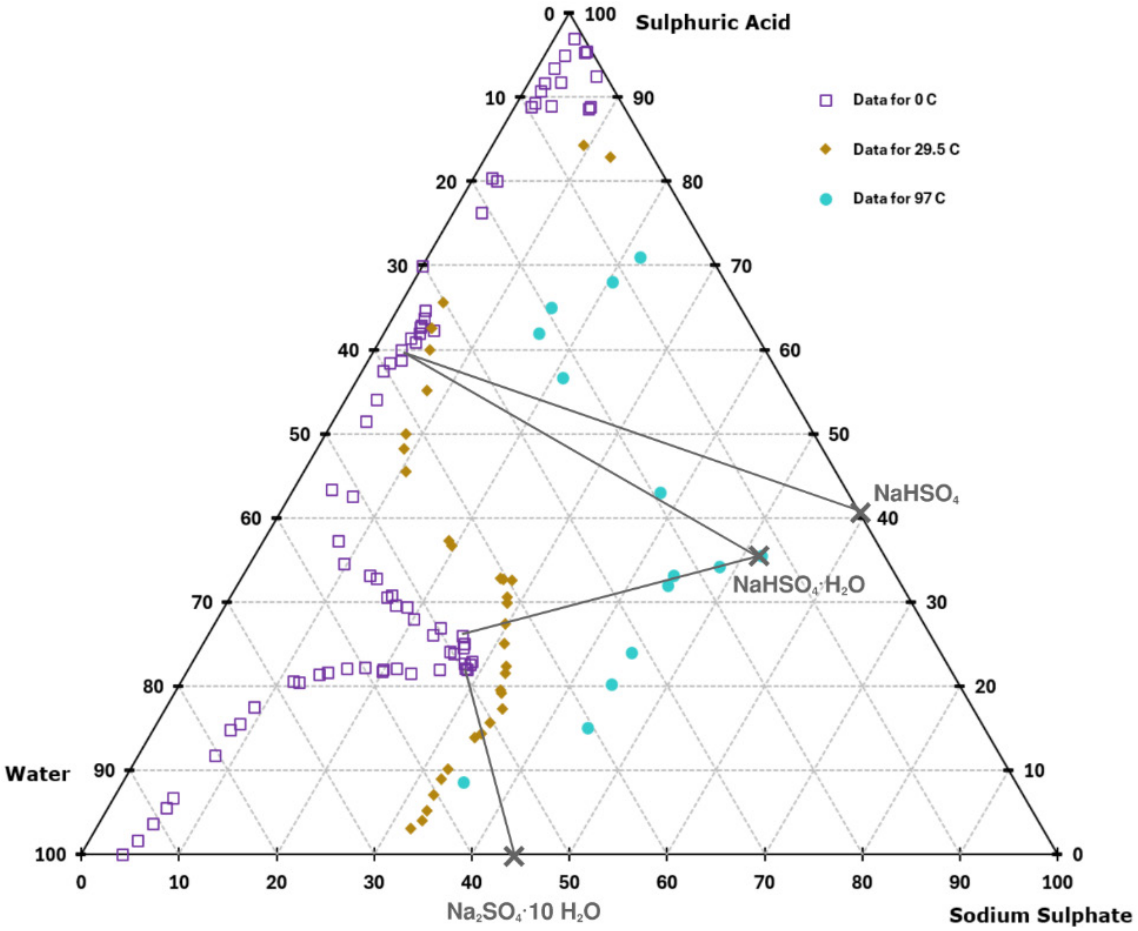


FIG 11 – Ternary phase diagram for the sodium sulfate – sulfuric acid – water system.

For the lithium sulfate system (Figure 10), evaporative crystallisation can be applied to reject lithium from the mixed sulfuric acid – lithium sulfate solution as lithium sulfate monohydrate. The resulting mother liquor can then undergo further lithium removal through cooling crystallisation, followed by concentration in a sulfuric acid re-concentrator (SARC) to restore the acid strength required for recycle to the spodumene roasting stage.

In contrast, the sodium sulfate system relies primarily on cooling crystallisation for salt rejection from the depleted anolyte stream, with sodium recovered initially as glauber's salt ($Na_2SO_4.10H_2O$) for recycle back to the electrolysis process. Additional sodium removal can be achieved through the formation and rejection of sodium bisulfate, before the remaining sulfuric acid solution is concentrated in a SARC to achieve the acid strength required for recycle. The reliance on a first stage of cooling crystallisation rather than evaporative crystallisation stages is a result of the fundamentally different phase behaviour of the sodium sulfate – sulfuric acid – water systems. At low temperature the sodium system is dominated by glaubers salt; cooling crystallisation allows crystallisation and recycle of sodium sulfate with low energy input. In the lithium sulfate – sulfuric acid – water system the initial crystallisation of sodium sulfate monohydrate is an evaporative crystallisation.

The principal benefit of implementing sodium sulfate electrolysis within a conventional lithium conversion flow sheet is the recovery of two high-value process reagents from a stream that is otherwise treated as a by-product with low value or a disposal cost. Regenerated sulfuric acid can be returned directly to the acid roasting or leaching circuits, while the sodium hydroxide can be utilised in neutralisation, impurity removal and pH control. In carbonate-based flow sheets, where caustic soda is not consumed in significant quantities during lithium conversion, surplus sodium hydroxide production can be directed to external markets, providing an additional revenue opportunity. Alternately soda ash can be made from sodium hydroxide and carbon dioxide which improves the carbon profile of the project. In any case, the requirement for externally sourced reagents is reduced, along with the associated transport, storage and handling requirements. In

addition, valorising the sodium sulfate effluent reduces disposal requirements or reliance on low-value external markets, improving internal utilisation of sodium and sulfur values and overall process circularity. For refineries operating in regions with volatile chemical prices or constrained reagent supply, on-site electrochemical regeneration can also improve operational resilience.

Compared with the implementation of a complete lithium sulfate electrolysis flow sheet, sodium sulfate electrolysis represents a potentially lower-risk pathway for existing refineries. It can be integrated into established process configurations without requiring fundamental changes to the primary lithium extraction and conversion circuits. The technology can be deployed to take the sodium sulfate by-product streams and return regenerated sulfuric acid and sodium hydroxide to the refinery process. This modular integration approach enables brownfield facilities to progressively adopt electrochemical processing, capturing associated decarbonisation and resource efficiency benefits while maintaining their existing refining infrastructure.

The integration of sodium sulfate electrolysis is particularly attractive when considered alongside renewable electricity. As with lithium sulfate electrolysis, electrical energy effectively replaces the manufacture and transport of bulk chemical reagents. Where low-carbon electricity is available, the regenerated sulfuric acid and sodium hydroxide can exhibit substantially lower life cycle greenhouse gas emissions than conventionally produced reagents, contributing to improved environmental performance of the overall lithium supply chain.

In summary, sodium sulfate electrolysis should be viewed not as a competing refining technology, but as an enabling circular process that complements conventional hard rock lithium refining. Existing refineries can recover value from an internal by-product stream, regenerate two major process reagents on-site, reduce waste generation, and move towards a more closed-loop chemical system. Considering both the lithium sulfate electrolysis route discussed earlier in this report, and sodium sulfate electrolysis illustrates how electrochemical technologies can progressively transform lithium refining from a linear reagent-intensive process into a more circular and resource-efficient manufacturing system.

CONCLUSIONS

Lithium refineries can use electrolysis steps to offer a competitive alternative to conventional processing routes for a variety of feedstocks, including spodumene concentrate. By regenerating key process reagents within the refining flow sheet, the technology improves process circularity, reduces fresh reagent consumption, and eliminates sodium sulfate as a by-product, simplifying both operations and waste management.

The combination of extensive long-term operating data and approval grade estimates demonstrate that direct lithium sulfate electrolysis is capable of producing high-purity lithium hydroxide while achieving capital and operating costs that are competitive with conventional refining technologies. Sodium sulfate electrolysis augments traditional flow sheets to greatly reduce waste and improve circularity.

Both lithium and sodium sulfate electrolyses can be conducted in either two or three-compartment cells. The choice depends upon other elements of the flow sheet.

Overall, the combination of reagent regeneration, improved sustainability, high product quality, and competitive economics positions electrolysis-based refining options as an important technology option for future lithium chemical production.

REFERENCES

Avalon Advanced Materials, 2024. Avalon Completes PEA: Post-Tax C$4.1 Billion NPV (8%) and 48% IRR at its Thunder Bay Lithium Processing Facility, ON [online]. Available from: <https://avalonadvancedmaterials.com/> [Accessed: 23 July 2026].

Blois, M, 2024. BASF battery project delayed because of environmental concerns [online]. Available from: <https://cen.acs.org/environment/pollution/BASF-battery-project-delayed-environmental/> [Accessed: 23 July 2026].

Frontier Lithium, 2023. NI 43-101 Technical Report Pre-Feasibility Study for the PAK Project [online]. Available from: <https://www.sedarplus.ca/csa-party/records/document.html?id=e6ea745bb52dabeb3591186787876bfd905f0a775c592a66a3c091fee447ef03> [Accessed: 03 Sept 2026].

Nemaska Lithium, 2019. NI 43-101 Technical Report on the Estimate to Complete for the Whabouchi Lithium Mine and Shawinigan Electrochemical Plant [online]. Available from: <https://www.sedarplus.ca/csa-party/records/document.html?id=580f2470793c279fd334d0f1c0b712804627af93b4b83b791045c9d17dfecbc3> [Accessed: 03 Sept 2026].

Piedmont Lithium, 2020. Chemical plant PFS demonstrates exceptional economics and optionality of USA location [online]. Available from: <https://www.businesswire.com/news> [Accessed: 23 July 2026].

Piedmont Lithium, 2021. Piedmont completes bankable feasibility study of the Carolina Lithium project with positive results [online]. Available from: <https://announcements.asx.com.au/> [Accessed: 23 July 2026].

Piedmont Lithium, 2023. Piedmont Lithium completes definitive feasibility study of Tennessee Lithium project [online]. Available from: <https://www.businesswire.com/news/> [Accessed: 23 July 2026].

RockTech Lithium, 2023. Rock Tech Lithium Completes Final Engineering Study Before Construction of its Guben Lithium Converter [online]. Available from: <https://www.prnewswire.com/news-releases/> [Accessed: 23 July 2026].

RockTech Lithium, 2024. Rock Tech completes Scoping Study for Canadian Lithium Converter [online]. Available from: <https://rocktechlithium.com/en/> [Accessed: 23 July 2026].

Sibanye Stillwater Limited, 2023. Technical Report Summary: Keliber Lithium Project, Finland [online]. Available from: <https://www.sibanyestillwater.com/news-investors/reports/annual/2022/> [Accessed: 03 Sept 2026].

Standardization Administration of China, 2020. GB/T 26008–2020: Battery grade lithium hydroxide monohydrate, Beijing: Standardization Administration of China [online]. Available from: <https://openstd.samr.gov.cn/bzgk/std/newGbInfo?hcno=EDE35159DCEFEE4EBD50689B422430DD> [Accessed: 03 Sept 2026].

Unlocking capacity – use of process control and monitoring to increase the barge loading capacity at Metro Mining Bauxite Hills Mine

M Graham[1] and R Dawe[2]

1. General Manager – Technical, Projects and Improvement, Metro Mining, Brisbane Qld 4000. Email: mgraham@metromining.com.au
2. Process Improvement Specialist, Metro Mining, Brisbane Qld 4000. Email: rdawe@metromining.com.au

ABSTRACT

The Bauxite Hills Mine has undergone a transformative expansion phase, transitioning from a localised mining operation to a high-capacity, integrated export hub. Following the 2024 completion of a multi-asset infrastructure program—including a new wobbler screening plant, an offshore floating terminal, and significant marine asset upgrades—the operation successfully scaled production from 4.6 million wet metric tonnes (WMT) in 2023 to 6.2 million WMT in 2025.

However, as physical capacity increased, the Barge Loading Facility (BLF) emerged as a critical systemic bottleneck, limiting the realisation of the mine's new theoretical nameplate capacity. To address this, a dual-pronged optimisation strategy was implemented in 2025, focusing on digital transformation and operational governance.

Central to this phase was the deployment of an integrated control system, enabling synchronised, real-time management of disparate plant elements. This technical upgrade was bolstered by the introduction of a dedicated production monitoring role, tasked with continuous performance analysis and tactical adjustments. The convergence of these technological and structural interventions has yielded a significant improvement in the facility's throughput capacity. This paper examines the technical architecture of the new control systems, the logistical impact of the 2024 expansion, and the methodologies used to eliminate the BLF constraint, providing a blueprint for brownfield optimisation in remote mining environments.

An alternate approach – heap leach flow sheet development for ASM's Dubbo rare earth project

D M Hunter[1], D J Readett[2], W Dicinoski[3], R J Laver[4] and D Molver[5]

1. Senior Metallurgist, Core Resources, Albion Qld 4010. Email: dhunter@coreresources.com.au
2. Principal Consultant, Mworx, Peregian Beach Qld 4573. Email: dreadett@mworx.net.au
3. General Manager – Technical, Australian Strategic Materials Ltd, Brisbane NSW 4000. Email: wdicinoski@asm-au.com
4. Laboratory Technician, Core Resources, Albion Qld 4010. Email: rlaver@coreresources.com.au
5. Senior Metallurgist, Core Resources, Albion Qld 4010. Email: dmolver@coresources.com.au

ABSTRACT

Core Resources is currently undertaking a comprehensive hydrometallurgical test work program to assist Australian Strategic Materials Ltd (ASM) in the flow sheet development for the Dubbo Project in New South Wales, Australia. This globally significant resource contains high-grades of critical magnetic rare earth elements (MREE), specifically neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb). Following an evaluation of several processing routes, a hydrochloric acid (HCl) heap leach flow sheet was selected due to its high extraction efficiency and its capability to generate a high-tenor rare earth pregnant leach solution (PLS).

This paper discusses and presents the results from the agitated beaker, bottle roll and column leach test work. Initial test work focused on the use of sulfuric acid as a lixiviant, however, due to double-salt precipitation causing challenges with variable and low recoveries, hydrochloric acid was selected as the lixiviant for this project. Bottle roll test work primarily investigated the effects of crush size and acid concentration, demonstrating that up to 75.5 per cent of MREE could be extracted from the ore at an acid dosage rate of 48.1 kg/t ore.

Column leach test work is briefly discussed in this report with focus placed on a single 8 m column test. Agglomerated ore was used in column leach tests and performance was generally consistent or improved performance when compared to bottle roll tests with high MREE extraction extents and lower acid consumption rates. Work on the development of the final flow sheet continues with a focus on agglomeration optimisation, geotechnical studies and downstream REE processing including impurity removal and rare earth precipitation stages.

INTRODUCTION

Over the past two years, Core Resources (Core) has been undertaking a significant metallurgical test work programme for Australian Strategic Materials Ltd (ASM), an emerging integrated producer of critical rare earth elements (REE). Located in central New South Wales, Australia, ASM's Dubbo project is a cornerstone of their business, providing a long-term and secure high-grade resource of REE and other critical minerals. In particular, the deposit is a globally significant resources of magnetic rare earth elements (MREE) neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and Terbium (Tb).

A geological study conducted by Spandley and Morris (2016) identified ASM's resource in Dubbo, also known as the Toongi deposit, as being a peralkaline trachyte deposit formed in the late Triassic to early Jurassic period. The mineralogy is primarily dominated by feldspar minerals including albite and aegirine. They reported that the REE are primarily hosted in eudialyte group minerals (EGM) as complex REE silicates but also secondarily as fluoro-carbonates such as bastnaesite.

In 2013, a definitive feasibility study (DFS) published by Alkane Resources described a flow sheet aimed at recovering not only REE but also other high value metals including zirconium and niobium (Alkane Resources Ltd, 2013). The process itself included a sulfuric acid roast followed by a water leach and solvent extraction to separate out different products. A subsequent flow sheet update detailed in an announcement in 2021 showed the addition of a chlor-alkali plant and brine concentrator to the project (ASM, 2021). These additions were to satisfy both ESG requirements, especially with regards to water consumption in a historically drought-prone region and improve long-

term project economics by producing hydrochloric acid (HCl) and sodium hydroxide (NaOH) on-site, reducing operating expenses.

Due to the high complexity and high capital cost of the project, arising primarily due to the acid roasting stage of the process. ASM has recently pivoted to a ‘rare earths first’ strategy using heap leaching (ASM, 2025). Figure 1 shows the currently proposed flow sheet for the Dubbo project.

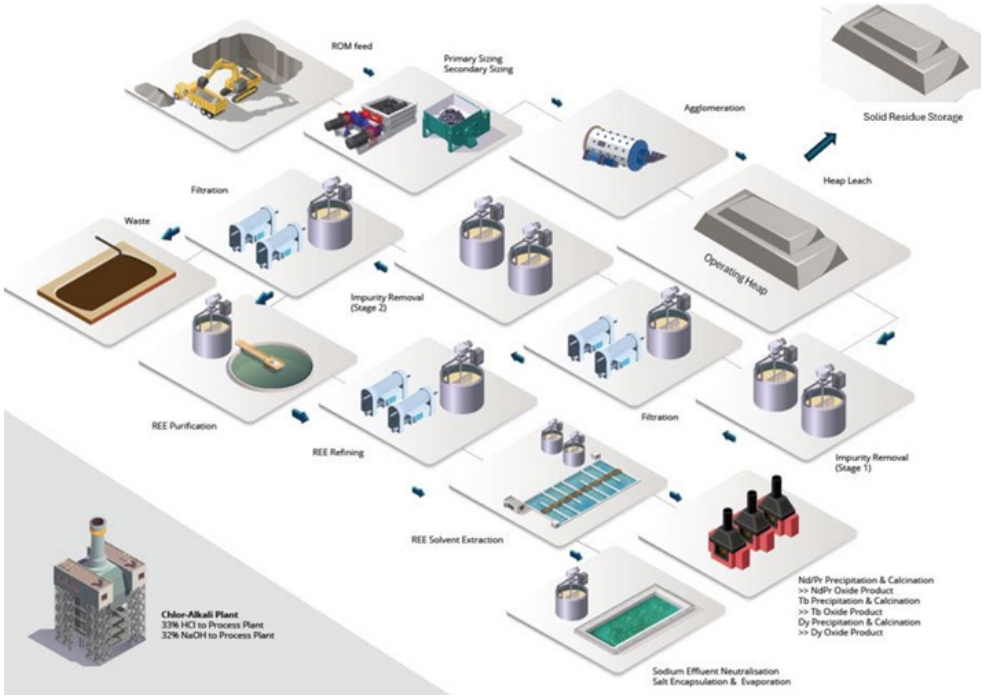


FIG 1 – Dubbo Project Heap Leach Diagram (ASM, 2025).

This paper brings together and summarises the variability, bottle roll leach test work completed by Core for ASM over the past two years, with brief mention to column leach test work. An initial discussion on the sample source and head characterisation is provided, prior to discussing the leaching test work including test methodology and results. Finally, conclusions from the test work are presented along with a brief update on the progress and future direction of the work.

For the sake of brevity, this paper will focus and discuss the testing results for the MREE only, rather than the full suite of REE and impurity elements. Furthermore, when discussing the bottle roll leach test work, the discussion will initially be limited to results from a single sample rather than all samples tested in the project, and a brief discussion will be provided on the bottle roll testing of five other samples.

HEAD CHARACTERISATION

The work discussed in this paper was conducted on samples collected from ASM’s Dubbo Project site. All samples in the program originated from drill holes shown in Figure 2 to varying degrees, with composites prepared for HLC-West (HLC1 and HLC4), HLC-Centre (HLC2 and HLC5) and HLC-East (HLC3 and HLC6) for the bottle roll test work.

Upon receipt of the samples at Core, the samples were crushed and rotary subdivided to prepare appropriately sized samples for test work. A subsample was also taken for head characterisation which included quantitative X-ray diffraction (QXRD) for mineralogy and ALS test methods ME-MS81, ME-ICP61 and ME-ICP81 for REE and elemental analysis.

Mineralogical analysis (QXRD) suggests that REEs are hosted primarily in eudialyte and nöggerathite and to a lesser extent, bastnaesite and xenotime, mostly agreeing with the findings presented by Spandley and Morris (2016).

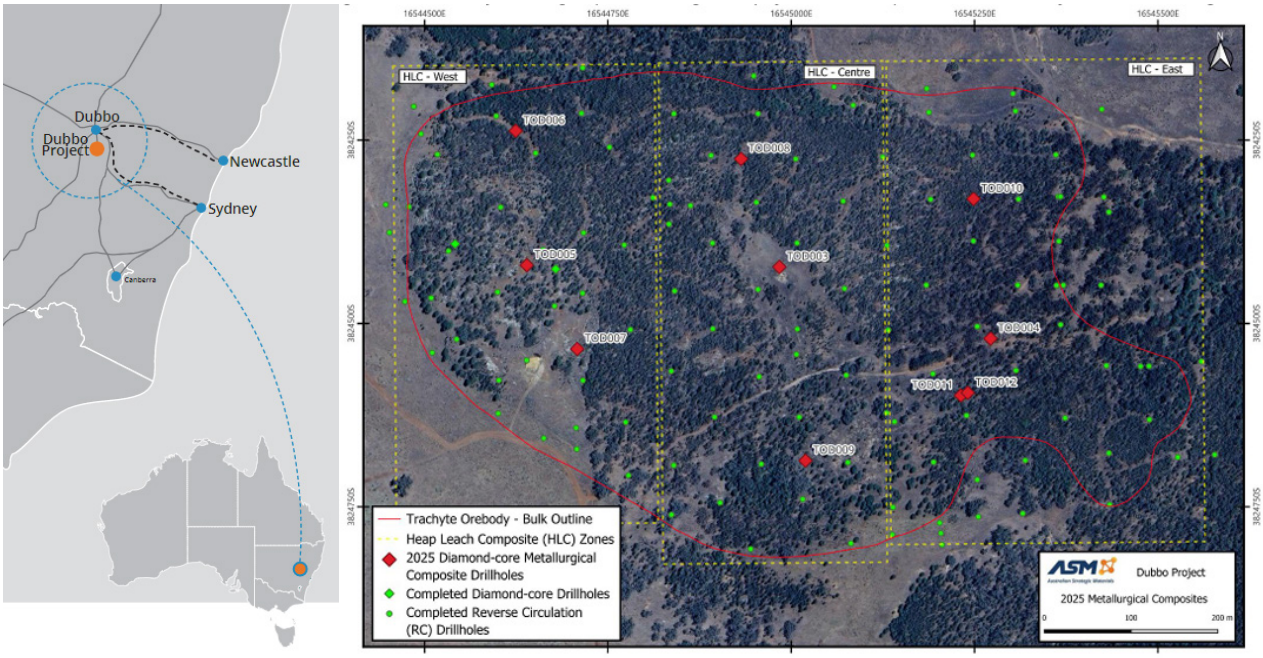


FIG 2 – Location of the Dubbo project (left) (ASM, 2026) and map of the Dubbo Project Toongi deposit showing overlay of the three composite zones tested in this project (right) (ASM, 2025).

Table 1 shows the average, high and low results from the head characterisation for REEs and other key elements for the samples tested in this work. Results show that little variability existed between the samples with relatively narrow range and small differences between the average and the upper and lower limits of the range. High sodium is however noted in the samples, being a feature of the trachyte alkali mineralogy.

TABLE 1

Average and range of head assay results for REEs and key elements for samples tested.

Analyte	Units	Average	High	Low
Al	mg/kg	65 117	67 000	63 400
Ca	mg/kg	4067	5400	3300
Fe	mg/kg	50 683	51 600	49 300
Mn	mg/kg	4238	5060	3630
Na	mg/kg	49 367	56 300	42 100
Si	mg/kg	291 500	302 000	286 000
Zr	mg/kg	13 542	13 800	13 250
Rare earth elements				
La	mg/kg	1555	1605	1480
Ce	mg/kg	2823	2910	2740
Pr	mg/kg	306	320	292
Nd	mg/kg	1039	1100	947
Sm	mg/kg	195	208	188
Eu	mg/kg	5.58	6.13	5.38
Gd	mg/kg	167	174	161
Tb	mg/kg	29.4	30.8	27.2
Dy	mg/kg	178	188	170
Ho	mg/kg	35.4	37.2	33.4
Er	mg/kg	100	103	94.5
Lu	mg/kg	11.4	12.8	10.8
Tm	mg/kg	14.5	15.7	14
Yb	mg/kg	87.1	94	83.8
Y	mg/kg	1011	1055	950
TREY	mg/kg	7561	7773	7293
MREE	mg/kg	1551	1638	1448
HREE	mg/kg	1638	1716	1574

VARIABILITY LEACH TEST WORK

Initial work conducted by Core for ASM aimed to investigate the variability of the leach performance across the Dubbo project site. In total, ASM provided 137 samples to Core which were all prepared by crushing and grinding to a nominal 80 per cent mass passing size (P_{80}) of 53 µm. In total, 141 beaker leach tests were conducted, with some samples undergoing duplicate leaching tests.

Tests were set-up using baffled 2 L borosilicate glass beakers on hot plates with PID temperature control. Agitation was provided by overhead stirrers using Teflon 4-blade axial impellers set at an agitation speed of 500 rev/min. Acid and de-ionised (DI) water was added to the reactor to provide a desired free acid concentration and heated to a target temperature of 50°C at which point the ground ore sample was added to the reactor and the residence time of the tests started. An image of four tests running in parallel is shown in Figure 3.



FIG 3 – Multiple variability leach tests operating in parallel (right).

The first 27 tests were kinetic tests aimed at determining a suitable residence time for the remaining tests and were conducted over a period of 24 hrs. Figure 4 shows the average extraction rate and average extraction extent versus time for MREE and demonstrates that under the test conditions terminal extraction was reached after approximately 3 hrs. As such, 6 hrs was selected as the residence time for the remaining tests after the completion of the kinetic leach tests.

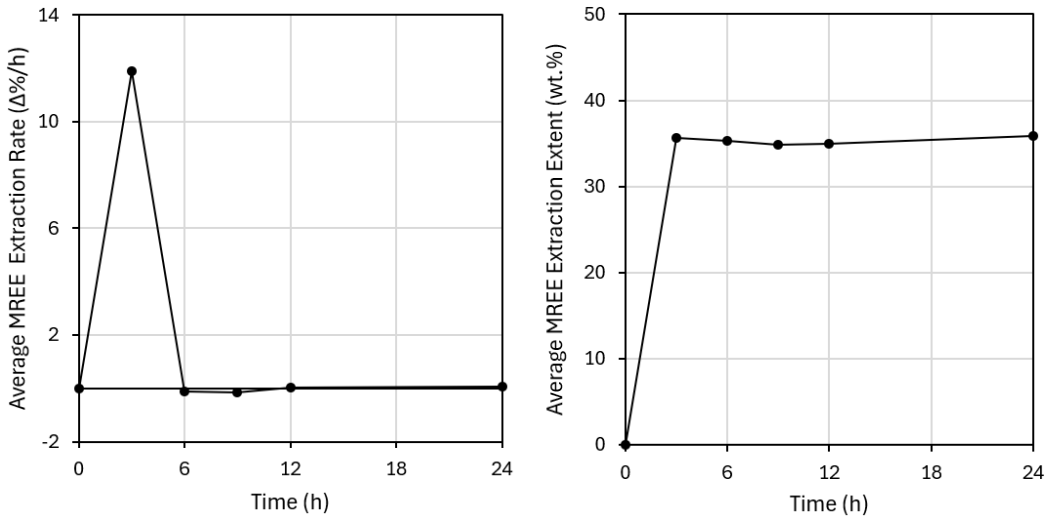


FIG 4 – Average MREE extraction rate (left) and MREE extraction extent (right) versus time for kinetic leach tests.

The first 120 tests, including the 27 kinetic tests all utilised sulfuric acid (H_2SO_4) as the lixiviant at a concentration of 50 g H_2SO_4/L and a pulp density of 50 wt per cent solids. Later tests were conducted using hydrochloric acid, in which cases the acid concentration used was 20 g HCl/L.

Analysis of final pregnant leach solution (PLS) from each test included ICP-OES elemental analysis, free acid measurement by titration and liquor density by gravimetric determination by Core's internal assay laboratory. Dried solid residues, which were thoroughly washed, were analysed via ALS methods ME-MS81 and ME-MS81h, and via 4-acid digest and sodium peroxide fusion ICP-OES by Core's assay laboratory.

Across all tests, variability was noted between test samples, however, no clear mineralogical marker could be reliably identified which could give rise to an explanation for the variability. It is presumed that this is due in large part to the heterogeneity of the orebody.

From a chemistry perspective, there was one significant trend that did arise in the test work utilising sulfuric acid. It was noted that in some instances recovery was significantly lower than others, and this appeared to be linked to sodium concentrations in the liquor. When plotting the MREE recovery versus the Na:TREY mass ratio in the liquor as shown in Figure 5, a clear trend was evident, demonstrating that high levels of Na resulted in poorer REE recoveries when using sulfuric acid. It was hypothesised that this was due to sodium-REE sulfate double salt precipitation.

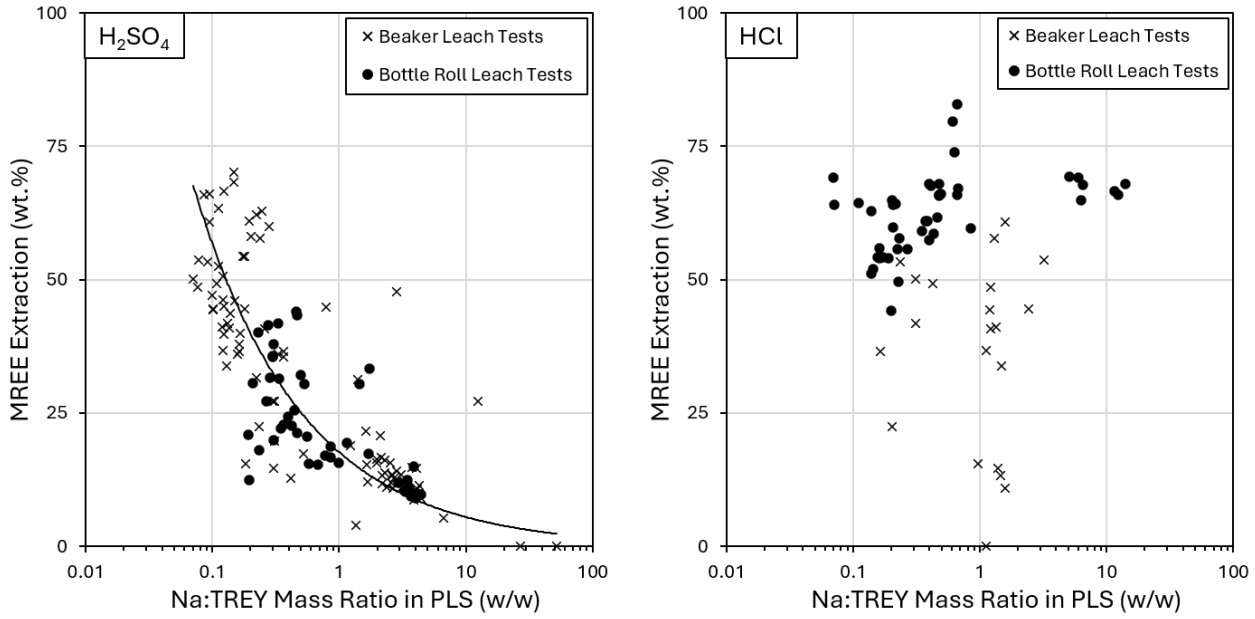


FIG 5 – MREE extraction results versus Na-to-TREY Mass ratio in PLS for beaker and bottle roll leach tests using H_2SO_4 (left) and HCl (right).

Precipitation of rare earths as sodium-double salts is a well-known consequence when high concentrations of sodium and sulfate exist with REE in solution as per the reaction shown in Equation 1.

$$REE^{3+}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + Na^{+}_{(aq)} + H_2O_{(l)} \leftrightarrow NaREE(SO_4)_2{\cdot}H_2O_{(s)} \quad (1)$$

Downstream double salt precipitation can be used to selectively precipitate a high purity REE product (Guzhov *et al,* 2023), however, in a leaching process double salt precipitation of REE leads to the loss of rare earths with the leach residues. Work conducted by Porvali, Wilson and Lundström (2018) demonstrated that the precipitation of REEs as sodium rare earth double salts in sulfuric acid leach liquors was primarily driven by the sodium-to-REE ratio, requiring relatively low ratios to cause double salt precipitation, agreeing with the findings of this test work.

As a result of this observation, it was decided to begin testing HCl as a lixiviant which, as shown in Figure 5, resulted in a decoupling of the MREE extraction extent dependency on Na:TREY mass ratio in the PLS. It was hence decided that all future work would be focused on HCl-based leaching.

Aside from the advantage using HCl provides in the extraction of REE, it also integrates well with the proposed Dubbo project flow sheet due to the 2021 inclusion of a chlor-alkali plant which can provide HCl to the heap leaching stage. Furthermore, it removes the need for a sulfur burning plant to manufacture sulfuric acid, which was also a feature of the Dubbo project flow sheet in 2021 (ASM, 2021).

Table 2 shows the average results, high/low range and standard deviations for the 21 variability leach tests that were conducted using HCl with respect to acid consumption rate and extraction extents for the MREEs. Of note, is that significant variability still exists despite the switch from sulfuric acid to HCl, with MREE extraction ranging from 14.0 to 78.2 per cent. Furthermore, the ‘heavy’

magnet REEs (Dy, Tb) typically extract to lower extents than the 'light' magnet REEs (Pr, Nd). This variability also extends to impurity elements including iron, manganese and zinc, which will need to be removed prior to precipitation of a REE product post-leaching.

TABLE 2

Average and high/low results for acid consumption and extraction extent for REE groups and selected impurity elements for variability leach tests using HCl.

Analyte	Units	Average	High	Low	Standard deviation
Acid consumption rate	kg HCl/t Ore	13.3	16.9	5.56	2.49
Extraction extent					
Pr	%	53.4	88.6	16.6	15.8
Nd	%	50.3	86.3	15.1	15.1
Dy	%	17.5	31.6	4.64	6.90
Tb	%	20.8	51.6	3.72	8.51
Total MREE	%	45.1	78.2	14.0	16.3

Despite the variability in the extraction extents, the overall acid consumption rates were found to be relatively low across all tests, ranging only from 5.56 to 16.9 kg HCl/t ore. While the data isn't explicitly reported here, the extraction trends moving from the light to heavy REEs (ie from La to Y) typically displayed decreasing extraction trends as consistent to the results shown in Table 2. This observation was typical throughout all test work conducted in the programme.

BOTTLE ROLL TEST WORK

In the test work programme a total of 35 bottle roll tests have been conducted. In this paper, discussion will focus on six of these tests which were run to optimise the crush size and acid addition rate (concentration) for a composite ore sample that was to be tested in column leaching work. Ore samples used in the test work were representatively split into three subsamples which were then crushed to nominal top-sizes of 25, 12.5 and 6.7 mm, before crushed samples were then further split to produce aliquots for the bottle roll tests. The bottle roll tests discussed in this work and their conditions are summarised in Table 3.

TABLE 3

Test conditions for bottle roll tests BR01 to BR06 conducted in this work programme.

Test ID (-)	Crush size (mm)	Target HCl conc. (g/L)	Pulp density (wt %)	Duration (days)
BR01	25	50	50	32
BR02	12.5	50	50	32
BR03	6.7	50	50	32
BR04	25	20	50	28
BR05	12.5	20	50	28
BR06	6.7	20	50	28

The bottle roll tests discussed in this paper were all run in intermittent operation over periods of time ranging from between 28 and 32 days. At the start of each bottle roll test, acid and DI water were

loaded into the bottle in proportions required to produce a liquor concentration of either 50 or 20 g HCl/L. Ore samples were then added to the bottle roll at a mass equal to that of the liquor to provide a pulp density of 50 wt per cent solids. The bottles were then placed on the bottle roller and rolling was commenced.

Monitoring of bottles was conducted twice weekly to measure the pH, temperature, ORP and free acid of the liquor in the bottles. At monitoring times, when required, additional acid was added to the bottle to maintain the target free acid concentration of the test. When monitoring was conducted, small liquor kinetic samples (~ 5 mL) were taken from the bottles via a syringe and filtered using a 0.45 µm syringe filter for elemental analysis via ICP-OES.

Two different types of bottle rollers were used in this work to maximise the number of tests which could be running simultaneously. These included single position bottle rollers and a large 20-position bottle roller which are shown in Figure 6. All bottle roll tests were conducted in intermittent mode with rolling being on for 5 mins and off for 55 mins in each 1-hour period while operating.



FIG 6 – Images of single position bottle rollers (top) and large 20-position bottle roller (bottom) used in this work.

At the conclusion of the bottle roll tests, the entire contents of the bottles were weighed and filtered to separate the final residues from the PLS. Final residues were thoroughly washed and submitted for assay via ALS method ME-MS81 and ME-MS81h, while 4-acid digest and sodium peroxide fusion ICP-OES were conducted at Core's internal assay laboratory.

Over the course of the bottle roll operation, extraction was tracked based on the liquor assay results and the head characterisation. However, after the completion of the bottle roll test, the final extraction was calculated based on the final residues and the head assay only considering the solids mass loss in the test. The kinetic results were then normalised to the final extraction results as the extraction result based on the final residue sample is typically considered a more robust measure of extraction. Table 4 shows the final results from the bottle roll tests including extraction figures for the MREEs and total acid consumption.

TABLE 4

Acid consumption and extraction results for MREEs for bottle roll leach tests BR01 to BR06.

Analyte	Units	BR01	BR02	BR03	BR04	BR05	BR06
Acid consumption	kg/t	57.4	63.1	68.0	36.6	46.2	48.1
Extraction extents							
Pr	%	80.0	84.9	79.5	73.5	81.8	82.5
Nd	%	75.1	79.9	71.7	68.1	77.0	77.2
Tb	%	38.6	44.2	25.1	31.5	40.9	40.8
Dy	%	30.6	37.3	26.9	21.3	29.8	29.8
Total MREE	%	61.7	75.3	75.6	59.1	71.9	72.1

Final extraction extent for total MREEs, individual MREEs and acid consumption rate are plotted versus crush size for tests using 50 and 20 g HCl/L in Figure 7 to provide a visual representation of the results. Overall, there is a dependency between the extraction extent and the crush size, however, this seems to be limited to the coarsest crush sizes tested, with a significant increase in extraction occurring when the crush size is reduced from 25 to 12.5 mm. This trend is relatively consistent across all of the individual REE elements with only a single point for dysprosium showing a drop in extraction at a crush size of 6.7 mm with 50 g HCl/L.

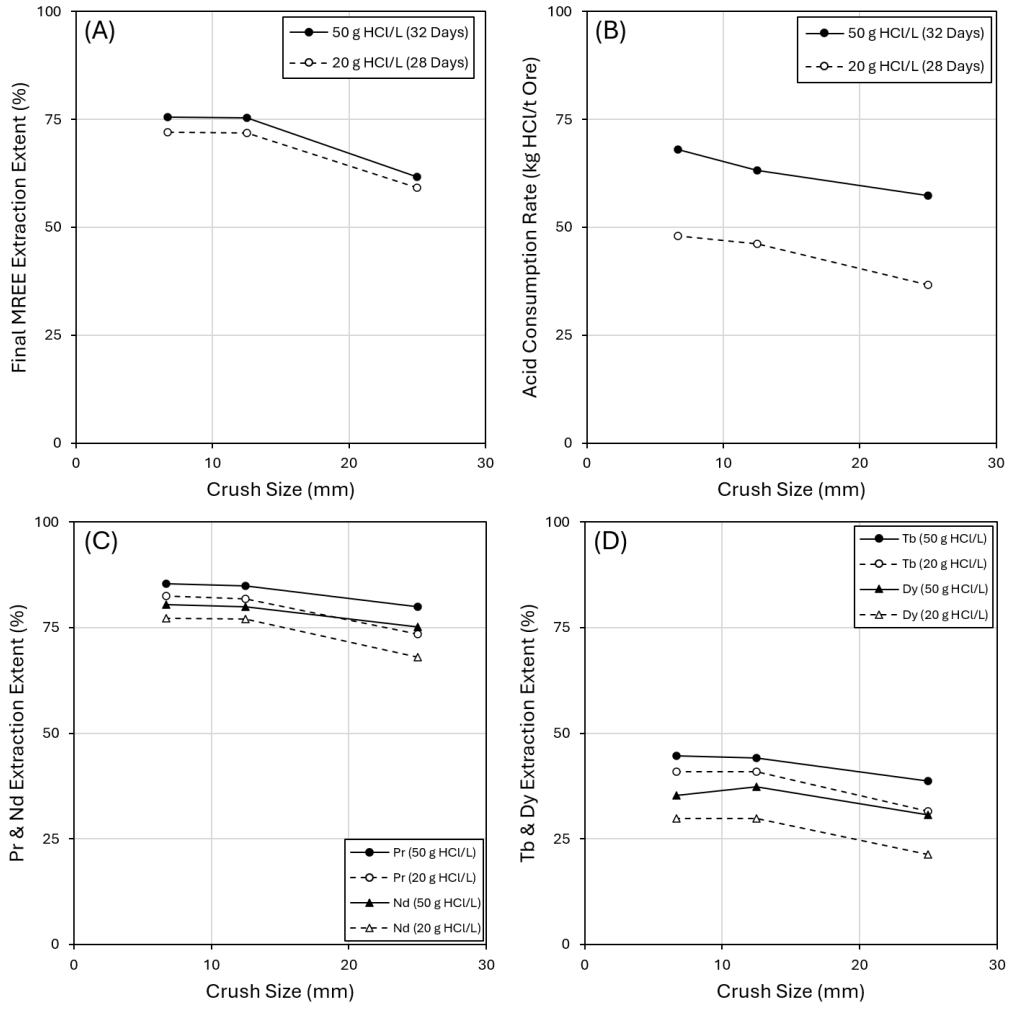


FIG 7 – Final MREE extraction extent (A), acid consumption rate (B) and extraction extents for Pr and Nd (C) and Tb and Dy (D) all versus crush size for bottle roll tests BR01 to BR06.

Acid consumption increases with decreasing crush size which is generally to be expected as finer crush sizes provide larger surface area for acid to access and be consumed, not just in the leaching of REE but also in the leaching of gangue elements. This is clear in the data with most impurity elements reported showing increased extraction with decreasing crush size.

Interestingly. There is only a slight advantage seen in the extraction of MREE with increasing acid concentration, however, a significant increase in acid consumption rate is noted. This primarily arises due to elevated levels of gangue acid consumption with higher acid concentration. This suggests that 20 g HCl/L should be the preferred acid concentration, as it still provides excellent MREE extraction while reducing unnecessary gangue acid consumption.

Figure 8 shows the MREE extraction and acid consumption rates versus time over the durations of all the bottle roll tests. For tests with the 25 mm crush size, the MREE extraction results indicate slower kinetics and overall lower extraction extents as expected. By contrast, the MREE extraction results for the 6.7 mm tests indicate fast kinetics and superior extraction extents.

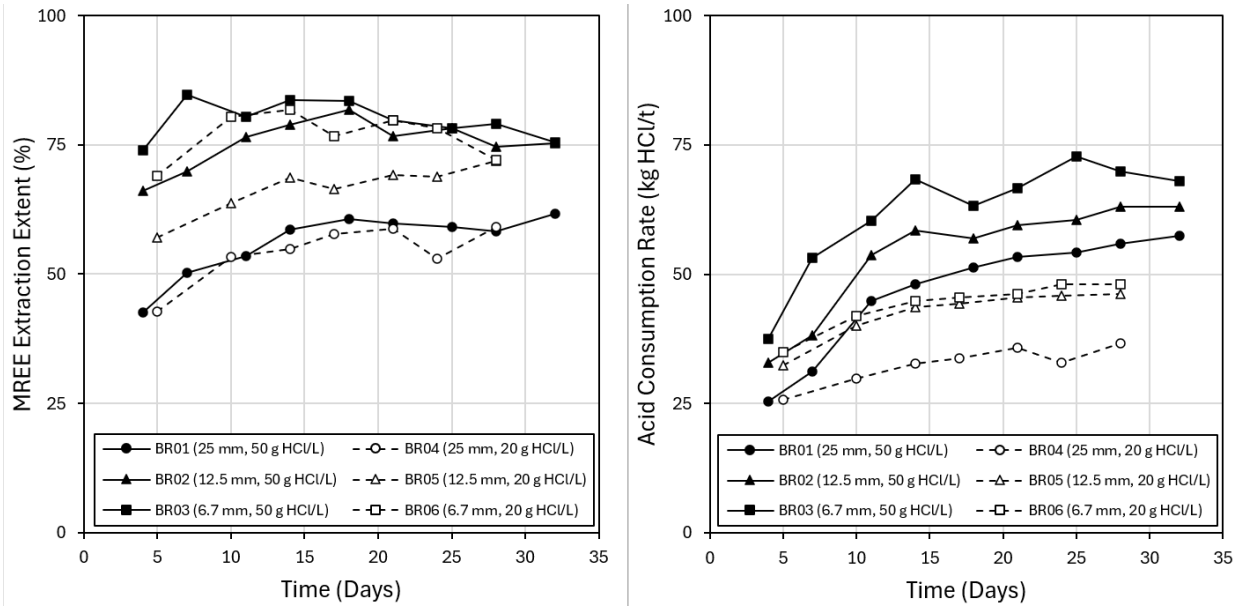


FIG 8 – MREE extraction extent (left) and acid consumption rate (right) versus time for bottle roll tests BR01 to BR06.

While there was little difference between the MREE extraction extent kinetic results for the 25 mm and 6.7 mm crush size when comparing the 20 and 50 g HCl/L acid dosage cases, there was significant difference between the two acid concentrations at a crush size of 12.5 mm. While no conclusive cause of this difference has been identified, it is possible that at the 12.5 mm crush size a transition occurs. At this crush size the material is sufficiently liberated to achieve higher extraction than at the 25 mm particle size, but the kinetics are still limited by the surface area available. Hence, the kinetics are faster when higher concentration acid is used. At the 6.7 mm crush size, the surface area is sufficient to effectively eliminate the particle size impact on the kinetics allowing for faster kinetics with a lower acid concentration. Ultimately though, after a period of 28–32 days, the extraction extents for MREE at a crush size of 12.5 mm converge on each other, negating the need for finer crushing.

Acid consumption rates showed significant variability across the six bottle roll tests, with the higher acid concentration showing the highest acid consumption rates, and the finer crush sizes also showing the highest acid consumption rates. Based on the kinetic and final extraction results, and the acid consumption rates, a crush size of 12.5 mm and an acid concentration of 20 g HCl/L appears to be the optimum, providing high MREE extraction (71.9 per cent) while minimising unnecessary gangue acid consumption.

Figure 9 shows the extraction extent for the individual MREEs versus time. As observed in Table 2, the extraction extents for terbium and dysprosium are lower than those for praseodymium and

neodymium. There is a suggestion that terbium and dysprosium are continuing to leach over time with their extractions continuing to trend upwards in most tests at the conclusion of the bottle rolls suggesting that higher residence times may provide improved extraction results.

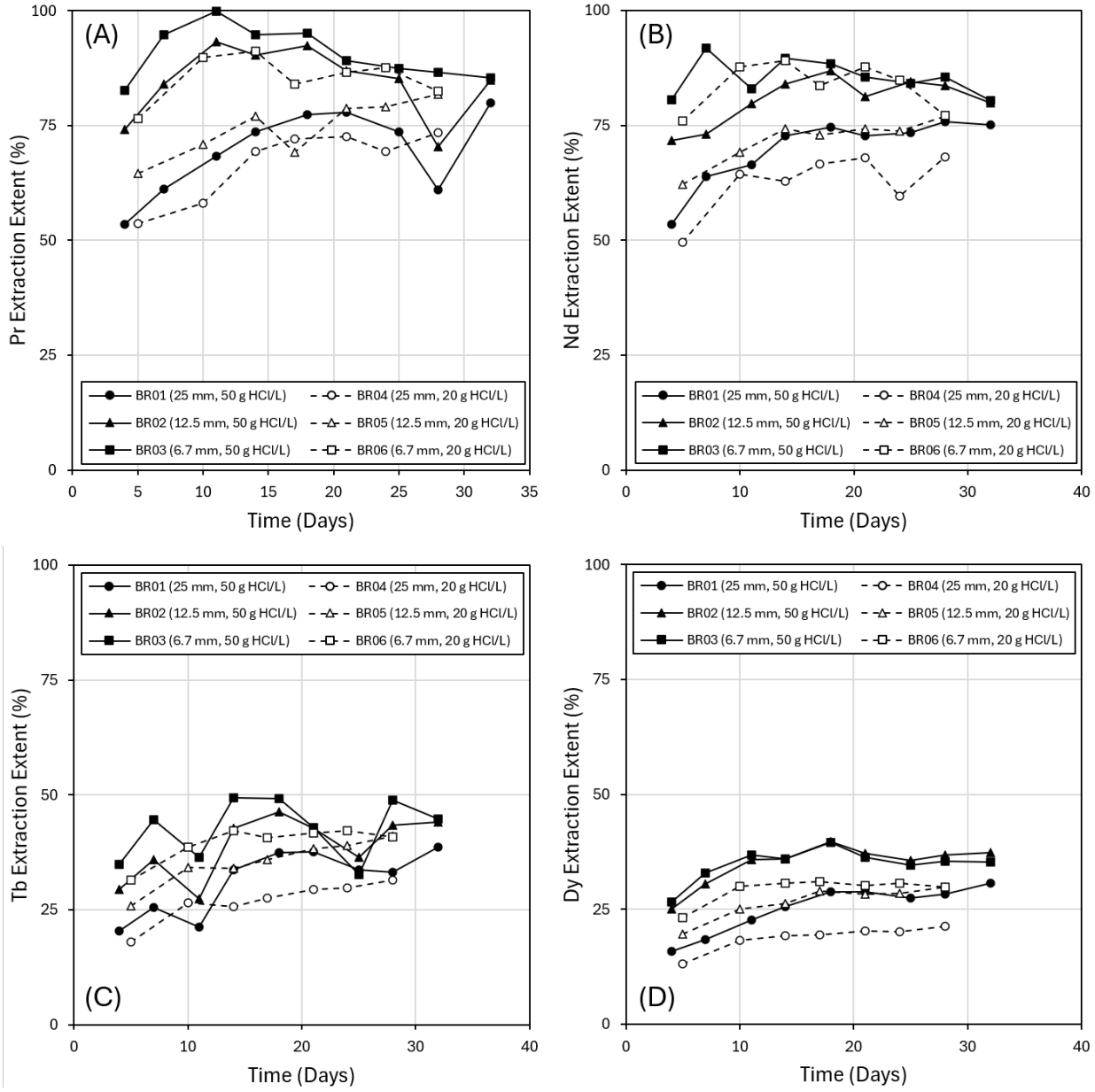


FIG 9 – Praseodymium (A), neodymium (B), terbium (C) and dysprosium (D) extraction extents versus time for bottle roll tests BR01 to BR06.

Table 5 shows the test conditions and results for bottle roll tests on each of the individual composites which provided optimal MREE extraction levels. Optimal conditions on all tests were found to be at a crush size of 12.5 mm except for one test on HLC2 where the optimal crush size was 25 mm. It is expected that this observation for HLC2 was an anomaly. Optimal acid concentrations for extraction were found to be 40–50 g HCl/L, however, as discussed earlier at these acid concentrations the total acid consumption rate is high and primarily driven by gangue acid consumption.

Extraction extents for the individual MREEs again show similar trends with Pr and Nd displaying higher extraction extents than Tb and Dy. It should be noted however that extraction extents for Tb and Dy do appear to be higher for HLC4–6 than for HLC1–3. The primary distinction between the HLC1–3 and HLC4–6 samples is that the HLC4–6 samples originate from deeper points in the drill holes.

TABLE 5

Test conditions and results for bottle roll leach tests with optimal MREE extraction results for all six composites tested in the bottle roll test programme.

Composite		**HCL1**	**HCL2**	**HCL3**	**HCL4**	**HCL5**	**HCL6**
Test ID		**BR02**	**BR07**	**BR14**	**BR22**	**BR26**	**BR28**
Crush size	mm	12.5	25	12.5	12.5	12.5	12.5
Acid concentration	g HCl/L	50	50	50	40	40	40
Duration	days	32	28	28	28	28	28
Acid consumption	kg/t	63.1	50.2	57.5	46.9	41.2	39.9
Extraction extents							
Pr	%	84.9	74.9	82.7	74.9	77.9	72.0
Nd	%	79.9	68.7	75.9	71.6	73.8	69.5
Tb	%	44.2	36.1	27.1	44.6	46.3	53.7
Dy	%	37.3	22.8	17.1	36.8	39.1	48.3
Total MREE	%	75.3	64.3	69.9	67.9	70.0	67.1

COLUMN LEACH TEST WORK

In this section, the column leach test work will be briefly introduced and discussed. In total 14 columns have been carried out in the test work program on different samples investigating different conditions including acid concentration, agglomeration conditions, crush size and salt addition. In this paper, however, the discussion will focus on a single 8 m column test that was conducted at Core. This test was designated as CLT11.

The 8 m column leach test was conducted on a composite sample of HLC4, HLC5 and HLC6 material. Agglomeration test work was used to optimise the agglomeration conditions in terms of moisture content and acid condition with the feed ore agglomerated to a moisture content of 6.0 wt per cent and an acid dosage of approximately 6.5 kg/t. Kappes percolation tests were conducted following the Kappes percolation test procedure (Pyper, Kappes and Albert, 2015) showed the agglomerated ore to have average auto and tapped slumps of 1.27 per cent and 15.6 per cent respectively and an average percolation rate of 20.7 $m^3/(h \cdot m^2)$. Figure 10 shows an image of the Kappes percolation tests.

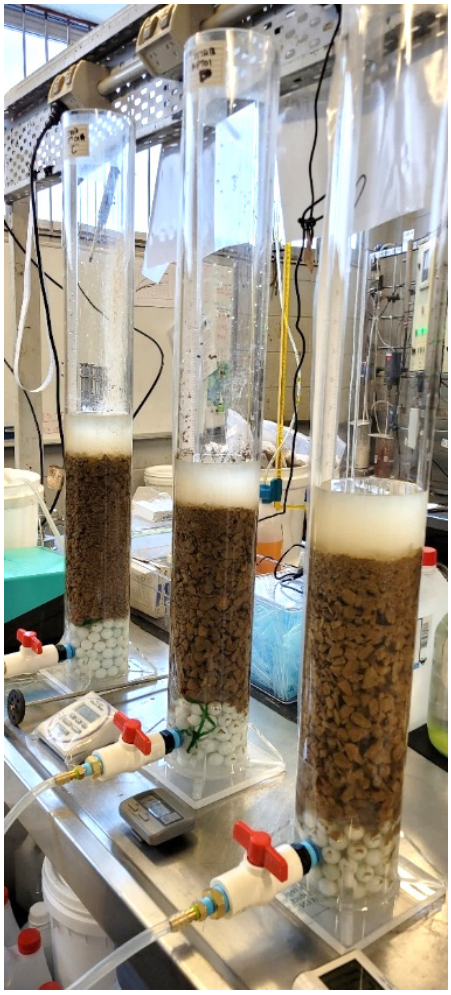


FIG 10 – Image of Kappes percolation test apparatus.

During the test work program, 13 of the 14 column tests utilised 2 m high columns consisting of a single 2 m column section with an internal diameter of 140 mm. For the 8 m column test however, the column was configured in two 4 m sections operated in series. The primary reason for this mode of operation is the height limitation of the laboratory. Figure 11 shows a schematic of the 8 m column test operation.

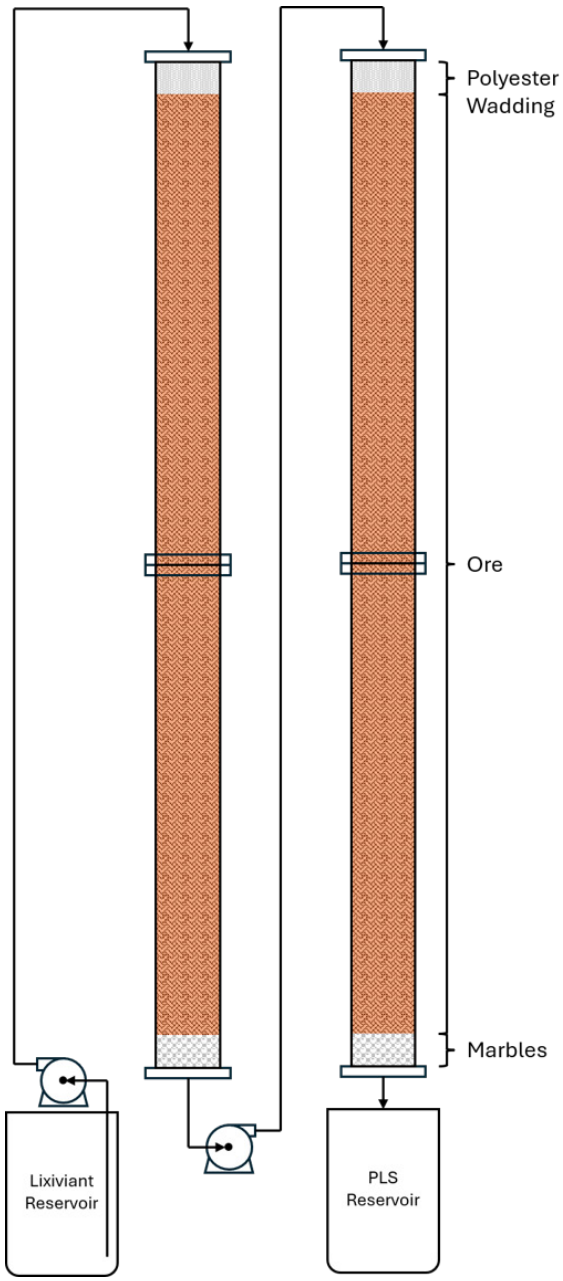


FIG 11 – Schematic of 8 m column leach test CLT12.

After the ore was agglomerated it was loaded into the columns on top of glass marbles which kept the ore from directly contacting the base of the column and allowing the lixiviant to completely drain from the ore at the base. Polyester wadding was placed on top of the ore to provide distribution of lixiviant entering the column over the top of the ore surface. Lixiviant was prepared in a reservoir and pumped into the first column using an Iwaki ES-B11VC metred pump and passed from the base of the first column to the top of the second column using a Watson Marlow 323S peristaltic pump which was seton a timer to pump for 1 min every 10 mins. The column was irrigated at a rate of 10.2 L/(h·m^2). The total operating time of the column was approximately 126 days. The lixiviant acid concentration was 10 g HCl/L for the first 63 days before being increased to 20 g HCl/L for the remaining time.

Monitoring of the column was conducted daily for the first week and three times weekly thereafter with monitoring involving topping up the lixiviant reservoir, collecting PLS from the PLS reservoir and measuring the free acid, pH, ORP and temperature of both reservoirs. At the conclusion of the column leach test, the columns were washed by submerging the ore in the columns with tap water for 24 hrs and rapidly discharging three times. The test conditions for column leach test CLT11 are given in Table 6.

TABLE 6

Test conditions for column leach test CLT11.

Variable	Units	CLT11
Feed material	-	HLC4/5/6 composite
Crush size	mm	12.5
Agglomeration moisture	wt %	6.0
Agglomeration acid	kg HCl/t ore	6.5
Lixiviant acid conc.	g HCl/L	10–20
Irrigation rate	L/(h·m^2)	10.2
Duration	days	126

Table 7 shows the final results after 126 days of operation for column leach test CLT11. Total MREE extraction for the column test was 71.9 per cent with the individual MREEs of Pr, Nd, Tb and Dy having extraction extents of 79.1 per cent, 75.4 per cent, 49.2 per cent and 42.7 per cent respectively. These extraction results align well with earlier bottle roll test work, and in some instances, especially for the Tb and Dy exceed many of the bottle roll test results. Additionally, the acid consumption rate for the column test was 30.2 kg/t, a lower result than observed in any of the bottle roll tests. It is hypothesised that the improve extraction and acid consumption rates observed in the 8 m column tests are primarily driven by enhanced acid efficiency as a result of an extended hydraulic residence time.

TABLE 7

Final acid consumption and extraction extent results for column leach test CLT11.

Variable		CLT11
Acid consumption	kg/t	30.2
Extraction extents		
La	%	83.0
Ce	%	72.1
Pr	**%**	**79.1**
Nd	**%**	**75.4**
Sm	%	63.5
Eu	%	53.8
Gd	%	54.9
Tb	**%**	**49.2**
Dy	**%**	**42.7**
Ho	%	36.9
Er	%	30.8
Lu	%	26.2
Tm	%	25.6
Yb	%	28.7
Y	%	37.6
Total MREE	**%**	**71.9**

Figure 12 shows the MREE extraction extent versus time. Initially the kinetic extractions are very fast with total MREE extraction increasing from 0 to 25 per cent within the first seven days of operation. The kinetics then gradual slow down before leveling out after between 100 and 120 days. The acid consumption rate increases virtually linearly for the first 63 days before the lixiviant acid concentration is increased to 20 g HCl/L. The impact of this change can be seen in acid consumption chart by an increase in acid consumption occurring after 63 days before slowing down after about 80 days. Interestingly, the increased acid concentration appears to have no impact on the MREE extraction suggesting that the increased acid consumption caused by the increased acid concentration was primarily driven by gangue acid consumption.

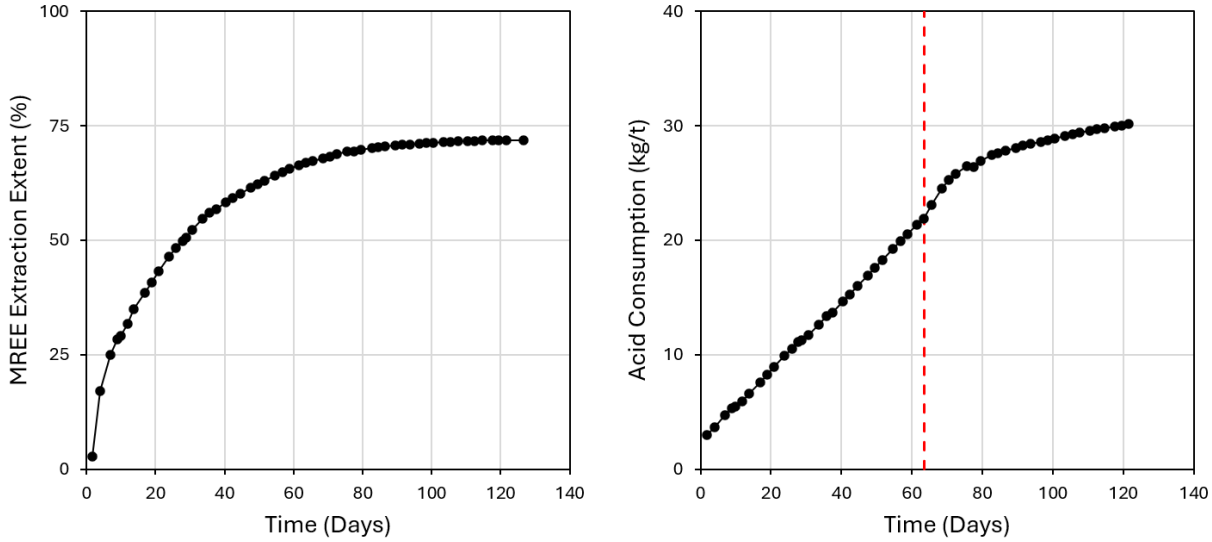


FIG 12 – MREE extraction extent (left) and acid consumption (right) versus time. The red vertical line on the acid consumption chart indicates the point the lixiviant acid concentration was increased from 10 to 20 g HCl/L.

Figure 13 shows the extraction extents versus time for the individual MRE elements Pr, Nd, Tb and Dy. As previously observed and discussed, the extractions for the 'light' MRE elements Pr and Nd were superior to the 'heavy' MRE elements of Tb and Dy. As the makeup of the total MREE is 86.6 per cent Pr and Nd, these elements account for most of the total MREE extraction making the total MREE extraction result more like the Pr and Nd results than the Tb and Dy results.

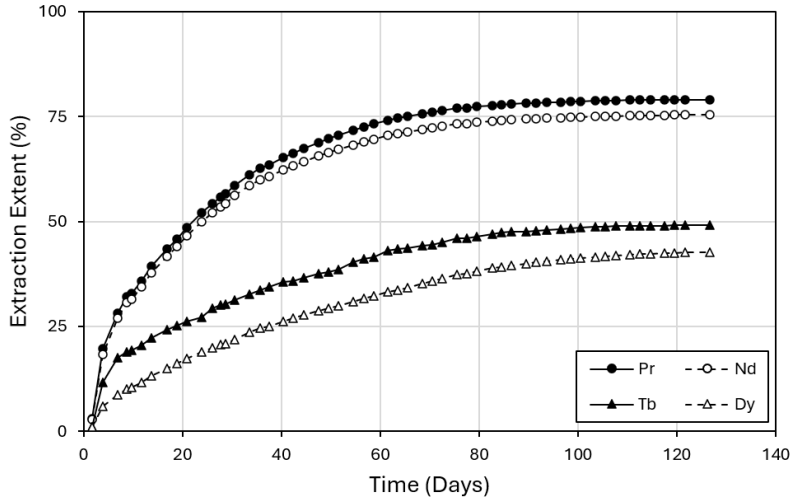


FIG 13 – Extraction extents versus time for individual MRE elements Pr, Nd, Tb and Dy.

Throughout all the test work, it has been clear that the ease of rare earth extraction decreases with increasing atomic mass (ie light rare earths leach easier than heavy rare earths). It is likely that this is driven by different mineralogical associations across the rare earth elements making heavier rare

earths more refractory than light rare earths, but also a shift from reagent limited to diffusion limited kinetics. This second observation arises due to the differing kinetic profiles between the Pr and Nd, and the Tb and Dy. While the kinetic rates are slower for Tb and Dy there is a suggestion that over an extended residence time Tb and Dy may continue to leach.

CONCLUSIONS AND FUTURE WORK

A comprehensive metallurgical test work program is currently underway at Core Resources in Brisbane, Australia for Australian Strategic Materials (ASM) to assist in the development of a heap leaching process for the Dubbo REE project. While the Toongi deposit is a world-class polymetallic resource containing not just REEs, but also deposit grade concentrations of other critical minerals including niobium and zirconium, ASM has recently made the shift to an 'REE first' strategy, to prioritise the development of the resource for REE extraction.

Initial test work conducted by Core focused on variability leach test work using sulfuric acid. Unfortunately, it was found that the variability was significant across the orebody. Poor extraction extents for magnet rare earth elements were noted and were found to be the result of sodium-REE double salt precipitation as evidenced by the relationship between MREE extraction and the Na:REE mass ratio in the PLS. As a result of this finding, it was decided to shift to a hydrochloric acid-based process.

The switch to hydrochloric acid was also noted to fit well with the current ASM flow sheet due to the prior inclusion of a chlor-alkali plant which would serve as a suitable source of HCl for the heap leach while also offering a means of recovering/recycling HCl on-site. While the continuation of the variability leach testing the HCl showed persistent variability, overall extraction results were improved and the dependence of MREE extraction on the Na:REE mass ratio was effectively decoupled.

Bottle roll test work investigating the effect of crush size and acid concentration on the leach extraction performance revealed an optimum crush size of 12.5 mm and an acid concentration of 20 g HCl/L. At these conditions, high extractions of 71.9 per cent MREE were achieved with total acid consumption rate of 46.2 kg HCl/t ore. While improvements in extractions with finer crush size and/or increased acid concentrations were noted, these improvements were slight and were offset by the consequence of elevated acid consumption rate due to further leaching of gangue elements. Further bottle roll test work conducted on samples collected from different drill holes showed excellent consistency of both extraction and acid consumption results across the Toongi deposit resource.

An 8 m column leach test confirmed the high levels of extractions observed in the bottle roll test work, and in some instanced exceeded their performance. Total MREE extraction over 126 days was found to be 71.9 per cent with individual MRE elements Pr, Nd, Tb and Dy having extraction extents of 79.1 per cent, 75.4 per cent, 49.2 per cent and 42.7 per cent respectively. Furthermore, the acid consumption rate was only 30.2 kg/t for the column test, lower than observed in any of the bottle roll test work indicating overall improved acid efficiency in the column test with continuous flow.

The information presented in this paper represents only a portion of the test work undertaken in the development of the HCl heap leach flow sheet for ASM's Dubbo Project. Further work is underway including additional column leach tests and downstream REE processing including impurity removal and mixed rare earth precipitation stages. Significant progress has been made in these areas with the intention to pilot precipitation stages of the process in late 2026.

ACKNOWLEDGEMENTS

The authors would like to thank ASM for their generosity in allowing us to publish data from testing conducted at Core Laboratories. The collaborative working team from ASM/Mworx/Core has provided an ideal forum for the rapid development of this heap leach-based flow sheet.

This project was support by grant funding under the Australian Government's International Partnerships in Critical Minerals (IPCM) Program.

REFERENCES

Alkane Resources Ltd, 2013. Definitive feasibility study confirms robust Dubbo zirconia project [online]. Available from <https://announcements.asx.com.au/asxpdf/20130411/pdf/42f5w86dfg7xyv.pdf> [Accessed: 25 July 2026].

Australian Strategic Materials Ltd (ASM), 2021. Dubbo Project Optimisation Delivers Strong Financials [online]. Available from: <https://announcements.asx.com.au/asxpdf/20211207/pdf/453w8493rvgqhv.pdf> [Accessed: 25 July 2026].

Australian Strategic Materials Ltd (ASM), 2025. Heap Leach options delivers major cost reductions for Dubbo Project [online]. Available from: <https://asm-au.com/investors/asx-announcements/#> [Accessed: 23 July 2026].

Australian Strategic Materials Ltd (ASM), 2026. The Dubbo Project [online]. Available from: <https://asm-au.com/mines/the-dubbo-project/> [Accessed: 25 July 2026].

Guzhov, B, Cassayre, L, Barnabé, A, Coppey, N and Biscans, B, 2023. Selective Precipitation of Rare Earth Double Sulfate Salts from Industrial Ni-MH Battery Leachates: Impact of Downstream Processing on Product Quality, *Batteries*, 9(12):574.

Porvali, A, Wilson, B P and Lundström, M, 2018. Lanthanide-alkali double sulfate precipitation from strong sulfuric acid NiMH battery waste leachate, *Waste Management*, 71:381–389.

Pyper, R, Kappes, D W and Albert, T, 2015. Evaluation of agglomerates using the Kappes Percolation Test, in *Proceedings of the 3rd International Conference on Heap Leach Solutions 2015*, pp 319–328 (Infomine Inc: Vancouver).

Spandley, C and Morris, C, 2016. Geology and genesis of the Toongi rare metal (Z, Hf, Nb, Ta, Y and REE) deposit, NSW, Australia, and implications for rare metal mineralization in peralkaline igneous rocks, *Contributions to Mineralogy and Petrology*, 171(104).

Hydrometallurgical processing of ferromanganese smelter wastes for high-purity manganese sulfate production

N D Ilankoon[1], E A Oraby[2] and J J Eksteen[3]

1. Research Fellow, Western Australian School of Mines, Curtin University, WA 6102. Email: nirmala.ilankoon@curtin.edu.au
2. Associate Professor, Western Australian School of Mines, Curtin University, WA 6102.
3. Professor, Western Australian School of Mines, Curtin University, WA 6102.

ABSTRACT

The increasing demand for battery-grade manganese products has created growing interest in recovering manganese from secondary resources. This study investigates the production of high-purity manganese sulfate monohydrate (HPMSM) from two ferromanganese smelter waste streams; slag and manganese mud derived from furnace dust. The mud, mainly composed of manganese carbonate, contains approximately 40 per cent Mn, while the slag contains around 20 per cent Mn. Separate leaching approaches were developed for each material due to their differing characteristics. Mud was treated via direct sulfuric acid leaching, achieving high manganese dissolution. Under optimum conditions, Mn recovery was above 90 per cent. In contrast, conventional acid leaching of slag led to silica-related gel formation, which made filtration difficult and time-consuming. To address this, a water-starved leaching method, also known as the ‘quick leach’ method, was developed. This approach involves an acid curing step followed by controlled leaching with limited water addition, resulting in significantly improved solid–liquid separation. Using this method, Mn recovery of approximately 85 per cent was achieved. Following leaching, the pregnant leach solutions (PLS) from both streams were purified through a combination of neutralisation-precipitation and solvent extraction (SX) processes. Neutralisation using hydrated lime effectively removed impurities such as Al, Fe, Si, and some Zn. Solvent extraction under proper conditions enabled selective extraction of manganese, while Ca and Mg remained largely in the raffinate. The purified manganese solution obtained after stripping was suitable for crystallisation. Preliminary crystallisation tests produced manganese sulfate crystals approaching Class II industry specifications for HPMSM. The proposed flow sheet demonstrates a practical and promising hydrometallurgical route for converting ferromanganese smelter wastes into a high-value product, supporting more circular and sustainable manganese processing.

An integrated power-process-data architecture for resilient critical mineral processing

E Kashi[1]

1. National Strategic Account Manager – Technology and Innovation, Schneider Electric, Melbourne Vic 3000. Email: ella.kashi@se.com

INTRODUCTION

Critical mineral supply chains are expanding under strategic demand, trade restrictions and high refining concentration. The International Energy Agency reports that the average share of the three largest refining countries rose from 82 per cent in 2020 to 86 per cent in 2024, while export controls are extending from raw materials to processing technologies (IEA, 2025). Resilience therefore requires more than new capacity: plants must maintain saleable product quality as ore mineralogy, power availability, reagent supply, customer specifications and market value change.

This paper proposes a Schneider Electric power-process-data architecture for beneficiation, extraction and refining. Sensor-based separation, coarse rejection, advanced flotation, hydrometallurgy and modular refining create value only when their control, electrical and information systems are engineered as one operating system. The objective is minimum risk-adjusted cost per saleable tonne within recovery, grade, energy, water, equipment and product-qualification constraints.

TECHNICAL DESIGN BASIS

Critical mineral flow sheets are highly sensitive to feed variability. Changes in hardness, liberation size, deleterious elements, clay content and oxidation state propagate from crushing and grinding into classification, flotation, leaching, solid-liquid separation and finishing. The design basis should couple geometallurgical domains with an online mass-water-energy balance. Measurements should include belt or slurry analysers, particle-size distribution, density, flow, pH, oxidation-reduction potential, conductivity, froth characteristics, motor current, vibration and power quality. Laboratory assays remain the calibration reference, while soft sensors estimate unmeasured states and detect model drift.

Early gangue rejection through sorting, screening or coarse separation can reduce downstream tonnes, but control must account for metal deportment and reject-stream uncertainty. Coarse-particle flotation or intensified leaching should likewise be evaluated against recovery, concentrate grade, water recovery, reagent intensity and downstream impurity loading, not a single unit-operation KPI. A digital process model should preserve these balances from design through operation so that gains are not achieved by transferring instability or cost downstream.

INTEGRATED POWER-PROCESS-DATA ARCHITECTURE

At the field and electrical layer, intelligent motor control centres, variable-speed drives, medium- and low-voltage distribution, protection relays and power-quality metres should share time-synchronised data with process instrumentation. Control logic can then distinguish a process constraint from an electrical disturbance and coordinate load shedding, restart sequencing and microgrid operation. For weak-grid projects, the power-management system should forecast available generation and storage and publish dynamic power constraints to the plant control system.

At the control layer, distributed control system (DCS) and programmable logic controllers (PLC) systems execute regulatory and sequence control, while advanced process control uses feed-forward variables, inferential measurements and multivariable model-predictive control. An economic objective can minimise J = CeE + CwW + CrR + CdD – VmMs, where E is energy, W water, R reagents, D downtime and Ms saleable product, subject to metallurgical, product, equipment and environmental limits. Manipulated variables may include mill load, water addition, cyclone pressure, air rate, froth depth, reagent dosage, leach conditions and thickener operation. Schneider Electric describes this integrated approach as combining power supply and process

control, with Advanced Process Control (APC) used to stabilise quality, maximise utilisation and reduce energy, water and chemical consumption (Schneider Electric, 2026).

At the operations layer, a redundant historian and common asset model contextualise tags by equipment, stream, ore type, shift and campaign. Production management automates mass balancing, downtime and rate-loss classification, time-usage accounting and metallurgical reconciliation. Asset analytics combine condition data with process duty; a pump vibration alarm, for example, is interpreted with slurry density, speed and recirculating load. At the product layer, genealogy links ore source, operating conditions, laboratory certificates, storage and shipment, allowing customer-qualification or impurity excursions to be traced. Role-based access, network segmentation, secure remote support, redundant critical services and open interfaces prevent digital dependency becoming a new single point of failure.

OPERATING EVIDENCE FROM SCHNEIDER ELECTRIC AND AVEVA

Published customer cases illustrate design patterns rather than universal performance guarantees. At Newcrest Mining's Cadia operation, a scalable, redundant AVEVA™ PI System™ architecture supported model-driven virtual sensors. The reported outcome was 650 000 additional tonnes of throughput in six months and a 50 per cent reduction in crushing-circuit downtime; virtual level estimation allowed the coarse-ore-bin, run-of-mine and conveying system to continue during physical sensor failure (AVEVA, nd[a]). This demonstrates the resilience value of redundant data infrastructure and state estimation.

Talison Lithium standardised KPI calculations, time-usage models, equipment types and cause-and-effect classifications across crushing, technical-grade and chemical-grade plants. AVEVA Production Management, Historian, Insight and Plant SCADA created a pit-to-port data chain; the case reports 50 per cent faster root-cause analysis, automated month-end reconciliation and more accurate downtime attribution (AVEVA, nd[b]). The lesson is that analytics become actionable only after event models, tag context and metallurgical accounting are standardised.

At Black Rock Mine Operations, three shafts and fragmented operational and MES environments were integrated through AVEVA System Platform, Historian and OMI in a central control room. Reported outcomes included more than five-fold improvement in some data-quality sources, in-shift reporting increasing from below 50 per cent to a sustained 90 per cent, and nearly double-digit productivity growth (AVEVA, nd[c]). This supports local autonomous control combined with a common information layer coordinating the value chain from face to train loading.

IMPLEMENTATION AND CONCLUSION

Implementation should be stage-gated. Concept selection requires a common mass, water, energy and impurity model plus a quantified control philosophy. During front-end engineering, the electrical single-line diagram, control narratives, data model, cybersecurity zones and product-genealogy requirements should be co-developed. Dynamic simulation should test start-up, shutdown, ore transitions, analyser failure, power limitation and recycle disturbances. Factory and site acceptance tests should verify data lineage, failover, alarm performance and communications recovery, not only individual devices.

In operation, value should be governed through reconciled metrics: saleable tonnes, recovery, specification compliance, energy and water per saleable tonne, reagent intensity, constraint time, unplanned downtime and forecast error. Advanced processing is a system capability, not isolated technology. Integrating selective flow sheets with power-aware control, soft sensing, production accounting and product traceability provides a credible route to lower operating cost and greater resilience in diversified critical mineral supply chains.

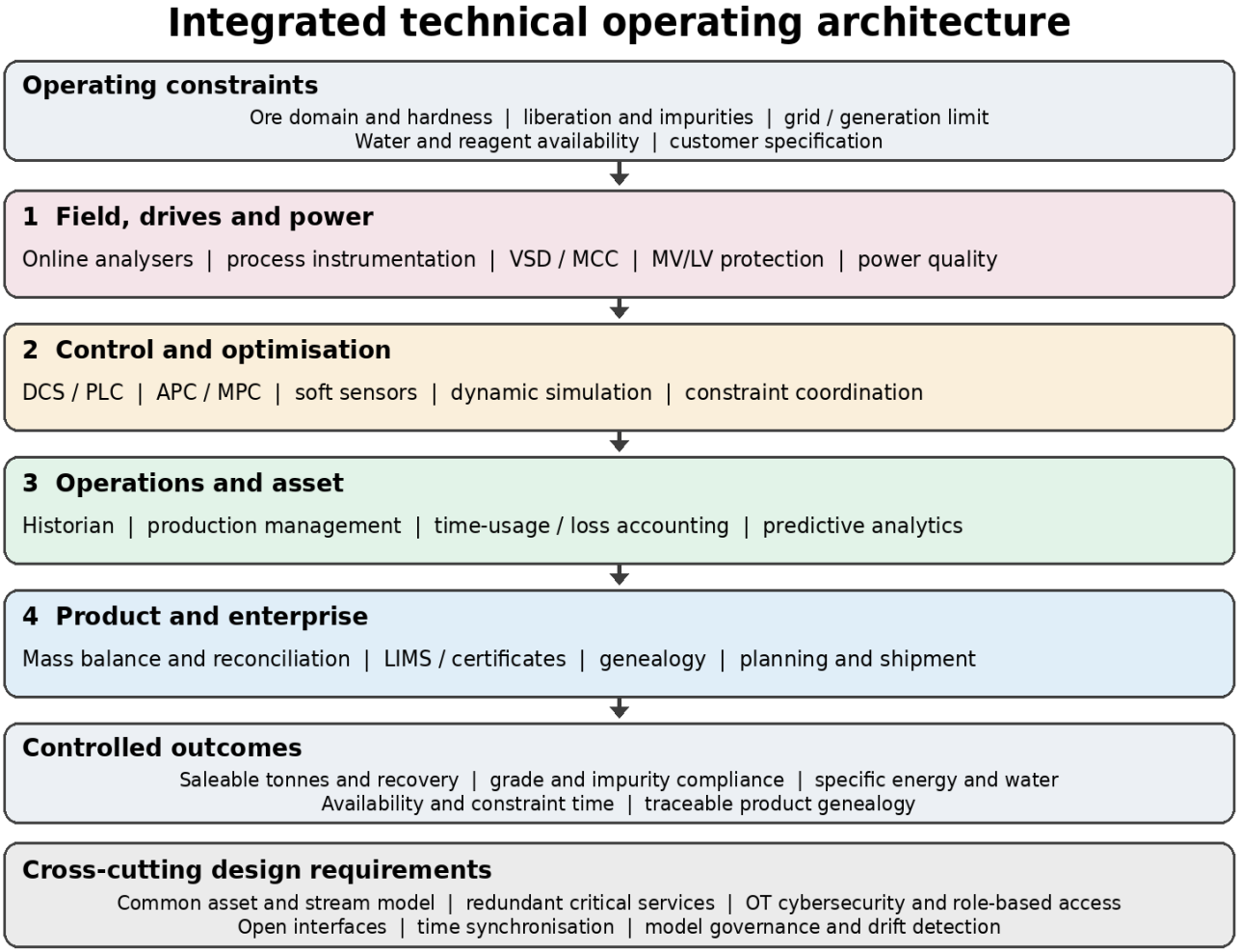


FIG 1 – Power-process-data architecture linking operating constraints to controlled metallurgical and resilience outcomes.

ACKNOWLEDGEMENTS

The author acknowledges Schneider Electric and AVEVA personnel whose published technical material and customer success stories informed this paper. Generative artificial intelligence supported language refinement and document formatting; all technical interpretations, claims and references were reviewed by the author (OpenAI, 2026).

REFERENCES

AVEVA, nd[a]. Newcrest Mining: analysing real-time data to reduce downtime in gold mines with AVEVA™ PI System™. Available from: <https://www.aveva.com/en/perspectives/success-stories/newcrest-mining/> [Accessed: 15 July 2026].

AVEVA, nd[b]. Talison Lithium boosts competitiveness and reduces downtime. Available from: <https://www.aveva.com/en/perspectives/success-stories/talison-lithium/> [Accessed: 15 July 2026].

AVEVA, nd[c]. Black Rock Mine Operations (BRMO). Available from: <https://www.aveva.com/en/perspectives/success-stories/brmo/> [Accessed: 15 July 2026].

International Energy Agency (IEA), 2025. Global Critical Minerals Outlook 2025, Paris: IEA.

OpenAI, 2026. ChatGPT, assistance with language refinement and document formatting. [Accessed: 15 July 2026].

Schneider Electric, 2026. Mining, minerals and metals processing and plant refining. Available from: <https://www.se.com/au/en/work/solutions/mining-minerals-metals/processing-and-refining/> [Accessed: 15 July 2026].

Turning pyrite to pyrrhotite for critical metal extractions – reactions during thermal decomposition

L Kng[1], O Mejías[2], X Ma[3], H Degeling[4], A Tong[5], A Randall[6], H Porteous[7] and A Parbhakar-Fox[8]

1. PhD candidate, University of Queensland, Sustainable Minerals Institute, Brisbane Qld 4068; ARC Training Centre in Critical Resources for the Future, Brisbane Qld. Email: l.kng@uq.edu.au
2. Research Fellow, University of Queensland, Sustainable Minerals Institute, Brisbane Qld 4068; ARC Training Centre in Critical Resources for the Future, Brisbane Qld. Email: o.mejiasgonzalez@uq.edu.au
3. Senior Research Fellow, University of Queensland, Sustainable Minerals Institute, Brisbane Qld 4068. Email: x.ma@uq.edu.au
4. Technical Director – Geoscience and Sustainability, Mining3, Brisbane Qld 4069. Email: hdegeling@mining3.com
5. Chief Executive Officer, Cobalt Blue Holdings, North Sydney NSW 2060. Email: andrew.tong@cobaltblueholdings.com
6. Operations Manager, Cobalt Blue Holdings, Broken Hill Technology Centre, Broken Hill NSW 2680. Email: adam.randall@cobaltblueholdings.com
7. Exploration Manager, Cobalt Blue Holdings, North Sydney NSW 2060. Email: heath.porteous@cobaltblueholdings.com
8. Honorary Professor, University of Queensland, Sustainable Minerals Institute, Brisbane Qld 4068. Email: a.parbhakarfox@uq.edu.au

ABSTRACT

Pyrite is widely treated as a non-valuable and problematic mineral by environmental and mineral processing professionals (Jefferson *et al,* 2023). However, pyrite is known for hosting potentially critical and economically valuable elements (Co, Zn, Cu, Pb, Ni, Se, Au; Steadman *et al,* 2021; Babedi *et al,* 2022; Erlandsson *et al,* 2025; Li *et al,* 2025) in various deposit types (Carlin, epithermal high- and low-sulfidation, epithermal alkaline, orogenic Au and porphyry Cu; Keith *et al,* 2018; Babedi *et al,* 2022). In fact, pyrite contributes 4–8 wt per cent within Cu tailings (Santander and Valderrama, 2019). When oxidised, it is the main contributor for acid rock and metalliferous drainage (AMD; Xu *et al,* 2025). To reduce environmental risks associated with tailings, pyrite could be selectively recovered as part of a rehabilitation measure. Cobalt Blue's patented technology – turning pyrite to pyrrhotite through thermal decomposition (Cobalt Blue Holdings, 2025), followed by leaching critical metals, has shown the potential to deliver benefits throughout the entire life-of-mine. They offer the potential to reduce mine waste acid-forming potential whilst enhancing recovery of critical metals, thereby contributing to the principles of a circular economy and sustainable development goals. This research will explain the pyrite-pyrrhotite reaction mechanisms using Cobalt Blue's patented technology and emerging technologies; identify the intrinsic and physical properties of pyrite and the behaviour of pyrite during the thermal decomposition process; explore the influence of secondary minerals on the mineral processing performance of pyrite and; combine all observed results to establish a pyrite prediction pathway for the thermal decomposition processing method for different deposits. This thermal decomposition-leaching technology enables the recovery of valuable metals to support the green energy transition (eg Co, Ni) and sulfuric acid production.

REFERENCES

Babedi, L, von der Heyden, B P, Tadie, M and Mayne, M, 2022. Trace elements in pyrite from five different gold ore deposit classes: A review and meta-analysis, *Geological Society, London, Special Publications*, 516:47–83.

Cobalt Blue Holdings 2025. Broken Hill Cobalt Project. Available from: <https://cobaltblueholdings.com/broken-hill-cobalt-project>.

Erlandsson, V B, Foltyn, K, Muchez, P, Rantitsch, G, Ellmies, R and Melcher, F, 2025. Chalcopyrite, sphalerite, and pyrite chemistry in stratiform sediment-hosted Cu(-Co) metallogenic districts: trace element characteristics and factors controlling polymetallic mineralization, *Mineralium Deposita*, 60(5):869–894.

Jefferson, M, Yenial-Arslan, U, Evans, C, Curtis-Morar, C, O'Donnell, R, Parbhakar-Fox, A and Forbes, E, 2023. Effect of pyrite textures and composition on flotation performance: A review, *Minerals Engineering*, 201:108234.

Keith, M, Smith, D J, Jenkin, G R, Holwell, D A and Dye, M D, 2018. A review of Te and Se systematics in hydrothermal pyrite from precious metal deposits: insights into ore-forming processes, *Ore Geology Reviews*, 96:269–282.

Li, L, Wang, H, Zhang, D, Zhou, J, Yang, C, Jiang, Y, Shen, L and Luo, K, 2025. Origin of the recently-discovered Zhongpai Co-rich pyrite deposit in the Lanping-Simao Basin, southwest China: Constraints of trace elements and S isotopes of pyrite and U-Pb ages of monazite, *Journal of Asian Earth Sciences*, 280:106471.

Santander, M and Valderrama, L, 2019. Recovery of pyrite from copper tailings by flotation, *Journal of Materials Research and Technology*, 8(5):4312–4317.

Steadman, J A, Large, R R, Olin, P H, Danyushevsky, L V, Meffre, S, Huston, D, Fabris, A, Lisitsin, V and Wells, T, 2021. Pyrite trace element behavior in magmatic-hydrothermal environments: An LA-ICPMS imaging study, *Ore Geology Reviews*, 128:103878.

Xu, C, Fu, H, Liu, W, Zhu, B, Xie, X, Hu, Y, Huang, J and Li, Z, 2025. Inhibitory effects and mechanisms of smoldering combustion-derived biochar covers on pyrite oxidation and acid mine drainage formation, *Journal of Environmental Sciences*, 165:38–48.

Simple yet accurate routine analysis of rare earth materials from ores through to concentrates using a single X-ray fluorescence application

A Komelkov[1], H Bhaskar[2], M Luce[3] and L Grimsley[4]

1. XRF Application Specialist, Malvern Panalytical B.V., Almelo 7602EA, The Netherlands. Email: alexander.komelkov@malvernpanalytical.com
2. Product Manager – Process and Automation Solutions, Malvern Panalytical, Canning Vale, Perth WA 6155, Australia. Email: hari.bhaskar@malvernpanalytical.com
3. Analytical Laboratory Lead, Malvern Panalytical Ltd., Tollerton Nottingham NG12 4GQ, United Kingdom. Email: miles.luce@malvernpanalytical.com
4. Quality Manager and Standards Production Supervisor, Malvern Panalytical Ltd., Tollerton Nottingham NG12 4GQ, United Kingdom. Email: leian.grimsley@malvernpanalytical.com

ABSTRACT

The analysis of rare earth elements (REEs) across beneficiation processes and in final concentrates is analytically challenging due to wide compositional variability, complex mineralogy, matrix effects, and inter-element spectral interferences. While wet-chemical, inductively coupled plasma (ICP), and X-ray fluorescence (XRF) techniques are commonly applied, XRF is often limited to process control rather than primary analysis. This is largely due to the lack of suitable calibration standards, certified reference materials, and limited specialist XRF expertise.

Accurate XRF analysis requires calibration standards that adequately represent the range of matrices and concentration levels encountered in REE processing. In this work, a suite of 25 synthetic calibration standards was developed to replicate the compositional diversity present across REE beneficiation flow sheets. These standards were specifically designed for borate fusion sample preparation for XRF analysis.

A dedicated REE wavelength-dispersive XRF (WD-XRF) application was established, incorporating more than 50 analytical and auxiliary fluorescence lines with optimised background correction. The method corrects for over 200 spectral overlaps and, combined with an inter-element matrix correction model, provides linear calibration over wide concentration ranges—from several hundred ppm to tens of per cent—for 44 analytes. The approach performs consistently across silicate-, clay-, and carbonate-rich ores, intermediate beneficiation products, and high-grade REE concentrates. It is also applicable to mineral sands with elevated Ti and/or Zr, as well as Ba-, Ta-, and Nb-rich materials relevant to critical minerals processing.

Method accuracy and trueness were validated using commercially available certified reference materials, demonstrating analytical performance comparable to established wet-chemical and ICP-based techniques. Limits of quantification typically fall within 200–400 ppm, depending on the element.

Borate fusion sample preparation offers reduced environmental impact and lower operating costs compared with conventional analytical workflows. The method is readily transferable between laboratories and can be combined with pressed-pellet WD-XRF techniques to achieve detection limits of a few ppm for selected elements.

Selective flocculation-flotation of fine spodumene – recovering lithium from particles currently lost to tailings

D Luo[1,4], W S Ng[2,4] and G V Franks[3,4]

1. Research Fellow, Department of Chemical Engineering, University of Melbourne, Parkville Vic 3010. Email: d.luo@unimelb.edu.au
2. Research Fellow, Department of Chemical Engineering, University of Melbourne, Parkville Vic 3010. Email: w.ng@unimelb.edu.au
3. Professor, Department of Chemical Engineering, University of Melbourne, Parkville Vic 3010. Email: gvfranks@unimelb.edu.au
4. Future Battery Industries Cooperative Research Centre, Bentley WA 6102; ARC Centre of Excellence for Enabling Eco-Efficient Beneficiation of Minerals, Callaghan NSW 2308.

ABSTRACT

A challenge in hard rock lithium processing is the loss of fine spodumene particles to tailings during desliming. At typical west Australian lithium sites, particles finer than 45 μm are classified as non-recoverable. Conventional froth flotation is inefficient for particles below approximately 38 μm due to poor particle–bubble collision efficiency. Flocculation-flotation is a promising approach of aggregating fine particles to sizes more amenable to recovery by flotation.

This study demonstrates selective flocculation-flotation as a viable approach to recover fine spodumene (d_{50} ~ 22 μm) from synthetic spodumene–quartz mixtures. Calcium ions serve as a dual activator, promoting sodium oleate (NaOl) and anionic polyacrylamide (PAM) flocculant adsorption onto spodumene surfaces to produce selective aggregates of approximately 100 μm, within the optimal size range for bubble–particle attachment. A key innovation is premixing PAM with NaOl before addition to the flotation pulp. Contact angle measurements show that premixed delivery raises the spodumene contact angle to 60.8° versus approximately 45° under sequential addition, while quartz surfaces remain near 45° and are not effectively recovered. Premixing shifts reagent adsorption from competitive to cooperative, with the preformed polymer–NaOl complexes promoting co-adsorption that neither reagent achieves alone in sequential dosing.

Optimal conditions were identified at pH 8.5, 625 g/t Ca(II), 6000 g/t NaOl, and 80 g/t PAM at high anionic charge. Spodumene recovery increased from 25 per cent (grade 82 per cent; 6.6 per cent Li_2O) without polymer to 72 per cent (grade 70 per cent; 5.6 per cent Li_2O); a nearly threefold improvement while maintaining commercially relevant grade. Higher polymer charge densities selectively excluded quartz from aggregates via electrostatic repulsion, improving concentrate grade without sacrificing recovery.

All results used commercially available polymers (Syensqo Cyfloc and BASF Alclar series) and standard flotation equipment, establishing a clear pathway to industrial scale-up. The approach offers a meaningful opportunity to improve lithium yield, reduce tailings volumes, and strengthen the sustainability of Australian spodumene operations.

Midstream in Australia – ambition versus reality: confronting the structural constraints

N Mackay[1] and S Salter[2]

1. Managing Director, Critical Minerals Association Australia, Brisbane Qld 4000.
   Email: namali@cmaaustralia.org
2. WA Representative, Critical Minerals Association Australia, Perth WA 6000.
   Email: simon@cmaaustralia.org

ABSTRACT

Despite increasing policy focus on value-adding within Australia's critical minerals sector, the development of a domestic midstream industry has seen limited progress beyond feasibility stage. This paper provides a commercially grounded assessment of why midstream processing and refining continue to develop offshore, despite Australia's strong resource endowment and growing strategic importance. The analysis identifies a set of persistent structural constraints. These include high and volatile energy costs, limited domestic demand, lack of integration with downstream industries, constrained access to capital, infrastructure gaps, and shortages in specialised metallurgical expertise. These challenges are particularly acute in non-commoditised critical minerals markets, where products are low-volume, non-fungible, and must meet precise customer specifications – resulting in thin margins and limited tolerance for cost inefficiencies. A central finding is that standalone midstream operations in Australia are rarely commercially viable under current conditions. This position has not materially shifted over the past 12–18 months, with most projects remaining at feasibility stage and limited evidence of scaled domestic processing. As a result, value-add continues to occur in jurisdictions with lower-cost energy, established chemical industries, and closer proximity to end markets. International experience reinforces that successful midstream industries do not develop in isolation. They require co-location with downstream demand, access to reliable and competitively priced energy, coordinated government support, and integration into broader industrial ecosystems. Without these co-existing conditions, midstream development remains structurally challenged. The paper concludes that Australia's midstream ambitions must be more tightly aligned with commercial realities. This includes prioritising upstream project development, focusing on a limited number of strategic commodities, investing in enabling conditions – particularly energy – and pursuing targeted international partnerships to integrate into allied value chains. The key message is clear: investment will follow commercial viability, not policy ambition. Without addressing the underlying structural constraints, Australia risks continuing to export raw materials while value creation occurs elsewhere.

Adapting to declining ore grades – two-stage copper smelting and the role of calcium ferrite slags

E Mercy[1], X Wen[2], M Shevchenko[3] and E Jak[4]

1. MPhil Student, PYROSEARCH, Brisbane Qld 4072. Email: e.mercy@uq.edu.au
2. Postdoctoral Research Fellow, PYROSEARCH, Brisbane Qld 4072. Email: x.wen@uq.edu.au
3. Senior Research Fellow, PYROSEARCH, Brisbane Qld 4072. Email: m.shevchenko@uq.edu.au
4. Centre Director, PYROSEARCH, Brisbane Qld 4072. Email: e.jak@uq.edu.au

ABSTRACT

Copper is classified as a strategic or critical metal in many countries. Its importance extends beyond complementing critical metals, as copper is indispensable for electrification technologies, including power generation, transmission, energy storage, and electric mobility. Ensuring secure and efficient copper production is therefore a prerequisite for enabling large-scale electrification goals worldwide.

For decades, the Australian copper industry has benefited from high-quality concentrates, enabling the widespread adoption of streamlined processing technologies. A prime example is the BHP Olympic Dam operation, which utilises the Direct-to-Blister (DB) smelting process. Although DB smelting is renowned for its efficiency and high throughput, it is inherently inflexible and requires high-grade feed to maintain stable operation. With declining ore grades, Olympic Dam is forced to adapt to the more accessible concentrates with lower copper grades and higher impurity levels.

To maintain metallurgical recovery and product quality under these conditions, a shift toward two-stage continuous processing comprising flash smelting followed by flash continuous converting is becoming increasingly important. This double-flash configuration offers greater flexibility for treating complex feeds and is already being implemented in rapidly growing processing hubs, such as the Manyar smelter in Indonesia. For Olympic Dam, this technology provides a potential pathway to maintain high throughput while reducing environmental impact.

The transition to two stage processing introduces additional complexity, particularly in slag chemistry, slag refractory interactions, and impurity removal mechanisms. Flash converting furnaces employ calcium ferrite slags, which differ fundamentally in chemistry from the more commonly studied fayalite slags and for which fundamental thermodynamic data remain limited. This study addresses that gap through an experimental investigation of the $CuO_{0.5}$-$FeO_{1.5}$-CaO-MgO-SiO_2-$AsO_{2.5}$ system equilibrated with metallic copper, using high temperature equilibration combined with electron probe microanalysis (EPMA WDS) to determine phase relationships and trace element partitioning. The resulting experimental data were used to refine the FactSage thermodynamic database for calcium ferrite slags, improving the accuracy of predicted phase boundaries and liquidus relationships within this system. A key finding demonstrates that the behaviour of arsenic bearing solid phases in the calcium ferrite slag system provides insight into how arsenic partitions between coexisting phases, with implications for impurity control and emission regulation compliance during converting. By generating new data for this less studied slag system, the study supports the development of resilient continuous copper processing technologies.

An investigation into the current leading solid-state battery chemistry options, precursor materials and processing requirements

A D R Millar[1]

1. Principal Process Engineer, Idemitsu Australia, Wynnum West Qld 4178.
   Email: andrew.millar@idemitsu.com.au

ABSTRACT

Solid-state batteries are widely regarded as a next-generation battery technology capable of delivering improvements in safety, energy density, cycle life and charging performance relative to conventional liquid electrolyte lithium-ion systems. While global attention has largely focused on cell design and electrochemical performance, less consideration has been given to the upstream implications for critical mineral supply chains, precursor processing, and value-added opportunities.

This paper examines the leading solid-state battery chemistry pathways currently under development, including sulfide-based, oxide-based and emerging sodium-based systems. Emphasis is placed on the mineral precursors required for each chemistry, their processing routes, and the technical challenges associated with achieving the purity, consistency, and scale demanded by advanced battery manufacture. The analysis highlights how different electrolyte chemistries generate materially different demand profiles, with lithium and phosphorus emerging as the most strategically relevant precursor elements in an Australian context, supported by additional requirements for sulfur, sodium, aluminium, silicon, lanthanum, titanium, zirconium and germanium.

Particular focus is given to sulfide and oxide electrolyte systems, which currently dominate research activity and early commercialisation efforts, together with sodium-based systems as an adjacent pathway. These systems present both opportunities and constraints from a minerals processing perspective, including moisture-sensitive sulfide handling, high-temperature ceramic processing and the need for tightly controlled impurity management. Conversely, they also offer potential pathways for downstream processing and chemical manufacturing that extend beyond traditional concentrate production.

The paper further considers where strategic opportunities may exist for Australia within the evolving solid-state battery supply chain, particularly in the context of national critical minerals strategies and investment frameworks. By linking battery chemistry to precursor requirements and downstream processing routes, this work aims to support more informed policy, investment, and project development decisions. Solid-state batteries are therefore framed not only as a battery technology, but as a shift in future critical mineral demand and downstream precursor production. This perspective provides timely context for stakeholders seeking resilient, diversified, and technically informed pathways into emerging battery materials markets globally.

INTRODUCTION

What are solid-state batteries?

Solid-state batteries use a solid electrolyte for transporting ions between the cathode and anode. This is unlike conventional lithium-ion batteries, which rely on liquid or gel electrolytes to transport ions.

As with conventional lithium-ion batteries, energy is stored and released through ion movement between a cathode and an anode. In solid-state systems, ions migrate through a crystalline, ceramic or polymer structure, typically via vacancy or interstitial diffusion within the electrolyte lattice (Famprikis *et al,* 2019). This change has important implications for battery design, material selection and manufacturing requirements.

Figure 1 illustrates the differences between the two battery types.

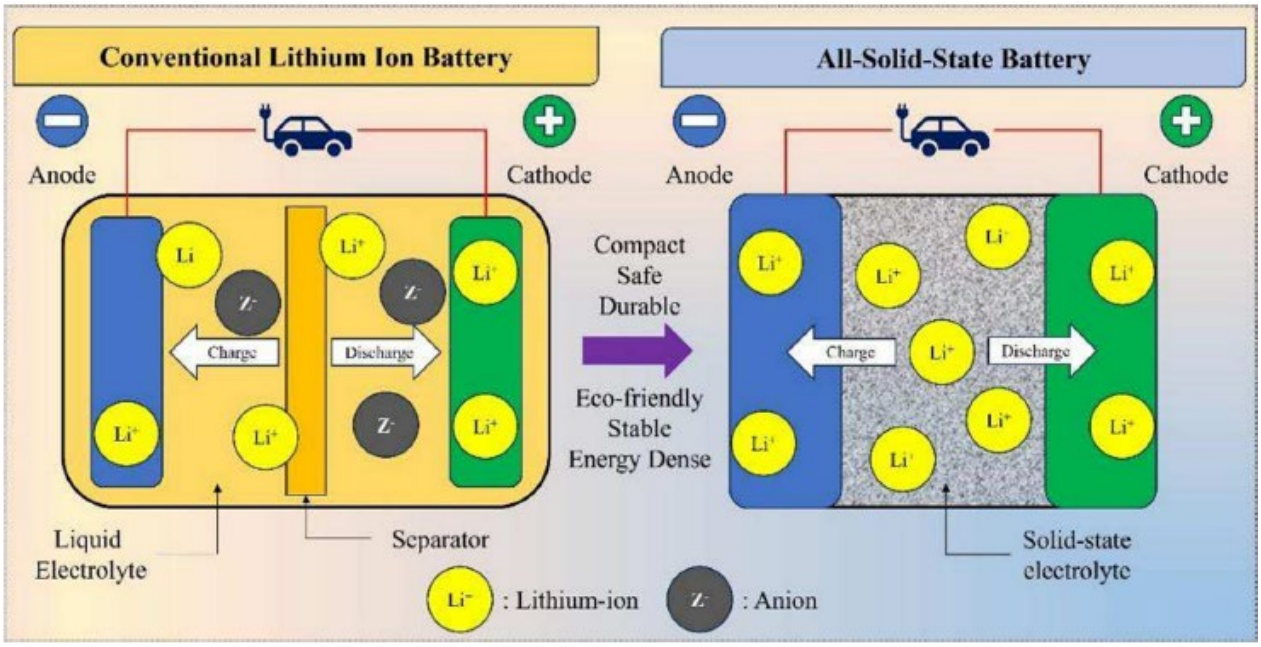


FIG 1 – Comparison of conventional lithium-ion battery and solid-state electrolyte battery (Joshi *et al,* 2025).

Development of solid-state batteries is focused on applications where high energy density, improved safety and charging performance are valued, including electric vehicles, stationary energy storage, aerospace and defence systems, and high-performance consumer electronics (Machín, Morant and Márquez, 2024).

Solid-state batteries are not a single technology, but a broad class defined by the solid electrolyte used. Sulfide-based, oxide-based, polymer, and hybrid or composite systems each have distinct material requirements, processing pathways and performance characteristics (Famprikis *et al,* 2019). Electrolyte selection therefore affects both battery performance and the upstream supply of critical minerals.

This paper examines the leading solid-state battery chemistry pathways and how they influence demand for key precursor commodities. By linking chemistry selection to mineral processing requirements, it provides a framework for understanding how emerging battery technologies may reshape critical mineral value chains and create downstream processing opportunities.

Advantages over conventional lithium-ion batteries

The principal advantages of solid-state batteries over conventional lithium-ion systems relate to energy density, safety, charging performance and durability.

Projected energy densities in the order of 400–500 Wh/kg have been reported, compared with approximately 250–300 Wh/kg for lithium-ion batteries (Sustainability Atlas, 2026).

Safety benefits arise from the removal of flammable organic liquid electrolytes. Solid electrolytes are typically non-flammable (Man *et al,* 2025).

Charging performance may also improve where solid electrolytes support higher current densities and more stable operation at elevated charge rates. Some studies report 10–80 per cent charge times of approximately 10–15 mins under controlled conditions, compared with 20–40 mins for conventional lithium-ion systems (Sustainability Atlas, 2026).

Solid-state systems may also offer improved cycle life because the absence of liquid electrolyte reduces degradation mechanisms. While performance varies considerably between chemistries and cell designs, laboratory-scale solid-state batteries have demonstrated cycle lives of several thousand cycles under controlled conditions (Man *et al,* 2025).

CURRENT LEADING CHEMISTRY OPTIONS

The leading solid-state battery chemistry options include sulfide-based, oxide-based, polymer, hybrid/composite and sodium-based systems. However, from a precursor materials and mineral processing perspective, sulfide-based, oxide-based and sodium-based systems are the most relevant to this assessment because they currently dominate research activity and early commercialisation efforts and create the clearest demand pathways for specific commodities. Polymer and hybrid systems are noted as enabling or transitional technologies.

As this paper is focused on mining and mineral processing implications for precursor commodities, detailed discussion of polymer electrolyte types and hybrid/composite types is outside the scope of this assessment.

Sulfide-based solid-state batteries

Sulfide-based solid-state batteries are one of the leading pathways because sulfide electrolytes can achieve high ionic conductivity and support high-energy cell designs. From a precursor and processing perspective, their significance lies in the use of lithium-, sulfur- and phosphorus-bearing chemicals.

The main technical constraints are a relatively narrow electrochemical stability window, possible instability against lithium metal and sensitivity to moisture or air exposure (Highstar, 2026).

The principal sulfide solid electrolyte families relevant to solid-state batteries include lithium germanium phosphorus sulfide (LGPS), lithium phosphorus sulfide (LPS), argyrodite-type electrolytes and thio-LISICON-type materials.

LGPS materials are generally prepared from lithium sulfide, phosphorus pentasulfide and germanium disulfide precursors; while LPS materials are typically prepared from lithium sulfide and phosphorus pentasulfide.

Argyrodite-type electrolytes are commonly represented by the chemical formula Li_6PS_5X, where X is a halide such as chlorine, bromine or iodine, with doped variants also reported. These materials are generally produced from lithium sulfide, phosphorus pentasulfide and lithium halide precursors.

Thio-LISICON-type materials are sulfur-based lithium superionic conductors and may use lithium sulfide, silicon disulfide, aluminium sulfide and/or phosphorus pentasulfide as precursor materials. In this context, ‘superionic’ refers to solid electrolyte materials that allow lithium or sodium ions to move through the solid structure unusually quickly, approaching the ion transport behaviour normally associated with liquid electrolytes.

Oxide-based solid-state batteries

Oxide-based solid-state batteries use ceramic oxide electrolytes, which are valued for chemical and thermal stability, non-flammability and compatibility with high-voltage cell designs. From a precursor and processing perspective, these systems require tightly controlled ceramic production, impurity management and downstream thermal processing (Famprikis *et al,* 2019).

The principal oxide solid electrolyte families include perovskite-type, garnet-type and LISICON-type materials.

Perovskite-type electrolytes are commonly represented by lithium lanthanum titanium oxide, ($Li_{3x}La_{2/3-x}TiO_3$, or LLTO). The precursor materials include lithium oxides, lanthanum oxides or nitrates and titanium oxides.

Garnet-type electrolytes are another important oxide family and are commonly represented by lithium lanthanum zirconium oxide ($Li_7La_3Zr_2O_{12}$, or LLZO). These materials typically require lithium oxide, lanthanum oxide, and zirconium oxide precursors (Umair *et al,* 2025).

LISICON-type materials (Lithium Super Ionic Conductor) are another oxide-based solid electrolyte family. They are also commonly associated with lithium-silicon-phosphate or lithium-germanium oxide frameworks. LISICON-type materials are typically produced from high-purity lithium, silicon, phosphorus and/or germanium-bearing precursor chemicals, with specific formulations also

requiring zinc, aluminium, titanium or zirconium oxides depending on the target electrolyte composition.

Figure 2 shows representative crystal structures of common oxide solid electrolyte materials used in solid-state batteries.

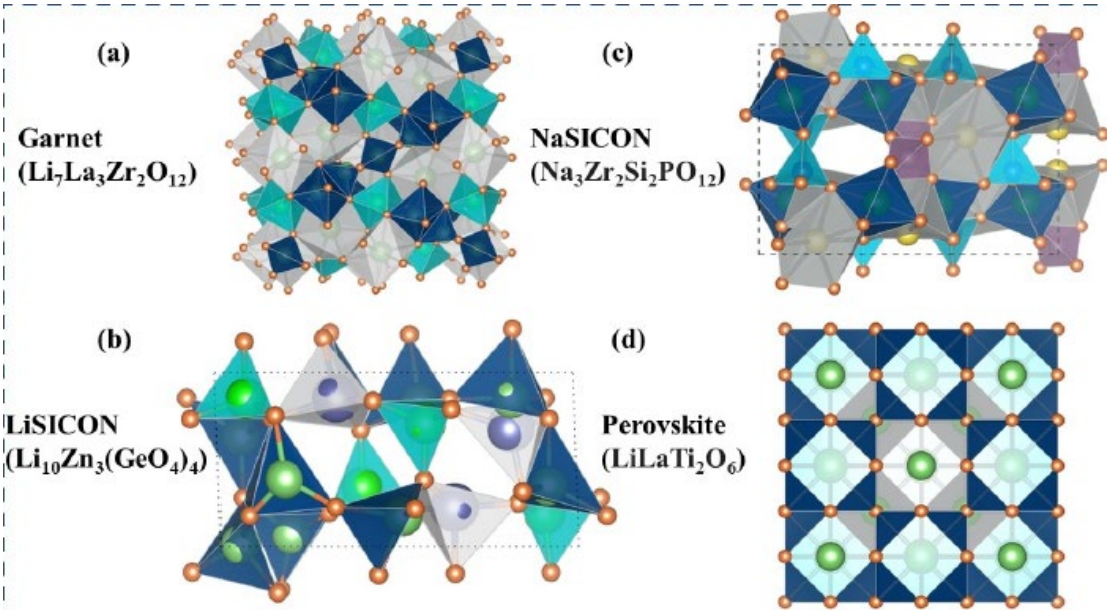


FIG 2 – Representative crystal structures of common oxide solid electrolyte materials used in solid-state batteries (Umair *et al,* 2025).

Across the main oxide electrolyte families, lithium is the common precursor element because it provides the mobile ion within the solid electrolyte structure. The key distinction is therefore not simply the presence of lithium, but the need to pair high-purity lithium chemicals with controlled rare-earth, zirconium or titanium-bearing precursor streams, depending on the target oxide chemistry. From a mineral processing perspective, this reinforces that oxide solid-state battery systems require multiple qualified chemical inputs rather than a single generic oxide feedstock (Famprikis *et al,* 2019).

Sodium-ion based systems

Sodium-based solid-state battery systems use sodium ions (Na^+) rather than lithium ions as the primary charge carrier. They are currently being investigated as a lower-cost, more resource-abundant alternative to lithium-based batteries. This is particularly important where cost, raw material availability and supply chain resilience are more important than maximum energy density. Sodium-based systems benefit from the abundance and low cost of sodium relative to lithium, with feedstocks available from widely distributed mineral and brine resources. This makes them attractive for stationary energy storage, grid support and lower-cost mobility applications.

Figure 3 shows the flow of sodium ions through the cathode and anode in a sodium ion solid-state battery.

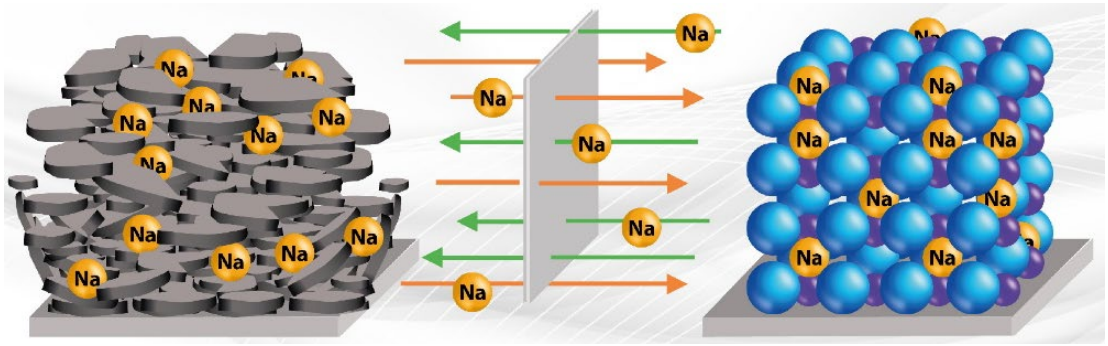


FIG 3 – Illustration of a sodium-ion solid-state battery (Flash Battery, 2023).

Their main limitations are lower energy density, due to the larger and heavier sodium ion, and lower technology maturity compared with lithium-based pathways. Further development is still required in electrolyte conductivity, electrode compatibility, interfacial stability and manufacturable cell design (Massaro *et al,* 2025).

One important sodium solid electrolyte family is the sodium super ionic conductor, or NASICON-type, group of batteries. These batteries contain oxides of sodium, silicon and phosphorus.

A common electrolyte family suitable for sodium-based systems is sodium-zirconium-silicon-phosphate oxide frameworks, such as $Na_{1+x}Zr_2Si_xP_{3-x}O_{12}$. From a precursor perspective, these contain high-purity zirconium, silicon and phosphorus-bearing chemical precursors.

A notable sodium-ion cathode material is sodium vanadium phosphate ($Na_3V_2(PO_4)_3$ or NVP), which belongs to the NASICON family of compounds. NVP has attracted significant research interest due to its high operating voltage, rapid sodium-ion transport, and long cycle life. The material incorporates sodium, vanadium and phosphorus within a three-dimensional phosphate framework. Although sodium-ion batteries are generally expected to target stationary energy storage and lower-cost mobility applications rather than high-energy electric vehicles, widespread commercialisation could create additional demand for vanadium and phosphorus-bearing precursor materials beyond their traditional markets (Birusew *et al,* 2026).

In addition to cathode and electrolyte selection, sodium-ion systems also differ from lithium-ion batteries in their preferred anode materials. Graphite, which is the dominant anode material in conventional lithium-ion batteries, is generally not suitable as the primary anode for sodium-ion batteries. Sodium ions are larger than lithium ions, so they do not fit easily between the tightly ordered layers of graphite. This makes it difficult for graphite to store and release sodium ions efficiently during normal battery operation. As a result, sodium-ion systems usually rely on alternative anode materials, with hard carbon currently regarded as the leading commercial candidate. Unlike graphite, hard carbon has a less ordered structure with wider internal spaces, which makes it easier for the larger sodium ions to be stored. This distinction is important from a precursor perspective because sodium-ion batteries are unlikely to create the same direct natural graphite demand pathway as lithium-ion batteries; instead, they may favour engineered hard-carbon materials produced from biomass, pitch, resin or other carbonaceous precursors (Tan *et al,* 2023).

PRECURSOR MATERIALS AND PROCESSING

Table 1 summarises the electrolyte types assessed in this paper and the corresponding precursor commodities associated with each chemistry. The table is intended to set the framework for the remainder of this section by showing that solid-state battery precursor demand is not uniform across all chemistries. Instead, each electrolyte family draws on a different combination of lithium, phosphorus, sulfur, sodium and selected secondary commodities such as germanium, aluminium, silicon, lanthanum, zirconium, titanium and halides.

TABLE 1

Summary of electrolyte types and corresponding precursor commodities.

Electrolyte type	Li	Na	P	S	Ge	Al	Si	La	Zr	Ti	Halides
LGPS (Sulfide)	✓		✓	✓	✓						
LPS (Sulfide)	✓		✓	✓							
Argyrodites (Sulfide)	✓		✓	✓							✓
Thio-LISICON (Sulfide)	✓		✓	✓		✓	✓				
Garnet/LLZO (Oxide)	✓							✓	✓		
Perovskite (Oxide)	✓							✓		✓	
LISICON/LAGP (Oxide)	✓		✓		✓	✓					
NASICON (Oxide)		✓	✓				✓		✓		

The major precursor commodities for solid-state batteries in an Australian context are lithium and phosphorus. Lithium is common to most leading solid-state battery chemistries, while phosphorus is important in sulfide electrolytes, phosphate-containing oxide systems and selected sodium-based materials. Sulfur is also important as a key precursor in batteries with sulfide electrolyte.

Lithium

The relevant lithium precursor forms vary according to the electrolyte chemistry requirements. In sulfide-based systems, lithium is commonly introduced as lithium sulfide, with lithium halides also used in argyrodite-type electrolytes. In oxide-based systems, lithium may be introduced as lithium carbonate, lithium hydroxide, lithium oxide or lithium fluoride, depending on the target phase, synthesis route and processing conditions.

Lithium demand is not limited to solid electrolytes; as lithium-bearing cathode materials also require high-purity lithium chemicals such as lithium carbonate or lithium hydroxide as precursor inputs.

From a processing perspective, lithium precursor production is not simply a matter of producing a bulk lithium product. Solid-state battery manufacture places strong emphasis on precursor purity, particle size control, moisture management and consistency between batches. Sulfide systems are particularly sensitive because lithium sulfide and related sulfide precursors can react with moisture, creating stringent handling and storage requirements.

Figure 4 presents a high-level flow sheet for the production of lithium-bearing solid-state battery precursors from hard rock spodumene ore.

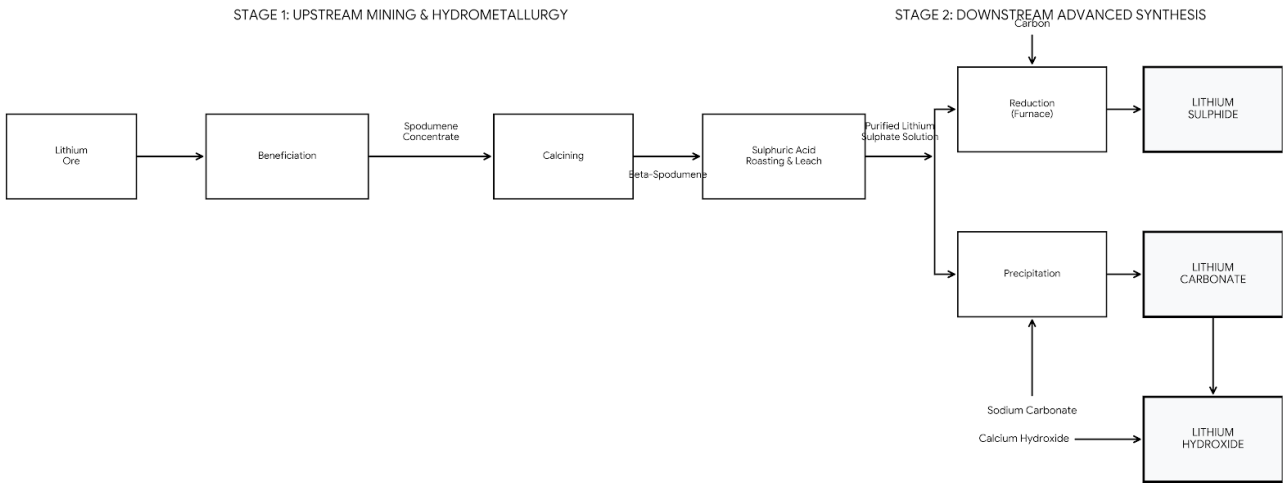


FIG 4 – High-level processing pathways from spodumene concentrate to lithium-bearing precursor chemicals for solid-state battery applications. Source: author's own.

Lithium precursor production typically begins with beneficiation to produce a spodumene concentrate.

The concentrate is then calcined at elevated temperature to convert naturally occurring α-spodumene to the more reactive β-spodumene phase. The calcined material is subsequently subjected to sulfuric acid roasting and leaching to produce a lithium sulfate solution, which is then purified to remove impurities prior to downstream conversion.

From the purified lithium sulfate intermediate, several lithium precursor pathways may be considered. A conventional route is precipitation with sodium carbonate to produce lithium carbonate. Lithium carbonate can then be further converted to lithium hydroxide through reaction with calcium hydroxide, depending on the required battery chemical product. For sulfide-based solid-state electrolyte systems, lithium sulfide represents a more specialised downstream precursor; it may be produced through additional chemical conversion routes from lithium-bearing intermediates or lithium carbonate/hydroxide feedstocks. In this context, the flow sheet illustrates how conventional spodumene processing can provide the upstream platform for a range of lithium-bearing solid-state battery precursor chemicals.

Australia's current lithium production predominantly supplies the existing lithium-ion battery value chain, with electric vehicles and battery energy storage systems representing the main end-use markets (Export Finance Australia, 2025). Most production is derived from hard rock spodumene and exported as concentrate or intermediate lithium chemicals for offshore conversion, refining and battery manufacture (particularly in Asia). While this supply currently supports conventional lithium-ion applications, it provides important context for solid-state batteries.

To supply future solid-state battery markets, Australian lithium producers would need to provide concentrates that can be reliably converted into high-purity lithium precursor chemicals. Key requirements include stable lithium grade, low deleterious impurities, predictable mineralogy, reliable conversion during calcination and consistent downstream leach and purification behaviour.

For oxide and sulfide systems, this means supporting the production of lithium carbonate, lithium hydroxide, lithium oxide, lithium sulfide or lithium halide precursors (Umair *et al,* 2025).

Phosphorus

Phosphorus is a key precursor element in several solid-state battery electrolyte families, particularly sulfide and phosphate-based oxide systems. In sulfide electrolytes, it is typically introduced as phosphorus pentasulfide for LPS, argyrodite and LGPS-type materials. In oxide and phosphate-containing systems, phosphorus may be introduced as phosphorus pentoxide, phosphoric acid-derived compounds or ammonium phosphate species.

Figure 5 presents a high-level processing pathway for converting phosphate rock into phosphorus-bearing battery precursor chemicals.

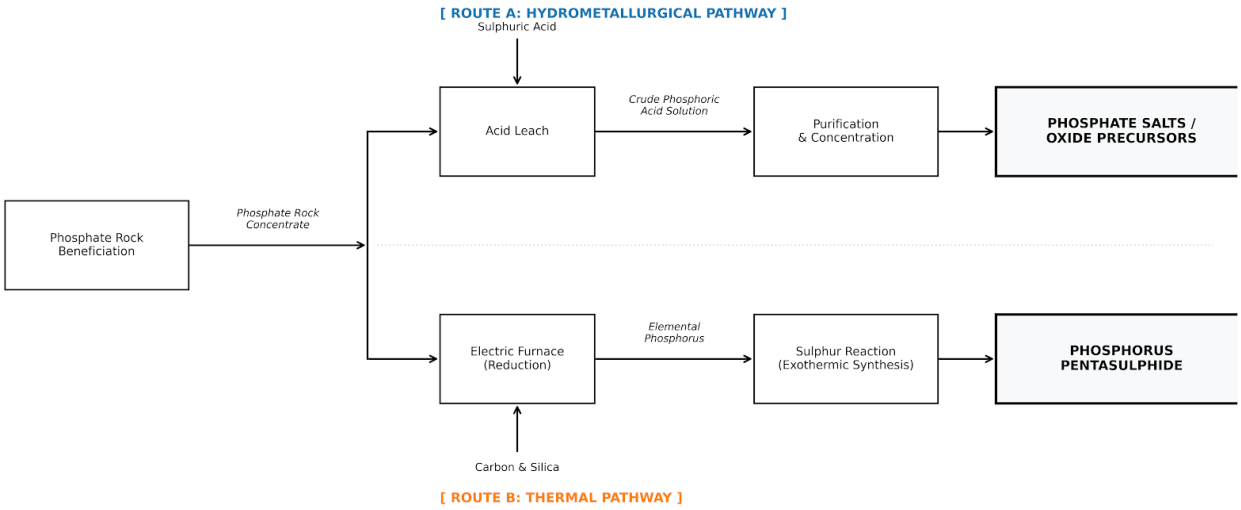


FIG 5 – High-level processing pathways from phosphate rock to phosphorus-bearing precursor chemicals for solid-state battery applications. Source: author's own.

Processing typically begins with mining and beneficiation to produce a phosphate rock concentrate. The concentrate can then follow two broad downstream routes.

The first is the hydrometallurgical pathway, where phosphate rock reacts with sulfuric acid to produce phosphoric acid. Phosphoric acid can be further processed into phosphate salts or phosphorus oxide precursors.

The second is the thermal pathway, where phosphate rock is reduced in an electric furnace to produce elemental phosphorus. Elemental phosphorus can then be converted into the higher-value phosphorus pentasulfide.

The distinction between these pathways is important for solid-state battery precursor production. Phosphate and oxide precursor pathways are more naturally aligned with phosphoric acid and phosphate salt production, whereas sulfide electrolyte precursors require phosphorus pentasulfide, which is a more specialised chemical product derived through additional downstream conversion. As a result, phosphate rock should not be treated as a direct solid-state battery precursor; rather, it is an upstream mineral feedstock that may support solid-state battery supply chains if suitable chemical conversion capability is developed.

In the context of minerals processing, phosphate projects provide an example of how an established bulk mineral product can connect to emerging battery chemical markets through downstream upgrading. This link is strongest where phosphate concentrate can be converted into high-purity phosphorus chemicals with appropriate impurity control, reagent management and product specification. For this reason, phosphorus warrants significant treatment in the paper, but the discussion should remain focused on the conversion from phosphate feedstock into relevant phosphorus-bearing precursor chemicals rather than on phosphate rock production alone.

Sodium-ion systems provide an additional pathway for phosphorus-bearing precursor chemicals. Materials such as sodium vanadium phosphate and related NASICON-type compounds contain phosphate groups as components, linking these chemistries to high-purity phosphorus chemical supply rather than direct phosphate rock use (Birusew *et al,* 2026). This reinforces the role of phosphate projects as potential upstream feedstocks where suitable downstream conversion to battery-grade phosphorus products is available.

Sodium

Sodium supply is unlikely to represent a primary resource constraint for sodium-based battery systems. Unlike lithium, sodium is abundant, low cost and geographically widespread. Industrial supply chains are already established through sodium chloride, soda ash and caustic soda production. For battery applications, the relevant issue is therefore not the availability of sodium as a bulk element, but the production of high-purity sodium-bearing precursor chemicals that can meet

cathode and solid electrolyte specifications. Sodium carbonate, sodium hydroxide and sodium salts may provide practical feedstocks for downstream sodium-ion battery materials, depending on the target chemistry and synthesis route (Massaro *et al,* 2025).

From an Australian project perspective, sodium is therefore better treated as a low-cost input rather than a strategic mineral opportunity in its own right. The higher-value opportunity is likely to sit in integrated chemical conversion pathways for sodium-phosphate, sodium-vanadium-phosphate or NASICON-type precursor materials, where sodium is combined with commodities such as phosphorus, vanadium, zirconium or silicon.

Sulfur

Elemental sulfur is significant in the production of sulfide-based solid-state batteries. Elemental sulfur is typically produced via petroleum, natural gas and related fossil resources.

For solid-state battery applications, sulfur quality is a critical consideration because battery performance is highly sensitive to impurities and material consistency. Trace contaminants can promote unwanted side reactions, reduce ionic conductivity and shorten battery cell life. Therefore, high-purity sulfur is required in electrolyte production to maximise battery performance (Man *et al,* 2025).

For Australia, the opportunity is therefore unlikely to be sulfur production itself. It is more likely to sit in chemical conversion pathways that connect lithium, phosphorus, silicon or aluminium feedstocks to qualified sulfide precursor products for solid-state electrolyte manufacture.

Secondary precursor commodities

The commodities discussed in this section are relevant to solid-state battery supply chains, but they should generally be treated as secondary rather than primary demand drivers. Their importance is linked to specific electrolyte or cathode chemistries, or specialised precursor forms, rather than broad exposure across all leading solid-state battery pathways. Common themes amongst all these commodities include the need for high-purity production, tight impurity control and clear alignment with a defined downstream battery chemistry. In most cases, the opportunity is therefore project- or chemistry-specific, and is unlikely to justify development on the basis of solid-state battery demand alone.

Aluminium

Aluminium is relevant to selected sulfide-based solid-state electrolyte systems where aluminium sulfide may be used as a precursor or dopant in thio-LISICON-type and related materials.

From a processing perspective, aluminium sulfide could theoretically be produced through a downstream flow sheet involving high-purity alumina, aluminium metal production and subsequent high-temperature reaction of aluminium with sulfur. However, this pathway may be commercially unattractive where high-purity alumina products command higher prices than the downstream aluminium sulfide product used in solid-state battery manufacture. For example, high-purity alumina values used in recent project assessments are materially higher than indicative aluminium sulfide pricing, suggesting that conversion to aluminium sulfide would only be justified where there is a specific technical requirement, secure offtake arrangement or clear value uplift from supplying specialist battery precursor markets. CSIRO states that the purest form of HPA (99.9999 per cent) has a price that can exceed US$70 000 per tonne (CSIRO, 2025). In comparison, publicly available aluminium sulfide pricing is limited and is largely based on small-volume, high-purity laboratory supply rather than transparent bulk commodity sales. Supplier listings for 99–99.9 per cent aluminium sulfide commonly quote gram-scale packages, with prices ranging from approximately US$94–373 for 5–25 gram packages.

Germanium

Germanium is used as a precursor in selected solid-state battery electrolyte chemistries, including LGPS-type sulfide systems, where it is introduced as germanium disulfide, and LAGP-type oxide systems, where it is introduced as germanium dioxide.

Germanium is typically recovered as a by-product from the mining and processing of ores of other commodities, primarily zinc, lead and coal (Quest Metals, 2025). Germanium products are produced by processing these raw materials through beneficiation and hydrometallurgical processes.

Australia is not currently a significant producer of refined germanium, but it is increasingly viewed as a strategically important future by-product opportunity (Geoscience Australia, 2024).

Graphite

The sodium-ion battery discussion is relevant to future graphite supply. Forecast growth in electric vehicles and conventional lithium-ion battery manufacture is expected to increase demand for battery-grade natural and synthetic graphite, particularly for coated spherical graphite used in anodes (International Energy Agency, 2024). However, sodium-ion batteries generally do not use graphite as the primary anode material and instead favour hard carbon, because the larger sodium ion is not readily accommodated within the ordered graphite structure. If sodium-ion batteries gain market share in stationary storage, low-cost mobility or other cost-sensitive applications, some future battery growth could therefore shift away from graphite-based anodes and toward hard-carbon supply chains. This would not remove the need for graphite, because lithium-ion batteries are likely to remain dominant in higher-energy applications, but it could moderate incremental graphite demand in market segments where sodium-ion batteries are technically and commercially suitable. From a mineral processing perspective, future graphite projects should therefore be assessed not only against lithium-ion battery growth, but also against possible substitution from sodium-ion systems and other anode technologies such as silicon-rich or lithium-metal designs.

Lanthanum

Lanthanum is used in oxide-based electrolyte systems, particularly garnet and perovskite-types. It is normally introduced as high-purity lanthanum oxide or lanthanum nitrate.

Lanthanum oxide and nitrate are produced by mining rare earth ores like bastnäsite, which are beneficiated. The concentrated ore undergoes leaching, followed by solvent extraction to isolate pure lanthanum from other rare earth elements. Pure lanthanum is calcined at high temperatures to create lanthanum oxide, or dissolved in nitric acid to produce lanthanum nitrate.

In terms of an Australian context, Mt Weld currently produces a concentrate that is refined offshore into a lanthanum oxide product.

Capturing this market segment requires highly sophisticated, multi-stage solvent extraction (SX) circuits to produce pure lanthanum fractions from adjacent rare earth elements within the cracked bastnäsite concentrate.

Silicon

Silicon is relevant through thio-LISICON sulfide and NASICON oxide-type batteries. In thio-sulfide types, the key precursor is silicon disulfide, whereas in NASICON types, the precursor is silicon oxide, either silica or tetraethyl orthosilicate.

Silica precursor quality can be demanding, with high-purity silica products for advanced applications commonly specified at 99.995 per cent SiO_2 or higher (Geoscience Australia, 2024). Achieving this level of purity generally requires substantial beneficiation, including significant fine grinding and intense flotation, chemical purification and impurity control. This can significantly increase processing complexity and cost. On this basis, high-purity silica production is unlikely to represent a realistic downstream pathway for most critical minerals projects in Australia, unless the feedstock already has favourable impurity characteristics and a clear commercial route to premium silica products.

Titanium

Titanium is relevant to selected oxide electrolytes, particularly the perovskite-type, where it is typically introduced as high-purity titanium dioxide.

Titanium oxide is produced by mining and concentrating titanium-bearing ores such as ilmenite or rutile, which are then refined through hydrometallurgical methods to create the final product.

Australia has extensive operating mineral sands mines which produce titanium concentrate and could potentially be used in the manufacture of solid-state batteries.

Vanadium

Vanadium is relevant mainly to sodium-based battery systems through sodium vanadium phosphate. Its significance is as a high-purity cathode precursor requirement, linked to both vanadium and phosphorus chemical supply.

Sodium vanadium phosphate is produced by combining sodium and phosphorus sources with vanadium products such as vanadium pentoxide or vanadium trioxide.

Australia has several prospective vanadium projects that could become relevant to future battery-material supply chains, especially where they can produce high-purity vanadium pentoxide or related precursor chemicals. Their strategic value will depend less on vanadium resource availability alone and more on the ability to convert suitable feedstocks into qualified battery-grade chemical products.

Zirconium

Zirconium is relevant to oxide electrolytes, such as garnet-type systems which use zirconium oxide as a precursor (either ZrO_2; $Zr(OH)_4$; $ZrOCl_2 \cdot 8H_2O$ or $ZrOCl_2$).

These zirconium oxide products are produced via initially mining and beneficiation to produce a zircon concentrate. The concentrate is then processed using thermal and hydrometallurgical methods to produce the different products.

As is the case with titanium, Australia has a well-established mineral sands industry that could provide raw materials for solid-state battery manufacture.

DISCUSSION

For Australia, the significance of solid-state battery development lies less in supplying additional bulk mineral product and more in moving further downstream into battery precursor production. Australia has established strengths in hard rock lithium, phosphate, mineral sands, graphite, vanadium and rare earth supply chains; however, higher-value opportunities are likely to sit in chemical conversion, impurity control, moisture management and reliable supply of battery-grade materials. The most realistic opportunities are therefore concentrated around lithium chemical production and, where suitable downstream capability exists, phosphorus-bearing chemicals.

From a minerals processing and hydrometallurgical perspective, commercialisation of solid-state battery systems represents a shift in product specification. The upstream sector is moving from bulk, standard-grade concentrates toward downstream chemical products where impurity deportment and physical material properties need to be tightly controlled.

Unit operations and plant design constraints

The main differences between processing pathways are the required handling environments and thermal processing conditions. Sulfide chemical circuits, such as those producing lithium sulfide or phosphorus pentasulfide, are highly moisture sensitive. Exposure to air can generate toxic hydrogen sulfide gas, so these downstream circuits require tight handling and process controls. Oxide-based ceramic pathways avoid this gas-evolution hazard, but require high-temperature calcination and sintering stages to achieve the required specifications. These stages can have a significant impact on the plant energy balance and operating costs.

Downstream capital and project-development implications

For Australian project developers, this changing technology landscape creates a trade-off around how far downstream a flow sheet should extend. The traditional domestic pathway is usually based on beneficiation to produce a clean mineral concentrate for export, such as spodumene, zircon or rare earth concentrates. Solid-state battery supply chains, however, require highly qualified, high-purity chemical inputs. This creates an economic decision for Australia: invest in advanced downstream hydrometallurgical conversion and chemical synthesis units to capture higher margins,

or produce bulk intermediates, such as standard battery-grade lithium carbonate or hydroxide, and leave the final specialised synthesis to offshore chemical plants and refineries.

Graphite and hard-carbon supply-chain implications

The emergence of sodium-based battery pathways creates a substitution risk that should be considered in long-term circuit sizing and demand forecasting. As described earlier, the larger sodium ion cannot efficiently intercalate within graphite, so sodium-ion technologies rely more heavily on disordered hard-carbon anodes derived from biomass or pitch. If sodium-based systems capture a meaningful market share, future demand growth for traditional coated spherical graphite circuits may be lower than expected. Plant design should therefore consider flexibility in graphite flotation and purification circuits, rather than assuming a linear increase in graphite demand. Miners and investors should also evaluate graphite assets against both conventional lithium-ion growth and possible substitution by hard-carbon technologies in selected market segments.

CONCLUSIONS

Solid-state batteries should not be viewed as a single technology, but as a family of related battery systems with materially different electrolyte chemistries, precursor requirements and processing implications. Sulfide, oxide, polymer, hybrid and sodium-based systems each present distinct technical advantages and limitations, and future market development is therefore unlikely to follow a single uniform pathway.

The choice of battery chemistry has a direct influence on the mineral and chemical precursors required. Sulfide systems place greatest emphasis on lithium, sulfur and phosphorus-bearing chemicals, particularly where lithium sulfide, phosphorus pentasulfide or related sulfide precursors are required. Oxide systems introduce additional demand for tightly specified lithium, lanthanum, zirconium, titanium and germanium-bearing precursor chemicals. Sodium-based systems provide an adjacent pathway for sodium, phosphorus, zirconium, vanadium and hard-carbon precursor demand, but should not be treated as a direct substitute for lithium-based solid-state battery supply chains.

Within an Australian context, lithium and phosphorus emerge as the most strategically relevant precursor elements. Lithium is central to most leading lithium-based solid-state battery systems, both as the charge carrier and as a structural component of many solid electrolytes. Phosphorus is important for sulfide electrolyte families, phosphate-containing oxide systems, LISICON-type materials and selected sodium chemistries. However, phosphate rock should be considered an upstream mineral feedstock rather than a direct battery precursor, with value depending on the development of suitable downstream conversion routes to high-purity phosphorus chemicals.

A key implication of solid-state battery development is that processing complexity is likely to increase relative to conventional concentrate production. Future supply chains will require tighter control of precursor purity, particle size, moisture exposure, impurity deportment and batch-to-batch consistency. Sulfide-based systems are particularly sensitive to moisture and may require specialised handling environments, while oxide-based systems are likely to require high-temperature ceramic processing and strict phase control.

Australia’s strongest opportunity is therefore likely to lie in downstream chemical conversion and precursor manufacturing rather than concentrate production alone. Established strengths in lithium mining, phosphate, mineral sands, graphite, vanadium and rare earth supply chains provide a platform, but greater value will be captured where mineral projects can connect to high-purity chemical production, impurity control and reliable supply into emerging battery materials markets. At the same time, demand should not be assumed to grow uniformly across all commodities. Sodium-ion systems may moderate future graphite demand in selected stationary storage and low-cost mobility applications, while secondary commodities such as lanthanum, zirconium, titanium, germanium and vanadium are likely to remain chemistry-specific opportunities. Solid-state and adjacent sodium-ion batteries therefore represent both a new source of mineral demand and an opportunity to reposition selected Australian projects further along the battery materials value chain.

ACKNOWLEDGEMENTS

The author gratefully acknowledges Idemitsu Australia for providing the opportunity and support to prepare this paper. The author also thanks colleagues within Idemitsu Australia for their encouragement, technical discussions and permission to explore the emerging implications of solid-state battery technologies for critical minerals, precursor materials and mineral processing.

REFERENCES

Birusew, D T, Ledwaba, K, Raphulu, M, Hardy, A and Palaniyandy, N, 2026. Sodium vanadium phosphate cathodes for Na-ion batteries: Carbon modification strategies and electrolyte compatibility, *Journal of Energy Storage*, 150:120253.

CSIRO, 2025. *High Purity Alumina (HPA)*, Australian Critical Minerals R&D Hub, Commonwealth Scientific and Industrial Research Organisation. Available from: <https://research.csiro.au/critical-minerals-hub/research-projects/high-purity-alumina-hpa/> [Accessed: 21 July 2026].

Export Finance Australia, 2025. *Australia – Higher lithium exports supported by strong mine output*, Export Finance Australia. Available from: <https://www.exportfinance.gov.au/resources/world-risk-developments/2025/may/australia-higher-lithium-exports-supported-by-strong-mine-output/> [Accessed: 21 July 2026].

Famprikis, T, Canepa, P, Dawson, J A, Islam, M S and Masquelier, C, 2019. Fundamentals of inorganic solid-state electrolytes for batteries, *Nature Materials*, 18:1278–1291.

Flash Battery, 2023. *Sodium batteries*: *The technology of the future?*, Flash Battery. Available from: <https://www.flashbattery.tech/en/blog/sodium-batteries/> [Accessed: 21 July 2026].

Geoscience Australia, 2024. *Critical mineral by-product potential*, Geoscience Australia, Australian Government. Available from: <https://www.ga.gov.au/scientific-topics/minerals/australian-critical-minerals-research-and-development-hub/critical-mineral-by-product-potential> [Accessed: 21 July 2026].

Highstar, 2026. *All-Solid-State Battery*: *The Future of Energy Storage Explained*, Highstar Battery Manufacturing, 14 January. Available from: <https://en.highstar.com/blog/all-solid-state-battery-technology> [Accessed: 21 July 2026].

International Energy Agency (IEA), 2024. *Global Critical Minerals Outlook 2024.* International Energy Agency, Paris. Available from: <https://www.iea.org/reports/global-critical-minerals-outlook-2024> [Accessed: 21 July 2026].

Joshi, A, Mishra, D K, Singh, R, Zhang, J and Ding, Y, 2025. A comprehensive review of solid-state batteries, *Applied Energy*, 386:125546.

Machín, A, Morant, C and Márquez, F, 2024. Advancements and challenges in solid-state battery technology: an in-depth review of solid electrolytes and anode innovations, *Batteries*, 10(1):29. https://doi.org/10.3390/batteries10010029

Man, B, Zeng, Y, Liu, Q, Chen, Y, Li, X, Luo, W, Zhang, Z, He, C, Jie, M and Liu, S, 2025. A comprehensive review of sulfide solid-state electrolytes: Properties, synthesis, applications and challenges, *Crystals*, 15(6):492. https://doi.org/10.3390/cryst15060492

Massaro, A, Squillantini, L, De Giorgio, F, Scaramuzzo, F A, Pasquali, M and Brutti, S, 2025. Advancements in solid-state sodium-based batteries: A comprehensive review, *arXiv*. https://doi.org/10.48550/arXiv.2505.04391

Quest Metals, 2025. *Germanium Mining 101*, Quest Metals, 26 March. Available from: <https://www.questmetals.com/blog/germanium-mining-101> [Accessed: 21 July 2026].

Sustainability Atlas, 2026. *Solid-State vs Lithium-Ion Batteries*: *Energy Density, Safety and Cost Compared*, Sustainability Atlas, last updated 28 February. Available from: <https://sustainableatlas.org/compare/solid-state-vs-lithium-ion-batteries> [Accessed: 21 July 2026].

Tan, S, Yang, H, Zhang, Z, Xu, X, Xu, Y, Zhou, J, Zhou, X, Rao, X, Gu, Y, Wang, Z, Wu, Y, Liu, X and Zhang, Y, 2023. The progress of hard carbon as an anode material in sodium-ion batteries, *Molecules*, 28(7):3134. https://doi.org/10.3390/molecules28073134

Umair, M, Zhou, S, Li, W, Rana, H T H, Yang, J, Cheng, L, Li, M, Yu, S and Wei, J, 2025. Oxide solid electrolytes in solid-state batteries, *Batteries and Supercaps*, 8:e202400667. https://doi.org/10.1002/batt.202400667

From mineralogy to process insight – advanced XRD analytics for critical minerals

O Narygina[1], M Pernechele[2], S Makvandi[2], L Negrão[3], I Duran[4], Y Gomes[5] and U König[6]

1. Application Specialist, Spectris Australia Pty Ltd (MP OpCo), Chipping Norton NSW 2170. Email: olga.narygina@malvernpanalytical.com
2. Application Specialist, Malvern Panalytical B.V., Almelo, The Netherlands.
3. Application Specialist, Spectris Do Brasil Instrumentos Eletronicos Ltda. (MP OpCo), São Paulo, Brazil.
4. Application Specialist, Spectris Canada Inc., Quebec, Canada.
5. Hydrometallurgy Analyst, Borborema Recursos Estratégicos, Belo Horizonte, Brazil.
6. Business Development Mining / Metals, Malvern Panalytical B.V., Almelo, The Netherlands.

ABSTRACT

As global demand for lithium, rare earth elements (REEs), nickel, and cobalt continues to grow, mining operations face increasing pressure to maximise recovery while supporting long-term sustainability. In this context, advanced analytical methods are required to reduce geological, metallurgical, and economic risks at every step of the ore-to-metal process.

X-ray diffraction (XRD) is an established tool for mineralogical analysis and is conventionally used to provide phase identification and quantification on a per-sample basis. This paper presents a suite of case studies that combine traditional XRD approaches with large-scale data analytics. This integration improves result reliability and extends the value of XRD beyond simple phase identification.

We demonstrate that quantitative phase analysis combined with data clustering provides a powerful framework for trend identification and geological modelling. Clustered XRD data from nickel laterite deposits differentiate between saprolite and laterite horizons, supporting efficient grade control and ore blending, and informing the selection of appropriate processing routes. The same approach, when applied to lithium and REE systems, provides mineralogical domain definitions that support processing performance prediction and exploration targeting.

Integration of XRD with Partial Least Squares Regression (PLSR) enables reliable prediction of key process parameters, including material grindability.

Finally, we present the Phase SNR (signal-to-noise ratio) method for smart filtering of minor mineral weight percentages. This approach enables more reliable automated quantification of problematic minor phases such as clays and quartz.

Collectively, these case studies demonstrate that XRD, when combined with multivariate analytics, evolves from a descriptive mineralogical tool into a predictive framework for process control, geometallurgical modelling, and energy optimisation.

The impact of co-occurring ions (potassium, sodium and calcium) in the recovery of lithium hydroxide from lithium liquors using electrodialysis

J Nsiah[1], K L Ang[2], T B Issa[3] and A N Nikoloski[4]

1. PhD student, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: 35047507@student.murdoch.edu.au
2. Senior Research Fellow, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: a.ang@murdoch.edu.au
3. Senior Research Fellow, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: t.issa@murdoch.edu.au
4. Professor, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: a.nikoloski@murdoch.edu.au

ABSTRACT

The presence of co-occurring ions poses a key challenge in solution purification for the conventional production of battery-grade lithium hydroxide, whether from hard rock minerals, brines, or end-of-life lithium-ion batteries. The production of battery-grade lithium hydroxide by electrodialysis is no exception. In this study, co-occurring ions, namely potassium (K), sodium (Na), and calcium (Ca), were investigated to determine their impact on lithium hydroxide production by electrodialysis. Lithium liquors studied include lithium sulfate and lithium carbonate. At impurity concentrations below 250 mg/L, the current efficiency across both systems remained stable, with no significant variation. However, as impurity concentrations increased, process performance declined below baseline levels due to increased competition between the impurity ions and lithium. Therefore, low levels of Na, K, or Ca impurities have minimal impact on process performance; nonetheless, product purity was negatively affected. Scaling of the cation-exchange membranes was observed in the lithium carbonate system. This was mainly driven by the interfacial precipitation of lithium carbonate, not the impurities, at the membrane surface. Electron-dispersive X-ray spectroscopy (EDS) results showed no detectable impurity peaks on the membrane surface, confirming that the scales were not caused by impurities.

Demonstration plants allow miners to test critical minerals processing before investing in commercial production

D Pianta[1]

1. Project Manager, Stantec, Brisbane Qld 4101. Email: damian.pianta@stantec.com

ABSTRACT

The global transition to renewable energy technologies is driving rapid growth in demand for critical minerals and rare earth elements. The International Energy Agency reports a 50 per cent increase in the mineral intensity of power generation over the past decade, with demand forecast to increase significantly as deployment of wind, solar, battery storage, and electric vehicle technologies accelerates. Meeting this demand requires the successful scale-up of critical minerals processing, particularly in jurisdictions seeking to develop domestic processing capability and secure supply chains.

Scaling critical minerals processing presents challenges distinct from those associated with bulk commodities. Many critical minerals have historically been produced at relatively small volumes, and processing routes developed at laboratory scale may not perform reliably when scaled directly to commercial operations. Large, single-step scale-ups introduce technical, financial, and environmental risks, with the potential for process instability, cost escalation, and schedule delays.

Demonstration plants provide an essential intermediate step between laboratory testing and full-scale commercial production. Operating at a representative scale, they enable validation of processing technologies, materials of construction, and operating conditions under realistic conditions, while allowing incremental scale-up and controlled optimisation. The development of a high-purity alumina demonstration plant in Brisbane demonstrates how bespoke equipment design and staged scaling can improve confidence in process performance and economic viability.

In addition to de-risking initial scale-up, demonstration plants deliver ongoing value by supporting process refinement, operator training, and adaptation to changing market requirements. As demand for critical minerals continues to grow, demonstration plants will play a key role in enabling technically robust, economically viable, and environmentally responsible processing solutions.

Economic considerations in the processing of clay-hosted rare earth deposits in Australia

J Quinn[1], M Valencia Bejarano[2], A Manis[3] and K Soldenhoff[4]

1. Senior Hydrometallurgist, Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights NSW 2234. Email: jamesq@ansto.gov.au
2. Senior Process Engineer, Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights NSW 2234. Email: maritzav@ansto.gov.au
3. Principal Consultant, Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights NSW 2234. Email: ama@ansto.gov.au
4. Principal Consultant, Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights NSW 2234. Email: khs@ansto.gov.au

ABSTRACT

The rare earth elements (REE) have become increasingly important as the world transitions towards electrification, with four of the REE (Pr, Nd, Tb and Dy) required for the permanent magnets used in wind turbines and electric vehicles. The REEs feature on virtually every country's published 'critical minerals list'; due to both their importance as well as the geopolitical risks associated with lack of diversification of supply.

Economically significant REE deposits can usually be grouped into two broad categories – namely the higher-grade hard rock and mineral sands deposits amenable to beneficiation (typically with monazite, bastnaesite and xenotime mineralisation), and lower grade ion adsorbed or 'clay-hosted' deposits. There are several advanced high-grade REE projects in Australia and one operating mine, while clay-hosted deposits have only received significant attention in the last five years and are at earlier stages of development.

The ADARER Project (Accelerating Development of Australia's Rare Earth Resources), funded by the Commonwealth Government, was operated under the umbrella of the Australian Critical Minerals Research and Development Hub. This multi-agency project targeted the development of Australia's low-grade REE deposits, with a specific focus on clay-hosted REEs.

One aspect of the ADARER project was to examine the processing options and associated overall flow sheets required to recover rare earths from Australian clay-hosted deposits. While the process routes and associated costs for higher grade projects have been well documented, the processing of clay-hosted deposits is in its infancy in Australia.

This paper outlines the impacts of several key process parameters on the overall project economics for these types of REE projects located in Australia. This includes a consideration of the grade of the deposit, the proportion of light and heavy rare earths, the type of leaching technology employed, reagent costs, washing requirements for the clay and the overall process flow sheet complexity.

Operational improvement in spodumene grinding circuits using Derrick fine screens

Y Reja[1] and A Newman[2]

1. Technical Manager, Derrick Corporation, Brisbane Qld 4006. Email: yreja@derrick.com
2. Country Manager – Australia, Derrick Corporation, Brisbane Qld 4006. Email: anewman@derrick.com

ABSTRACT

The detrimental effects of ultrafine material in mineral processing circuits are well established: reduced grinding-mill energy efficiency, lower flotation recovery, and increased dewatering load, among others. For spodumene, the ultrafine fraction of concern is material finer than 20 µm, and is the major barrier to closing the gap between design and achieved lithium recoveries. The principal mechanism is behavioural: -20 µm spodumene particles exhibit markedly lower affinity for the fatty-acid collector than the associated gangue, so they interfere with flotation rather than reporting cleanly to concentrate or tailings (Xu, 2017). Many operations pre-emptively deslime ahead of flotation, but this simply converts the interference problem into a direct loss, rejecting spodumene to the slimes stream (Cunningham, 2024). The only durable fix is to restrict the generation of -20 µm particles in the first place.

Analysis of plant survey data from an operating spodumene concentrator indicates that roughly 75–80 per cent of all slimes are generated within the milling circuit itself, a consequence of poor undersize classification efficiency in the hydrocyclones closing the circuit: misplaced fines recirculate to the mill and are overground well past the size at which they were already liberated. This paper presents plant survey data from that spodumene concentrator and quantifies, through circuit simulation built on a mass- and energy-conserving relative-capacity model (Magdalinovic, 1991; Jankovic and Valery, 2013; Reja *et al,* 2023), the improvement available from replacing or supplementing cyclone classification with Derrick high-frequency fine screens. The simulation shows classification efficiency lifting from 46 per cent to 90 per cent (undersize basis), circulating load falling from 328 per cent to 134–175 per cent, and circuit capacity increasing by 10–22 per cent. The finer material reporting to the flotation feed is reduced due to reduced overgrinding. There are 14 per cent fewer fines at 100 microns and 48 per cent fewer fines at 25 microns; this is consistent with a 50 per cent reduction in true -20 µm ultrafine generation.

Combined with the published linear relationship between mass rejected during desliming and lithium lost to slimes (Cunningham, 2024), this yields a modelled 30–50 per cent reduction in spodumene losses to slimes. The resulting recovery uplift gives a calculated payback of only 8 months. A documented copper cyclone-to-screen conversion at CIA Minera Condestable, Peru (Delgado, Diaz and Chambi, 2007; Dundar *et al*, 2014), against which the same capacity model was independently validated, is presented as field precedent for the same classification-efficiency mechanism. The advanced fine-screening technology has broader implications for mineral processing circuits generally, offering enhanced milling capacity, improved energy efficiency, and better flotation recovery together rather than as a trade-off.

REFERENCES

Cunningham, R, 2024. Spodumene concentrator design – lessons learned, in Proceedings 56th Annual Canadian Mineral Processors Operators Conference, Ottawa, Ontario, 23–25 January.

Delgado, M, Diaz, G and Chambi, R, 2007. Expansion de produccion de Condestable con innovaciones tecnologicas de clasificacion de molienda, in Proceedings XXVIII Convencion Minera Extemin 2007, Peru.

Dundar, H, Kalugin, A, Delgado, M, Palomino, A, Turkistanli, A, Aquino, B and Lynch, A, 2014. Screens and cyclones in closed grinding circuits, in Proceedings XXVII International Mineral Processing Congress (IMPC 2014).

Jankovic, A and Valery, W, 2013. Closed circuit ball mill – basics revisited, *Minerals Engineering*, 43–44:148–153.

Magdalinovic, N, 1991. *Grinding and Classification of Raw Materials* (Naucna Knjiga: Beograd).

Reja, Y, Zhang, B, Jain, A and Makola, J C, 2023. A simple methodology to predict improvements in capacity of closed grinding circuits, in Proceedings Comminution ‘23, MEI Conferences, Cape Town.

Xu, L P, 2017. Anisotropic surface physicochemical properties of spodumene and albite crystals: implications for flotation separation, *Applied Surface Science*, pp 1005–1022.

Meeting rising global sulfuric acid demand and constrained fossils supply – the role of copper derived output

T G Ryan[1], S A Northey[2], B Mendonca Severiano[3] and D P Giurco[4]

1. PhD Candidate, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW 2007. Email: tara.ryan-1@student.uts.edu.au
2. Research Director, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW 2007. Email: stephen.northey@uts.edu.au
3. Research Consultant, The University of New South Wales, Kensington NSW 2033. Email: b.mendonca_severiano@unsw.edu.au
4. Professor, Faculty of Engineering and Information Technology, The University of Melbourne, Parkville Vic 3010. Email: damien.giurco@unimelb.edu.au

ABSTRACT

Sulfuric acid is the most widely used chemical in the global economy by volume, reaching an estimated 230 million tonnes of production in 2025. Its use in minerals processing, metals recycling, battery manufacturing, phosphate fertiliser production, and water treatment industries is set to expand significantly to 2040, driven by the global energy transition, economic development, and increasing populations. Within minerals processing, sulfuric acid is a foundational, largely non-substitutable reagent across the critical minerals sector, including in the production of nickel (via high-pressure acid leach), copper (via solvent extraction-electrowinning), lithium, rare earth elements, cobalt, uranium, zinc, and manganese. Reflecting this importance, sulfuric acid is often reported as a distinct operational cost category, and recent price volatility has already placed financial pressure on these producers.

Currently, around 60 per cent of global sulfuric acid supply is sourced via de-sulfurisation processes during fossil fuel refining, required to meet fuel sulfur limits and local sulfur dioxide emissions regulations. The remaining 40 per cent is produced as a by-product of non-ferrous metal smelting and pyrite roasting. This by-product dependency on the fossil fuel industry gives rise to an emerging structural vulnerability for global sulfur and sulfuric acid supply, as the industry faces declining output in several regions due to a combination of heightened geopolitical tensions and tightening climate policy. Concerningly, this likely structural shift in supply – and the potential for shorter-term disruption – remains largely unaddressed within industrial chemical and critical mineral risk assessments and supply forecasting.

Given this future supply uncertainty, this study investigates the scale of future sulfuric acid supply from alternative means, with specific emphasis on supply as a by-product of copper. The study uses the open-source Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) model (Northey *et al*, 2023) to explore how much sulfuric acid could be supplied from the copper industry across a range of long-term scenarios. Unlike conventional by-product systems, sulfur grades are rarely reported, and sulfur is treated as a contaminant to be removed, rather than recovered, during mining and beneficiation stages. However, during high-temperature smelting, exothermic oxidation of sulfur in concentrates provides useful heat to the system, and the resulting sulfur dioxide gas is recovered to produce sulfuric acid. As a result, sulfur supply from the copper sector is governed not by ore grades or geological constraints but by concentrate compositions, mining-to-smelting trade networks, and smelter blending requirements and emissions limits.

Modelling demonstrates that base metals industries could play a significant role in future sulfur supply markets, offsetting declining fossil derived sulfur supply, but the scale of this contribution is highly uncertain and dependent on future primary copper supply scenarios, smelter configurations and regulatory trajectories. Understanding these system dynamics becomes essential for ensuring sufficient sulfur supply and economic security. Given this, consumers of sulfuric acid in the critical minerals sector should seek to evaluate risks in their specific sulfuric acid supply chains, while also exploring opportunities to increase rates of sulfur recovery at smelters.

REFERENCE

Northey, S A, Klose, S, Pauliuk, S, Yellishetty, M and Giurco, D, 2023. Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) model: Towards a stochastic understanding of the mineral discovery, mine development and co-product recovery requirements to meet demand in a low-carbon future, *Resources, Conservation and Recycling Advances,* 17:200137. https://doi.org/10.1016/j.rcradv.2023.200137

Thermodynamic re-optimisation of the Ni-Fe-Cu-S-As system – supporting the processing of complex Australian ores

I Shakirova[1], D Shishin[2] and E Jak[3]

1. Higher Degree by Research (HDR) student, The University of Queensland, St Lucia Qld 4072. Email: i.shakirova@uq.edu.au
2. Theme Leader Thermodynamic Modelling and Education, The University of Queensland, St Lucia Qld 4072. Email: d.shishin@uq.edu.au
3. Leader of the Pyrometallurgy Innovation Laboratory, The University of Queensland, St Lucia Qld 4072. Email: e.jak@uq.edu.au

ABSTRACT

Australia has large deposits of critical minerals that are mainly exported for processing in other countries. Building a strong domestic pyrometallurgical and hydrometallurgical infrastructure is essential for transforming these raw ores into high-purity products. This step will help Australia improve its position in the global energy transition. By processing these resources locally, the country can secure its own supply chains and promote industrial independence. The recent shift of the Kalgoorlie Nickel Smelter to care and maintenance highlights a strategic vulnerability in Australia's midstream processing ability. To ensure national independence and gain the full economic benefits of our resources, it is crucial to improve the technical frameworks that support our metallurgical sites.

A primary barrier to the processing polymetallic concentrates domestically is managing harmful impurities, especially arsenic (As). This research addresses this issue by re-optimisation of the Ni-Fe-Cu-S-As system from a thermodynamic perspective. The development of a high-fidelity predictive model for high-temperature phase equilibria facilitates the efficient processing of complex, arsenic-rich sulfide ores that would otherwise present significant economic or environmental challenges. By developing a reliable predictive model for phase equilibria at high temperatures, this study enables more efficient treatment of complex sulfide ores. This precision is key to cleanly separating valuable metals from waste, helping to overcome the economic and environmental hurdles that typically stall the processing of these deposits.

By combining equilibration-quenching experiments with precise Electron Probe Micro-Analysis (EPMA), this work provides the fundamental data required to improve furnace settings at major Australian sites, including Olympic Dam, Mount Isa, and the Kwinana Refinery. Crucially, this research provides the technical foundation and offers options to support the potential reopening and long-term sustainability of important facilities like the Kalgoorlie Nickel Smelter. By improving our understanding of impurity behaviour and phase equilibria, this work ensures that when market conditions improve, Australia has the necessary metallurgical tools process various sulfide deposits locally. This will help secure a self-sufficient and sustainable supply of metals for Australian industry and infrastructure.

Selective leaching of rare earth elements from NdFeB magnet waste using salt solution

J Shree[1], W Bruckard[2], N Haque[3], V Jegatheesan[4] and B Pramanik[5]

1. PhD Student, RMIT University, Melbourne Vic 3000. Email: s3986831@student.rmit.edu.au
2. Honorary Fellow, CSIRO, Clayton Vic 3168. Email: warren.bruckard@csiro.au
3. Principal Scientist, CSIRO, Clayton Vic 3168. Email: nawshad.haque@csiro.au
4. Professor, RMIT University, Melbourne Vic 3000. Email: jega.jegatheesan@rmit.edu.au
5. Associate Professor, RMIT University, Melbourne Vic 3000. Email: biplob.pramanik@rmit.edu.au

ABSTRACT

Spent neodymium-iron-boron (NdFeB) magnets represent a valuable secondary source of rare earth elements (REEs). This study presents an innovative process for recovering Neodymium (Nd) from spent NdFeB magnets using inorganic salt solution composed of aluminium nitrate nonahydrate ($Al(NO_3)_3{\cdot}9H_2O$) and water referred to as a 'green Brønsted solvent'. Hammett acidity measurements confirm that concentrated solutions of $Al(NO_3)_3{\cdot}9H_2O$ and H_2O exhibit strong Brønsted acidity, enabling the selective leaching of Nd from NdFeB magnet sample roasted at 660°C. A high separation factor of 4150 for Nd over iron (Fe) was achieved. This salt solution offers significant advantages, including non-volatility, safety, high solubility, and excellent selectivity for REEs. Under optimal conditions (80°C, solid-to-liquid ratio of 1:20, and leaching time of 150 min), 96.9 per cent of Nd was leached, while Fe leaching was limited to just 0.9 per cent. The dissolved Nd^{3+} was subsequently recovered from the leachate by precipitation with oxalic acid, followed by oxidative roasting, yielding Nd_2O_3 with a purity greater than 99 per cent. This high selectivity and product purity demonstrate the feasibility of this process for producing high-quality Nd_2O_3 suitable for reuse in NdFeB magnet manufacturing. Moreover, the approach minimises impurity incorporation and downstream processing requirements, offering an environmentally friendly strategy for REE recovery from secondary resources.

Towards sustainable cobalt extraction – carbothermic reduction-assisted microwave leaching of heterogenite cobalt oxide ores

B Siame[1] and I M Reaney[2]

1. PhD Student/Researcher, School of Chemical, Materials and Biological Engineering, University of Sheffield, Sheffield S13JD, United Kingdom. Email: bisiame1@sheffield.ac.uk
2. Supervisor, Dyson Chair in Ceramics, School of Chemical, Materials and Biological Engineering, University of Sheffield, Sheffield S13JD, United Kingdom. Email: i.m.reaney@sheffield.ac.uk

ABSTRACT

Sodium metabisulfite is the most widely used reductant for cobalt extraction from both primary and secondary sources; however, it generates sodium sulfate, which poses environmental challenges and increases processing costs. In this work, for the first time, the carbothermic reduction of Co^{3+} to Co^{2+} in complex ores (heterogenite, CoO·OH) from Zebesha Mine in Mwinilunga, North-Western Zambia, followed by microwave-assisted leaching (MWL) using sulfuric acid (H_2SO_4) benchmarked against conventional leaching (CL), is demonstrated. MWL achieved approximately 98.5 per cent cobalt extraction within 30 mins, compared to 120–180 mins for conventional leaching, under optimised conditions (P_{80} ≈ 100 µm, solid-to-liquid ratio of 25 wt per cent, 100 W, and 60°C). XRD analysis confirmed the presence of CoO in the reduced ores, enabling effective leaching of heterogenite without the use of external reductants such as sodium metabisulfite. Furthermore, H_2SO_4 consumption in MWL at 214 kg/t was 40 per cent less than CL at 358 kg/t. The combination of high extraction efficiency, reduced processing time and reagent consumption, and elimination of external reductants highlights carbothermic reduction coupled with MWL as a novel and sustainable approach for cobalt extraction from primary ores, with potential applicability to secondary sources.

OpenCu – an open source framework for evaluating renewables integration in the copper value chain

R Singh[1], M H A Khan[2], S Saydam[3], I Canbulat[4], I MacGill[5] and R Daiyan[6]

1. PhD Student, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney NSW 2052. Email: rasmeet_singh.singh@unsw.edu.au
2. Research Associate, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney NSW 2052. Email: muhammadhaiderali.khan@unsw.edu.au
3. Professor, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney NSW 2052. Email: s.saydam@unsw.edu.au
4. Professor, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney NSW 2052. Email: i.canbulat@unsw.edu.au
5. Professor, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney NSW 2052. Email: i.macgill@unsw.edu.au
6. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney NSW 2052. Email: r.daiyan@unsw.edu.au

ABSTRACT

Global decarbonisation and electrification are driving growth in copper demand while increasing scrutiny of metal's embodied emissions and supply chain resilience. As a foundational energy-transition metal underpinning renewable systems, electrification, transmission infrastructure and low-carbon technologies, copper plays a critical role in broader critical minerals ecosystem. This paper develops a transparent techno-economic framework to quantify cost-emissions trade-offs along the primary copper value chain, covering ore extraction and concentration, smelting and anode casting, electrorefining, rail transport and seaborne shipping. The Python-based model links mass and energy balances with capital, operating and carbon costs under user-defined ore grades, power mixes, fuel choices, carbon prices and logistics routes, reporting results per tonne of contained copper. A fossil-intensive business-as-usual configuration, representative of current global practice, yields mine-to-export costs of about US$4900 t^{-1} Cu and emissions near 5.9 t CO_2-e t^{-1} Cu. We then design 'green corridor' portfolios that combine higher-efficiency comminution, renewable power purchase agreements, electrified stationary loads, lower-carbon fuels for smelting and logistics, and optional hydrogen or e-fuels for premium low-carbon products. Under the lowest-emissions portfolios, levelised costs for cathode exports fall to around US$3900–4000 t^{-1} Cu (≈20 per cent reduction) while emissions decline to ≈1.6 t CO_2-e t^{-1} Cu (≈75 per cent reduction), implying an effective abatement cost of roughly -220 to -230 US$ t^{-1} CO_2 at the mine-to-export scale.

The results identify three strategic levers for copper supply chains:

1. Decarbonising mining and stationary electricity through low-cost renewable power.
2. Targeting hydrogen and e-fuels to hard-to-abate processing and transport segments.
3. Leveraging regional resource and infrastructure to determine where value is captured along the value chain, particularly the shift from concentrate exports to onshore cathode.

While demonstrated for copper, the modular framework is transferable to other critical minerals and strategic materials (Li, Ni, CO, REEs), providing practical decision-support platform for low-carbon, resilient mineral supply chains.

Optical sorting for coarse REE pre-concentration by ink-coating and magnetic lifting

H Su[1], A Yolalmaz[2], R Bheemireddy[2], Y Wu[2] and F Di Maio[2]

1. Postdoc, Resource and Recycling, Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2628CN, Netherlands. Email: h.su-3@tudelft.nl
2. Resource and Recycling, Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2628CN, Netherlands.

ABSTRACT

Mineral comminution is one of the most energy-intensive stages in beneficiation, and early rejection of barren material offers a direct route to reducing downstream processing demand. This study presents an opto-magnetic sorting approach for coarse rare earth element (REE)-bearing ore pre-concentration prior to grinding. The process combines image-based optical detection, selective inkjet wetting, magnetite adhesion, and magnetic lifting to achieve particle separation at the millimetre scale. In contrast to conventional compressed-air actuation, which can suffer from limited selectivity for small particles, the proposed method enables localised and controllable particle actuation through surface functionalisation and subsequent magnetic response.

Rauhaugite particles in the 2–4 mm size fraction were used as a model REE-bearing material. Optical classification was performed using ore-specific RGB thresholding under controlled imaging conditions, after which target particles were selectively wetted and coated with reusable magnetite powder for magnetic lifting. The system was operated in a reject-oriented mode to maximise early removal of low-grade material before comminution. Experimental results showed that 30.4 wt per cent of the feed could be rejected as a low-grade fraction. The retained high-grade fraction represented 57 wt per cent of the feed and reached a total rare earth oxide (TREO) grade of 2.32 wt per cent, compared with 1.71 wt per cent in the feed, corresponding to an enrichment factor of approximately 1.35. The sorter operated at 84 kg/h in the present lab-scale configuration, with a power draw of about 0.8 kW, low water consumption (~0.48 L/h), and magnetite recyclability above 99 per cent. These results demonstrate the feasibility of coupling selective wetting and magnetic lifting for coarse particle REE pre-concentration. The process provides a new route for reject-oriented sensor-based sorting at millimetre scale and shows potential to reduce unnecessary comminution of low-grade material in future mineral processing flow sheets.

Impact of transition metal impurities (Co, Cu, Ni, Fe) on vanadium electrolyte performance – toward direct electrolyte production from leach liquors

G Thompson[1], T B Issa[2], P Singh[3] and A N Nikoloski[4]

1. PhD Student, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: 35034309@student.murdoch.edu.au
2. Senior Research Fellow, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: t.issa@murdoch.edu.au
3. Emeritus Professor, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: p.singh@murdoch.edu.au
4. Professor, Extractive Metallurgy Hub, Harry Butler Institute (Centre for Water, Energy and Waste), Murdoch University, Murdoch WA 6150. Email: a.nikoloski@murdoch.edu.au

ABSTRACT

The integration of renewable energy into the power grid has intensified the need for reliable, large-scale energy storage to mitigate intermittency. Vanadium redox flow batteries (VRFBs) are a promising solution due to their long cycle life, rapid response, and operational safety. However, their widespread deployment remains limited by high capital costs, largely driven by stringent electrolyte purity requirements. Currently, the absence of well-defined impurity tolerance limits necessitates the use of high-purity vanadium electrolytes to minimise potential adverse effects, thereby increasing production costs. In practice, impurities may originate from vanadium-bearing feedstocks during extraction or from system component degradation during battery operation. These impurities may affect electrolyte stability, electrochemical kinetics, and overall battery performance. An alternative approach to reduce electrolyte costs is the utilisation of lower-grade vanadium sources; however, this requires a clear understanding of the effects of impurities inherent in these materials. This study investigates the impact of key transition metal impurities on VRFB electrolyte performance using cyclic voltammetry, electrochemical impedance spectroscopy, and charge-discharge testing. The results demonstrate that impurity concentrations above critical thresholds reduce electrochemical reversibility, increase cell resistance, and promote side reactions, ultimately decreasing the battery's energy efficiency. Building on these findings, the study explores direct electrolyte production from vanadium-bearing leach liquors by applying identified impurity tolerance limits to ensure acceptable performance. The approach reduces the need for extensive purification, thereby lowering processing complexity and electrolyte production costs.

Upgrading rare earth from clay deposits in Western Australia – mineralogical controls via physical and thermochemical treatments

Q T Tran[1], J J Eksteen[2], R D Alorro[3] and C C Beh[4]

1. PhD Candidate, Critical Minerals, Metals and Materials for the Energy Transition (C3MET), Curtin University, Bentley WA 6102. Email: q.tran6@postgrad.curtin.edu.au
2. Professor, Critical Minerals, Metals and Materials for the Energy Transition (C3MET), Curtin University, Bentley WA 6102. Email: jacques.eksteen@curtin.edu.au
3. Associate Professor, Critical Minerals, Metals and Materials for the Energy Transition (C3MET), Curtin University, Bentley WA 6102. Email: richard.alorro@curtin.edu.au
4. Senior Research Fellow, Critical Minerals, Metals and Materials for the Energy Transition (C3MET), Curtin University, Bentley WA 6102. Email: jane.beh@curtin.edu.au

ABSTRACT

Clay-hosted rare earth element (REE) deposits in Western Australia represent an emerging resource; however, most are non–ion-adsorption types and are refractory to conventional low-intensity leaching. This study systematically evaluates physical, thermal, and thermochemical treatments to upgrade eight clay-hosted REE samples, where upgrading is defined as both increasing REE concentration and enhancing leachability. Mineralogical and chemical responses were evaluated using quantitative X-ray diffraction (QXRD), elemental assays, and leaching test results. Based on QXRD, samples were classified into two groups: Group I clays, categorised by crandallite-group minerals, and Group II clays, characterised by high K-feldspar content. Initial ammonium sulfate screening confirmed that all samples are refractory, necessitating pre-treatment prior to leaching.

Physical upgrading by wet (<45 µm) and dry (<212 µm) sieving increased total rare earth oxide (TREO) concentrations by up to 79 per cent and 64 per cent, respectively, demonstrating effective REE enrichment through particle size control. Thermal (calcination) and thermochemical treatments (acid baking with H_2SO_4 and caustic cracking with NaOH) were subsequently assessed. Calcination induced complete dehydroxylation of kaolinite to metakaolinite and significantly improved REE leachability in Group I samples, achieving high recoveries during subsequent leaching. In contrast, calcination was detrimental to Group II samples due to the stabilising effect of K-feldspar.

Caustic cracking transformed kaolinite into hydroxylsodalite and promoted effective dephosphorisation with minimal dissolution of radionuclides, while acid baking converted REE phosphates into soluble sulfates but resulted in substantial gangue and radionuclide dissolution. Mineralogical transformations and elemental deportment were systematically analysed to describe REE upgrading behaviour across treatments. The contrasting behaviour of these two methods highlights important trade-offs among REE recovery, gangue dissolution, radionuclide mobilisation, and reagent consumption.

Overall, the study establishes mineralogically controlled pathways for upgrading refractory clay-hosted REEs and provides a baseline framework for selecting appropriate physical and thermochemical treatments for the future development of Western Australian clay-hosted REE resources.

Beyond the flow sheet – scaling ultra-high purity alumina for semiconductor and AI infrastructure

R Williamson[1]

1. Managing Director, Alpha HPA, Brisbane Qld 4170. Email: rwilliamson@alphahpa.com.au

ABSTRACT

The rapid acceleration of artificial intelligence infrastructure is redefining material performance thresholds across global semiconductor supply chains. Increasing chip density, higher power loads and intensified thermal management requirements are placing new pressure on advanced material inputs, including ultra-high purity alumina (HPA), where impurity control and consistency are critical to device reliability.

Developing a novel refining pathway is only the first milestone. The greater challenge begins once the chemistry works: delivering semiconductor-grade material at scale, under extended qualification cycles and application-specific performance constraints.

This presentation examines the transition from pilot-scale innovation to commercial manufacturing of ultra-high purity alumina using a proprietary solvent extraction refining process. The focus moves beyond flow sheet development to the operational realities of scaling for AI-driven semiconductor markets, including impurity management at trace levels, process stability during plant ramp-up, specification refinement through customer feedback, and maintaining batch-to-batch consistency under validation protocols that may extend for years.

In advanced electronics supply chains, the constraint is often not chemistry, but repeatability. Semiconductor qualification requires sustained material performance while facilities are being optimised and production volumes increase. Achieving this demands tight integration between engineering, operations and product development functions, supported by governance frameworks that enable rapid problem resolution without compromising quality standards. In practice, organisational alignment becomes as important as process design.

As AI adoption accelerates globally, geographically concentrated supply chains for critical inputs present increasing strategic risk. Establishing downstream advanced materials capability in Australia contributes not only to technical innovation, but to greater resilience within high-value technology ecosystems.

By shifting the lens from invention to industrial execution, this case study provides insight into what it takes to supply qualification-ready materials into AI-enabled semiconductor markets. It highlights the intersection of precision processing, manufacturing discipline and organisational capability required to move from process breakthrough to globally competitive advanced materials production.

A circular economy approach for critical mineral recovery and high-performance geopolymer production from mine tailings

S Yadav[1], W Bruckard[2], N Haque[3] and B Pramanik[4]

1. Research Fellow, RMIT University, Melbourne Vic 3000. Email: sachin.sachin@rmit.edu.au
2. Scientist, CSIRO, Melbourne Vic 3169. Email: warren.bruckard@csiro.au
3. Scientist, CSIRO, Melbourne Vic 3169. Email: nawshad.haque@csiro.au
4. Associate Professor, RMIT University, Melbourne Vic 3000.
   Email: biplob.pramanik@rmit.edu.au

ABSTRACT

Mine waste represents a growing global challenge due to increasing volumes, aging tailings storage facilities, escalating management costs, and stringent environmental regulations. This study addresses the dual environmental and economic burden of mining waste in Australia by proposing a sustainable valorisation pathway for its utilisation in high-strength construction materials. A circular economy framework is introduced to convert mining tailings, traditionally considered a liability, into valuable resources. The research focuses on the recovery of critical minerals (eg Ni, Mn, and rare earth elements) from sulfide tailings, followed by the utilisation of the residual aluminosilicate matrix for the synthesis of high-performance geopolymer composites. Selective leaching of nickel was systematically investigated and optimised. Under the optimal conditions of 5 per cent HNO_3 and 10 per cent H_2O_2, a liquid-to-solid ratio of 5, a leaching duration of 30 mins, and a temperature of 60°C, a nickel extraction efficiency of 95 per cent was achieved, with minimal co-leaching of aluminium (~10 per cent), the primary impurity. The post-leaching residue, enriched in aluminium and silicon, was effectively repurposed as a precursor for geopolymer production. The resulting geopolymer composites demonstrated a ~20 per cent enhancement in compressive strength and a ~47 per cent reduction in total porosity compared to conventional ordinary Portland cement. Overall, the proposed approach offers a cost-effective, environmentally sustainable strategy for reprocessing sulfide tailings with relatively mild reagents. This work highlights a significant advancement in the circular utilisation of mining waste, contributing to resource recovery, waste minimisation, and the development of next-generation construction materials.

Sustainable and energy-efficient flow sheet optimisation for integrated recovery of niobium and tantalum oxide from carbonatite ores

S Zafar[1], V Pareek[2] and T Bhatellia[3]

1. Researcher, Western Australia School of Mines – Minerals, Energy and Chemical Engineering, Curtin University, Perth WA 6102. Email: sohail.zafar1@postgrad.curtin.edu.au
2. Professor, Western Australia School of Mines – Minerals, Energy and Chemical Engineering, Curtin University, Perth WA 6102. Email: v.pareek@curtin.edu.au
3. Associate Professor, Western Australia School of Mines – Minerals, Energy and Chemical Engineering, Curtin University, Perth WA 6102. Email: t.bhatelia@curtin.edu.au

ABSTRACT

Processing of carbonatite-hosted niobium (Nb) ores are not only energy-intensive (~24 GJ t^{-1} Nb_2O_5) but also often results in incomplete recovery of associated critical elements such as tantalum (Ta). This study develops an integrated modelling and optimisation approach for the recovery of niobium and tantalum as oxide products (Nb_2O_5 and Ta_2O_5) from low-grade carbonatite ores with the objective to improve the overall process efficiency and resource utilisation.

A steady-state process model was developed for a 1000 t/h carbonatite ore containing 2.1 per cent Nb_2O_5 to carry out a detailed mass and energy balance for the process. The flow sheet incorporates all of the important unit operations, including comminution, classification, magnetic separation, flotation, acid leaching, solvent extraction using methyl isobutyl ketone (MIBK), stripping, precipitation, and calcination. The model enables quantitative tracking of metal distribution, reagent consumption, and energy demand across all unit operations.

Unlike conventional flow sheet studies, this work establishes a fully integrated mass energy recovery framework that directly links unit-level improvements to overall process performance. The optimised flow sheet achieves approximately 80 per cent recovery of both Nb and Ta from a low-grade feed (2.1 per cent Nb_2O_5), while reducing overall energy intensity from approximately 24 to 19 GJ t^{-1} Nb_2O_5 (20 per cent reduction). These improvements are attributed to reduced circulating loads, enhanced phase separation efficiency, and improved reagent utilisation.

Exploration, discovery and resource development

Novel fluorescence for spodumene imaging

A Baensch[1], C Wilske[2], J E Moffatt[3], D Beniwal[4], N A Spooner[5] and E P Schartner[6]

1. CEO, TeraGlo, Adelaide SA 5000. Email: aaron@teraglo.io
2. Postdoctoral Researcher, Adelaide University, Adelaide SA 5000. Email: cornelia.wilske@adelaide.edu.au
3. Postdoctoral Researcher, Adelaide University, Adelaide SA 5000. Email: jillian.moffatt@adelaide.edu.au
4. Lead Data Scientist, Adelaide University, Adelaide SA 5000. Email: deeksha.beniwal@adelaide.edu.au
5. Professor, Adelaide University, Adelaide SA 5000. Email: nigel.spooner@adelaide.edu.au
6. Technical Lead, Adelaide University, Adelaide SA 5000. Email: erik.schartner@adelaide.edu.au

ABSTRACT

As global lithium demand escalates, rapid spodumene identification is critical for the economic evaluation of pegmatite-hosted resources. Traditional mineralogical characterisation typically relies on sub-sampling then back-feeding for intensive laboratory assays, or on-site expensive scanning instruments that lack high throughput. This study introduces 'Novel Fluorescence' (NF) imaging, a new technique for mineralogical characterisation that distinguishes itself from traditional fluorescence through detailed interrogation of emitted fluorescence to achieve superior mineral specificity. By capturing unique spectral signatures, NF allows for the identification of spodumene from other minerals that could be misidentified using either visual identification or conventional UV fluorescence. Furthermore, NF is near-real time, non-contact, requires no sample preparation and is equally applicable to wet or dry samples.

The versatility of the NF sensor is shown through the demonstration of an automated prototype measuring across multiple sampling formats: drill core, chip trays, and heavy mineral concentrates (HMC). The system generates mineral phase maps in near real-time with no user intervention required. NF enables rapid screening of minerals in different sample types where it provides spatially resolved data essential for understanding target mineral concentration, deportment and textural relationships.

Results indicate that NF compares very favourably with established techniques like Laser-Induced Breakdown Spectroscopy (LIBS). Comparative mapping of drill core samples shows high correlation between NF spodumene and LIBS-derived lithium maps, providing useful mineralogical insights, but achieved at a much faster rate by NF. An additional significant advantage is operational flexibility; all data in this study—from coarse core to fine concentrates—was generated using a single prototype benchtop unit. By providing immediate feedback across diverse sample types, this Novel Fluorescence approach bridges the gap between field-based sampling and metallurgical assessment, offering a scalable, efficient tool for the critical minerals sector with strong potential for use both as a lab instrument or as a field-deployable system.

Crustal architecture, granites and critical minerals – machine-assisted mapping of the Yilgarn Craton, Australia

M Gazley[1], Y Lu[2], M Dunham[3], L Tannock[4], K Lilly[5], L Kendall-Langley[6], R Quentin de Gromard[7] and H Smithies[8]

1. General Manager Geoscience and Exploration, RSC, Thorndon Quay Wellington 6011, New Zealand. Email: m.gazley@rscmme.com
2. Principal Geoscientist, RSC, West Perth WA 6005, Australia. Email: y.lu@rscmme.com
3. Senior Product Owner: Geodata Science, ALS Geoanalytics, North Vancouver BC V7H 0A7, Canada. Email: michael.dunham@alsglobal.com
4. Regional Manager Geoscience and Exploration – Australia, RSC, West Perth WA 6005, Australia. Email: l.tannock@rscmme.com
5. Principal Geoscientist, RSC, West Perth WA 6005, Australia. Email: k.lilly@rscmme.com
6. Research Fellow, School of Earth and Oceans, University of Western Australia, Crawley WA 6009, Australia. Email: lillian.kendall-langley@uwa.edu.au
7. Senior Geologist, Geological Survey of Western Australia, East Perth WA 6004, Australia. Email: raphael.quentindegromard@dmpe.wa.gov.au
8. Geoscience Mapping and Geochemistry Specialist, Geological Survey of Western Australia, East Perth WA 6004, Australia. Email: hugh.smithies@dmpe.wa.gov.au

ABSTRACT

The Yilgarn Craton is one of the world's largest fragments of Archaean crust and among the most mineral-rich regions globally. Granites comprise >70 per cent of the surface area and are linked to major mineral systems, including gold (Au), lithium (Li), and rare earth elements (REE). Robust classification and mapping of granite suites are therefore fundamental to understanding craton-scale architecture, early Earth geodynamics, and metallogenic fertility.

Traditional geological mapping of the Yilgarn Craton has relied on manual interpretation of geophysical data supplemented by field observations. While effective at local scales, this approach is labour-intensive, subjective, and difficult to scale consistently, particularly in covered terrains. Existing granite classifications are largely based on petrographic, geochemical, geochronological, and isotopic analyses of outcrop samples. Although these studies successfully define granite groups, they are constrained by exposure bias and limited capacity to integrate large, multi-parameter geophysical data sets coherently across the entire craton.

Here, we apply machine-learning (ML) techniques to integrate regional gravity, magnetic, and radiometric data sets to classify granites across the entire Yilgarn Craton — at a scale not previously demonstrated. Both unsupervised and supervised ML approaches are applied. Unsupervised clustering identifies domains with similar petrophysical signatures, while supervised models produce a predicted granite classification map calibrated to granite classes derived from geochemical data.

Unsupervised clustering identifies coherent craton-scale domains that closely align with recognised terrane boundaries and independently derived Sm-Nd and Lu-Hf isotopic provinces. A sharp contrast in granite clusters is present between the Youanmi and South West terranes. Within the Youanmi Terrane, clustering supports similarities between the obsolete Southern Cross and Murchison domains, supporting disestablishment of the two domains, while also identifying a distinct granitic and textural domain along the western margin of the terrane, suggesting a previously unrecognised internal subdivision. Along the southern segment of the boundary between the Youanmi Terrane and the Eastern Goldfields Superterrane (EGST), a north-trending belt of similar clusters extend further east than currently mapped, implying that a revision of the terrane boundary is required.

A supervised ML-derived granite classification identifies a strong craton-scale contrast between the EGST and older terranes of the western Yilgarn Craton. The EGST is dominated by High-Ca, high-Sr/Y granites, whereas the Youanmi, South West, and Narryer terranes are dominated by Low-Ca granites. Low-Ca (high-Ti) granites occur almost exclusively within the most isotopically evolved parts of the craton. Our newly identified granitic subdivision within the Youanmi Terrane likely

represents different crustal exposure levels related to variations in metamorphic grade, indicating existence of a previously unrecognised major crustal boundary.

These ML results have direct implications for mineral exploration. Newly defined terrane boundaries and internal granite domains may represent favourable zones for Au and Li-pegmatite mineralisation. Low-Ca granites are predicted beneath shallow cover in the Yamarna Terrane, opening new exploration search space for potential Li-pegmatite mineralisation. Ultimately, this study demonstrates the power of integrating unsupervised and supervised ML with regional geophysics to resolve crustal architecture and bedrock geology at the craton scale. The approach is transferable to smaller scales, offering significant potential for greenstone-belt-scale targeting of Li, Au, and other critical commodities using high-resolution geophysical data, de-risking exploration in underexplored or covered terrains.

Applying generative AI to geological data discovery – the GSQ digital librarian

M Gordon[1]

1. Director, Geoscience Information, Department of Natural Resources and Mining, Manufacturing, Regional and Rural Development, Brisbane Qld 4000. Email: mark.gordon@nrmmrrd.qld.gov.au

ABSTRACT

The resources industry operates within an increasingly complex data landscape. Decades of exploration activity have produced vast archives of geological reports, surveys and data sets, yet extracting meaningful insights from these collections remains time-intensive and fragmented. While modern data portals have improved access to individual reports, geoscientists still face the challenge of synthesising insights across thousands of documents.

The Geological Survey of Queensland (GSQ) initiated the Digital Librarian Proof-of-Concept to explore how Generative Artificial Intelligence (GenAI) could assist exploration professionals in discovering and synthesising information across large collections of geological reports. Using large language models combined with retrieval-augmented generation techniques, the system enables natural language queries across curated report collections and returns synthesised responses derived from the underlying geological literature.

The proof-of-concept demonstrated that GenAI can significantly accelerate data discovery by extracting insights from unstructured exploration reports and presenting them in accessible, contextualised responses. This capability has the potential to shift exploration workflows from manual data searching toward higher-value geological interpretation and decision-making.

The project also revealed the important role that this kind of proof-of-concept plays in helping broker organisational change by enabling stakeholders to visualise both the significant benefits and potential risks in AI deployments. These insights highlight both the promise of AI-enabled discovery tools and the practical challenges associated with deploying them in operational environments.

This presentation shares the design, outcomes and lessons from the Digital Librarian experiment, and explores how AI may transform geological data discovery while supporting faster, more informed exploration decisions.

The evolving role of precompetitive geophysics in supporting exploration success in Queensland

M Greenwood[1]

1. Manager Regional Compilations, Geological Survey of Queensland, Brisbane Qld 4000. Email: matthew.greenwood@nrmmrrd.qld.gov.au

ABSTRACT

Precompetitive geophysics has increasingly become a strategic tool for government in driving critical mineral exploration success across Queensland, particularly as easily discoverable deposits decline and exploration focuses shifts undercover. The acquisition and delivery of high-quality geophysical data sets, such as high resolution airborne magnetic and radiometric surveys, regional airborne gravity gradiometry (AGG) and deep seismic surveys, are reducing uncertainty and giving explorers greater confidence in area selection and targeting concealed mineral systems.

In Queensland, there has been a shift from broad, standardised regional coverage towards more targeted, purpose-driven surveys designed to further enable exploration and discovery as well as complementing other geoscientific programs. Rather than uniform data acquisition, programs are increasingly aligned with GSQ priorities, mineral systems understanding, and industry input, focusing on areas of highest resource potential or critical knowledge gaps. Higher-resolution surveys and novel uses of emerging methods like regional AGG and grid-based Magnetotelluric surveys are being deployed to address specific geological questions, particularly in undercover regions. This more focused approach helps ensure precompetitive investment delivers real impact by enabling and de-risking exploration in priority regions.

In addition to undertaking new precompetitive data acquisition, GSQ is the custodian of open file exploration data sets. This allows the integration of newly acquired surveys with historical and industry-submitted data, building more complete and consistent data holdings over time. Through the Geoscience Open Data Portal, GSQ enables the exploration industry to leverage both legacy and contemporary data sets in there are selection and exploration workflows.

Through collaboration with organisations such as Geoscience Australia, data sharing, joint acquisition programs, and alignment with national-scale frameworks further enhance the value and reach of Queensland's precompetitive geoscience investment.

As exploration becomes increasingly data-driven, precompetitive geophysics will remain central to de-risking exploration in greenfield terranes, guiding investment decisions, and ultimately sustaining Queensland's pipeline of mineral discoveries in a more challenging exploration environment.

From discovery to development – a beneficiation-first approach for the Jupiter clay-hosted REE deposit

T T Hien-Dinh[1], N K Bonnici[2] and S R Owen[3]

1. Chief Metallurgist, Critica Limited, West Perth WA 6005. Email: hien@critica.limited
2. Senior Exploration Geologist, Critica Limited, West Perth WA 6005. Email: natalee@critica.limited
3. Exploration Manager, Critica Limited, West Perth WA 6005. Email: stuart@critica.limited

ABSTRACT

Clay-hosted Rare Earth Element (REE) deposits are increasingly recognised as a potentially important future source of REEs. However, their fine-grained clay-rich nature, and generally poorly understood mineralogy and deportment present significant challenges for conventional processing routes.

The Jupiter clay-hosted REE deposit, located 60 km west of Mt. Magnet, Western Australia 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 lower cut-off. Extensive quantitative microanalysis (TIMA, LA-ICPMS and EPMA) conducted on the various mineralised materials, shows the REEs are largely deported to hydrated secondary REE phosphate phases including gorceixite-goyazite-florencite, rhabdophane-monazite and churchite-xenotime, within a matrix dominated by kaolinite, quartz, iron (hydr)oxides, minor titanium oxides, manganese (hydr)oxides, baryte, smectite, montmorillonite and vermiculite, and relict silicate and oxide phases. Both REE and gangue mineralogy is both vertically and laterally zoned reflecting an interplay between protolith composition and weathering intensity.

(* TREO is the sum of 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).

The microanalytical work and mineralogical understanding led to a beneficiation first strategy to upgrade the REE phosphate mineral concentration and reduce gangue feed to conventional REE extractive processes. Beneficiation currently involves scrubbing attrition and targeted comminution followed by magnetic separation and flotation to selectively concentrate the key-REE bearing phosphate minerals. The initial REE mineral beneficiation test work demonstrated a 6–10 times REE upgrade with up to 96 per cent mass rejection to produce intermediate concentrates grading 1–2 per cent TREO at recoveries of 60–70 per cent of TREO from feed (*in situ*) grades of 1300–2200 ppm TREO. Further work continues improve REE concentrate grade and recovery.

The results highlight the critical role of microanalytical techniques and mineralogical understanding in designing effective beneficiation strategies and demonstrate the potential of beneficiation-first flow sheets to improve the economic viability of clay-hosted REE deposits.

INTRODUCTION

Western Australia (WA) hosts significant deposits of critical minerals which are integral to Australia's efforts to establish a globally significant 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 growing domestic and international demand for critical minerals required for modern technologies, including renewable energy infrastructure, electric vehicles, battery storage systems, robotics as well as aerospace and defence applications. Among these, Australian clay-hosted REE deposits represent an emerging deposit style with considerable development potential. Despite the very significant resource inventory these deposits have received less attention than hard rock REE and ionic clay deposits due to the challenges associated with the efficient extraction of secondary REE phases from such clay-rich hosts.

The Jupiter deposit is currently Australia's largest clay-hosted REE deposit and requires extensive metallurgical work to advance to development. A beneficiation-first flow sheet has been successfully developed for the deposit, demonstrating the ability to upgrade mineralised material by up to ten

times while rejecting approximately 95 per cent of the gangue prior to hydrometallurgical treatment. The successful development of this processing route demonstrates a new and viable pathway for pre-concentration of clay-hosted ores prior to hydrometallurgical treatment and provides an important framework for the assessment and development of similar deposits in Australia.

PROJECT LOCATION AND HISTORY

The Jupiter clay-hosted REE deposit forms part of Critica Limited's Brothers REE Project 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 bitumen Yalgoo-Mount Magnet highway, then via gravel pastoral station and exploration tracks.

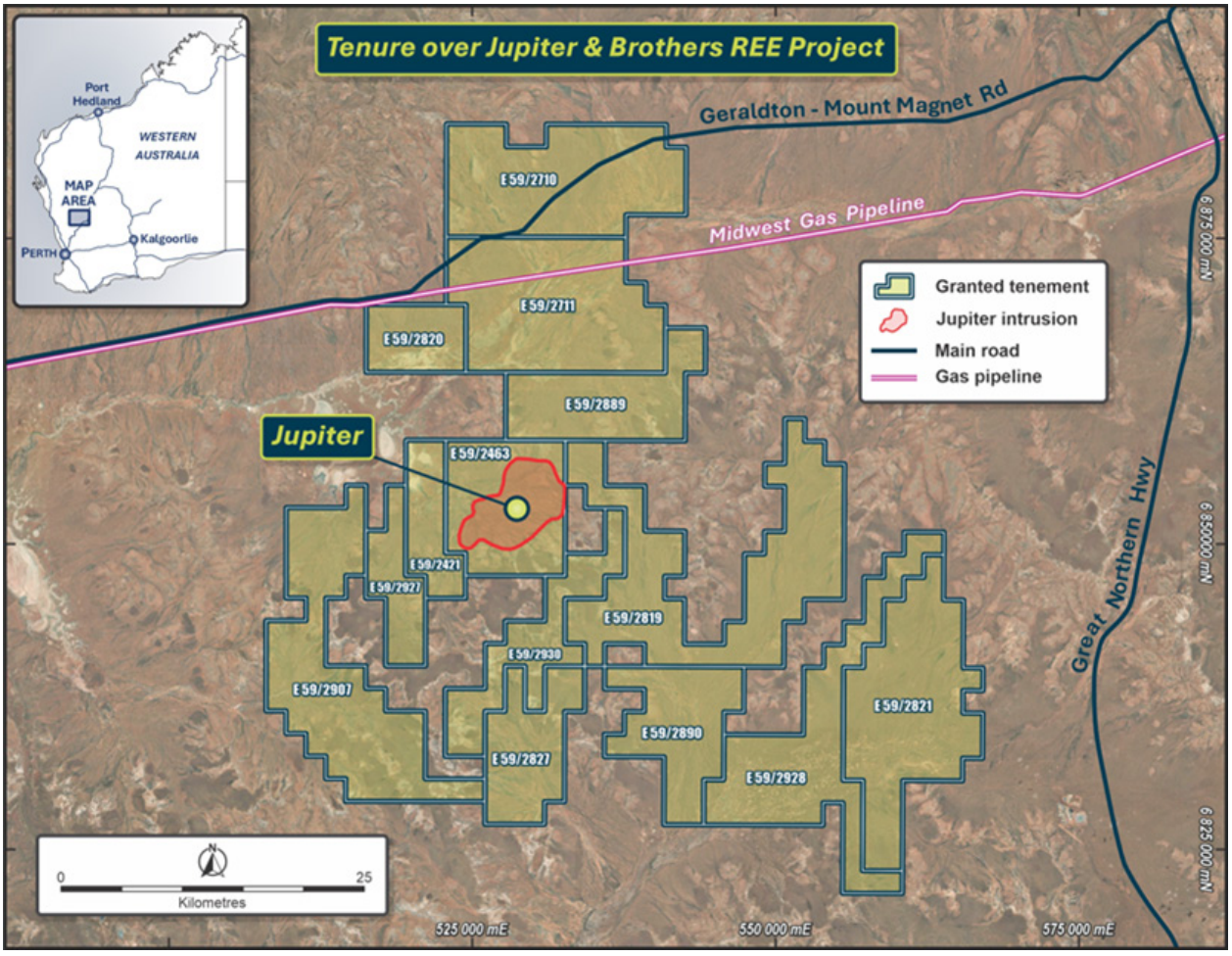


FIG 1 – Project location map; MGA94 Zone 50.

The Jupiter target was identified by Critica from a combination of regional laterite geochemistry and geophysics (GSWA open file data) and WA DMPE Exploration Incentive Scheme co-funded drill holes (Ross, 2020). First pass Air Core (AC) drilling of the Jupiter target was completed in June 2023, with every drill hole reporting significant REE mineralisation within clay and saprolite zones. Several AC, Reverse Circulation and Diamond Core drilling campaigns followed and in early 2025 an initial Inferred Resource of 1.8 Bt at 1700 ppm TREO was established for Jupiter at a 1000 ppm TREO lower cut-off (Critica Limited, 2025a). Jupiter is currently the largest and highest-grade clay-hosted rare earth deposit in Australia and second largest by TREO metal endowment behind Mt Weld, WA. Selected parts of Jupiter are being drilled to improve resource delineation for development scoping studies and provide additional material for bench and pilot scale metallurgical test work. Exploration drilling of satellite targets indicates very district-scale clay-hosted REE resource potential and preliminary microanalysis of the satellites suggests very similar REE mineralogy to Jupiter.

GEOMETALLURGY

Geometallurgy is driven by the commercial need to maximise metal recovery and profitability through a more geologically informed approach to metallurgical ore characterisation. It typically integrates geology, process mineralogy, metallurgy, engineering, resource modelling and geostatistics. The effectiveness of this integration depends on the quality, consistency, and capture of data, particularly in the early stages of a project.

Geological data acquisition forms the foundation of any geometallurgical program and is typically the first source of information collected during exploration. As a project advances through resource definition, scoping, pre-feasibility and other developmental stages, this information is progressively transferred to metallurgists and engineers. Collecting relevant and high-quality data early in the project enables more informed decision-making and increases the likelihood of technical and commercial success.

At the Jupiter deposit, a geometallurgical approach was adopted during the early exploration phase (Table 1). This framework has underpinned the development of the metallurgical flow sheet and facilitated a smooth progression from exploration through metallurgical testing and pilot plant development as part of an ongoing Scoping Study.

TABLE 1

Geometallurgical inputs used for the Jupiter REE deposit.

Geometallurgical inputs	Description
Multi-element geochemistry	Routine geochemical analyses appropriate for the style of mineralisation. Fusion (total) methods with ICP-MS finish for REE-phosphate minerals with a broad suite of major and trace element pathfinders for mapping gangue mineral distributions.
Hyperspectral scanning	Routine collection of hyperspectral data for clay mineral speciation and modelling.
Magnetic susceptibility	Routine collection magnetic susceptibility data provides additional validation to geological logging and geochemical data sets.
Mineral deportment	Identification of REE bearing mineral species and textural attributes (grain size, morphology, mineral association).
Gangue mineralogy	Identification of dominant gangue mineral phases and minerals that may have negative impact on mineral processing behaviours.
Geological logging	Consistent logging of key geological features (regolith, mineralogy, colour, water table) across all geologists.
Ore type characterisation	Identification of dominant naturally occurring mineral populations (ore minerals and gangue) with predicted variable metallurgical behaviours.

Mineralisation

Clay-hosted REE and gangue mineralogy is typically very fine grained and requires microanalytic techniques to resolve. 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.

The microanalytical work shows the REEs at Jupiter are mainly deported to the hydrated phosphates florencite $(REE)Al_3(PO_4)_2(OH)_5(OH)_6$ – gorceixite $(Ba,REE)Al_3(PO_4)(PO_3OH)(OH)_6$ – goyazite $(Sr,REE)Al_3(PO_4)_2(OH)_5(OH)_6$ solid solution and rhabdophane $REE(PO_4)(H_2O)$, and localised zones with churchite $(Y,HREE)PO_4{\cdot}2H_2O$. Dominant gangue minerals are kaolinite, quartz, magnetite,

hematite, feldspar, epidote, biotite, muscovite, illite, chlorite, barite, rutile, titanite, ilmenite, Mn-oxides, zircon and apatite (Figure 2).

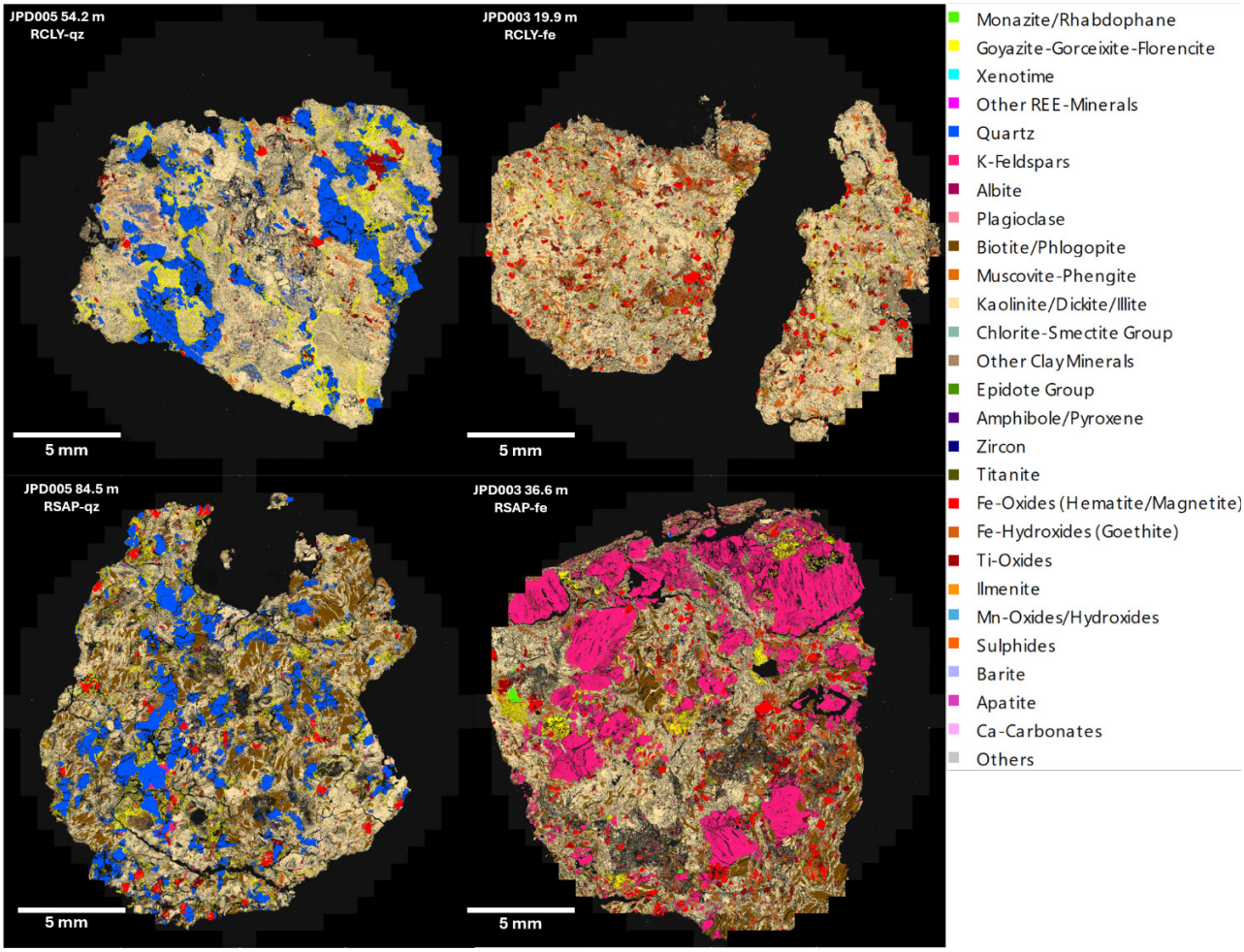


FIG 2 – Classified images from TIMA analysis of diamond drill core from the Jupiter REE deposit.

Rare Earth Element mineralisation within the Jupiter deposit is broadly vertically zoned from an upper Clay Zone dominated by the gorceixite-goyazite-florencite mineral group downwards to a rhabdophane-monazite and locally churchite-xenotime dominated Saprolite Zone with increasing relict primary REE phase deportment (apatite, titanite, allanite and REE fluoro-carbonates) in the Saprock Zone as fresh basement is approached. Zircon is widely residually enriched in the Clay Zone. Gangue phases kaolinite, quartz and secondary iron-(hydr)oxides and titanium oxides dominate the Clay Zone, and relict primary phases such as feldspar, biotite, magnetite, epidote, amphibole, chlorite and pyroxene increase with progress downwards through the Saprolite Zone to Saprock and fresh basement. Protolith control on residual and secondary mineralogy, both gangue and REE, becomes more significant as fresh Jupiter Intrusive Complex (Bonnici *et al,* 2025) is approached. The Jupiter Intrusive Complex is a zoned, strongly REE anomalous alkaline intrusion that ranges in composition from syenite and alkali gabbro through monzodiorite to quartz monzonite and granite.

The naturally occurring populations of gangue and accessory minerals form the basis of ore type characterisation at Jupiter. Metallurgical test work programs were therefore designed around the mineralogical and textural characteristics of each ore type. The primary objective was to selectively concentrate the REE-phosphate minerals while rejecting the gangue phases, thereby producing a higher-grade intermediate concentrate suitable for downstream hydrometallurgical REE extraction.

Ore type characterisation

Four dominant ore-types are currently identified within the Jupiter deposit, representing naturally occurring mineralogical and textural populations that exhibit distinct mineral processing behaviours. Classification of the ore-types was based on an integrated assessment of mineralogical, textural and geochemical data. Detailed mineralogical analyses identified three dominant REE mineral phases that account for the majority of the REE metal inventory within the Jupiter deposit. As a result, variability in processing behaviours is expected to be driven primarily by differences in gangue mineralogy rather than REE mineralogy.

A Principal Components Analysis (PCA) was undertaken using the major rock-forming oxides of Al_2O_3, CaO, Fe_2O_3, K_2O, Na_2O and SiO_2 (a proxy calculation was applied where SiO_2 analyses were unavailable) to identify natural populations (Figure 3). The PCA results demonstrate clear separation between clay-rich upper saprolite and lower saprolite regolith domains. Variations in gangue mineralogy are reflected by changes in the major-rock forming oxides, with high Fe_2O_3 associated with magnetite, hematite and goethite; SiO_2 with quartz; Na_2O and K_2O with albite, K-feldspar, plagioclase and/or biotite; CaO with pyroxene, amphibole and/or epidote). Transported overburden, which typically contains less than 300 ppm TREO, forms a distinct population separate from both the upper and lower saprolite domains. Three-dimensional modelling of the ore types demonstrates spatial continuity over distances ranging hundreds of metres to several kilometres and broadly reflects the primary mineral zonation of the underlying Jupiter Intrusive Complex.

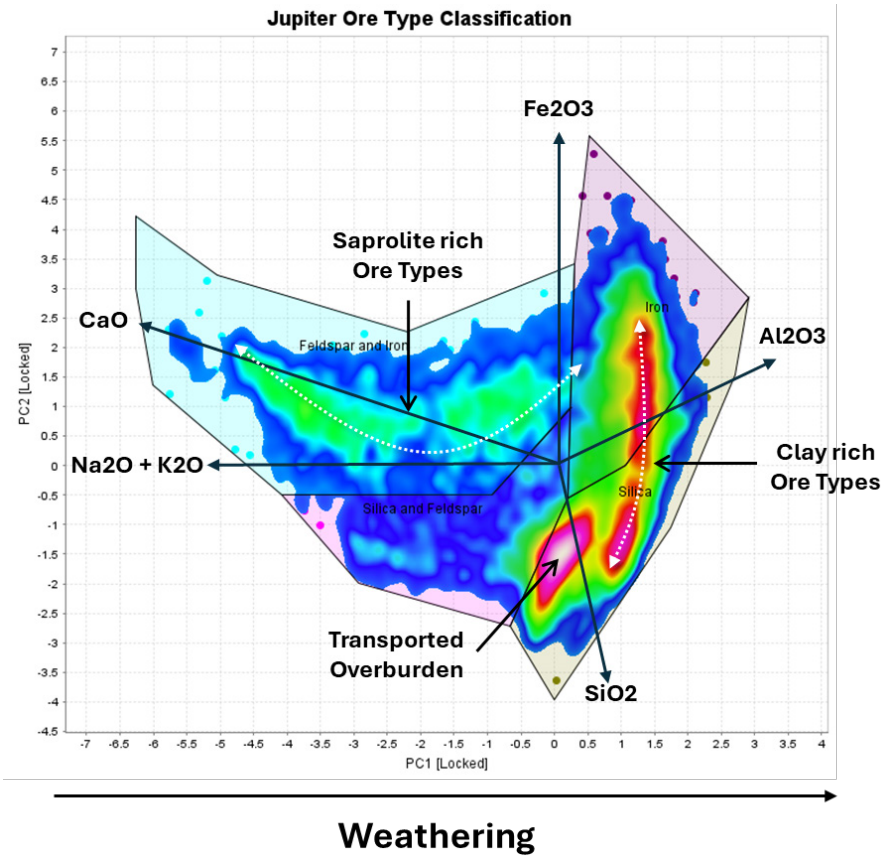


FIG 3 – Principal components analysis: PC1 (39.0 per cent) versus PC2 (35.3 per cent).

The four ore-types are described in Table 2 and illustrated in Figure 2. These ore-types inform the metallurgical test work design for the Jupiter deposit and provide a framework for understanding and predicting processing behaviours across the deposit. The PCA-derived classification enables automated assignment of ore-types using routine geochemical assays, providing a practical and reproducible methodology for ore-type classification. This approach supports representative metallurgical sample selection by ensuring that the full range of mineralogical and geochemical variability within the deposit is captured. Consequently, metallurgical test work results can be more

confidently extrapolated across the resource, improving the reliability of process design and mine planning studies.

TABLE 2

Jupiter ore types.

Ore-type	REE minerals	Major gangue minerals	Description
RCLY-fe	goyazite-gorceixite-florencite	kaolinite, fe-oxides, fe-hydroxides, quartz	>80% kaolinite with fine-grained aggregates of REE-phosphate minerals. Fe-oxides > quartz.
RSAP-fe		fe-oxides, fe-hydroxides, K-feldspar, albite, biotite, kaolinite, apatite, Ti-oxides	<20% kaolinite with fine-grained aggregates of REE-phosphate minerals typically with kaolinite or weathered mineral surfaces/fractures.
RCLY-qz	monazite-rhabdophane	kaolinite, quartz, fe-oxides	>80% kaolinite with fine-grained aggregates of REE-phosphate minerals. quartz > Fe-oxides.
RSAP-qz	xenotime	Quartz, kaolinite, fe-oxides, k-feldspar, albite	<20% kaolinite with fine-grained aggregates of REE-phosphate minerals typically with kaolinite or weathered mineral surfaces/fractures.

Predictive metallurgical behaviours

Clay-hosted REE deposits are typically large-tonnage, low-grade resources for which conventional hydrometallurgical processing can be economically challenging due to the large volumes of material requiring treatment and consequently potentially high reagent consumption and elevated processing costs. Project economics can be significantly improved by increasing the grade and reducing the mass of material reporting to downstream hydrometallurgical REE extraction processes.

The beneficiation strategy for the Jupiter deposit was developed from the mineralogical and deportment evidence rather than from the direct transfer of a conventional hard rock rare earth element (REE) flow sheet. Commercial and development-stage REE ores are commonly treated using combinations of gravity, magnetic, electrostatic and flotation separation, but the appropriate sequence is strongly controlled by the identity, grain size and associations of the REE-bearing minerals (Jordens, Cheng and Waters, 2013). Reviews of REE flotation similarly emphasise that differences in mineral surface chemistry, gangue assemblage and liberation can lead to markedly different responses to nominally similar reagent schemes (Chelgani *et al,* 2015; Marion, Li and Waters, 2020).

At Jupiter, the REEs occur mainly in fine-grained secondary phosphate minerals, including members of the gorceixite-goyazite-florencite group, rhabdophane-monazite and churchite-xenotime, within a regolith matrix dominated by kaolinite, quartz, iron (hydr)oxides and relict silicates (Table 3). Comparable lateritic REE systems may also contain diverse secondary phosphate hosts rather than a single coarse, readily liberated REE mineral (Verplanck *et al,* 2025). This distinction is important because phosphate-hosted regolith ores are mineralogically different from ion-adsorption clays, in which a substantial fraction of the REEs may be weakly adsorbed on clay surfaces and recovered directly by salt leaching without prior mineral concentration (Marion, Li and Waters, 2020; Foley and Ayuso, 2024).

TABLE 3

Metallurgical significance of the major mineral groups identified in the Jupiter deposit.

Minerals	Metallurgical behaviours
REE-bearing phosphate minerals (gorceixite–goyazite–florencite, rhabdophane–monazite, xenotime)	Primary REE hosts. Amenable to recovery by flotation using anionic collectors. Depending on reagent chemistry, flotation may also recover other phosphate minerals (eg apatite, if present) and some accessory heavy minerals.
Iron oxides and hydroxides (goethite, hematite, magnetite)	Amenable to magnetic separation, allowing early rejection of Fe-bearing gangue and potential production of an iron-rich by-product. Residual Fe minerals increase flotation reagent consumption, consume acid during hydrometallurgical processing, and contribute dissolved Fe impurities to the pregnant leach solution.
Clay minerals (kaolinite, smectite)	Dominant gangue minerals. Their ultrafine nature promotes slime generation, entrainment, increased pulp viscosity and reagent consumption during flotation. Strong association with REE phosphate minerals requires attrition scrubbing to disperse clay aggregates and expose mineral surfaces. Clay-rich feeds may also increase acid consumption and adversely affect solid–liquid separation during downstream processing.
Quartz	Major barren gangue mineral. Readily rejected by flotation under the selected reagent scheme. Its hardness provides beneficial abrasion during attrition scrubbing, assisting removal of clay coatings from particle surfaces.
Micas (biotite, phlogopite, muscovite)	Fine mica particles may report to flotation concentrates through entrainment or partial collector adsorption, reducing concentrate grade. Their platy morphology can also increase pulp viscosity and froth stability, thereby decreasing flotation selectivity.

The very fine-grained REE mineral deportment at Jupiter means that additional grinding is not necessarily beneficial. Fine grinding can increase liberation, but in clay-rich ores it can also increase the production of ultrafine particles, pulp viscosity, entrainment, reagent demand and slime coating. These effects can lower both concentrate grade and recovery and are widely recognised in the flotation of clay-bearing ores (Jeldres *et al,* 2019). The design objective was therefore not complete liberation through intensive comminution. Instead, the flow sheet sought to preserve natural liberation, disperse weak aggregates and surface coatings, reject readily separable gangue early, and then recover the phosphate-hosted REE assemblage by flotation.

This reasoning led to a beneficiation-first strategy comprising attrition scrubbing, magnetic separation and flotation. Each stage addressed a different mineralogical constraint: attrition targeted clay aggregation and coatings; magnetic separation targeted iron-rich material; and flotation targeted the REE-bearing phosphate assemblage. The intended product was an intermediate REE concentrate for subsequent hydrometallurgical treatment rather than a final high-purity mineral concentrate. This distinction is central to the process concept because the value of beneficiation lies not only in concentrate grade, but also in the amount and nature of gangue rejected before acid baking and leaching.

BENEFICIATION STRATEGY AND FLOW SHEET DEVELOPMENT

The laboratory programme was organised as a staged development study. Four mineralisation types were selected to cover the principal mineralogical variation identified within the available Jupiter samples (Table 2). Rather than presenting each experiment chronologically, the programme is interpreted here according to the process questions that it addressed: (i) whether physical upgrading was feasible without intensive grinding; (ii) whether iron-bearing material could be rejected before

flotation; (iii) which pulp chemistry and reagent system best recovered the phosphate-hosted REEs; and (iv) whether the selected conditions remained effective in multi-stage open- and closed-circuit configurations.

The most mineralogically complex ore type was used as the principal optimisation sample. This conservative approach reduced the likelihood that the final reagent scheme would be overfitted to the easiest material. Once the main pH, depressant and collector conditions had been selected, the flow sheet was applied to the other representative ore types to test its robustness across the observed variations in kaolinite, illite, quartz, feldspar, iron minerals and accessory heavy minerals (GAVAQ, 2025).

The preferred flow sheet was deliberately kept simple. Scrubbing and attrition were followed by wet magnetic separation, after which the non-magnetic stream was subjected to rougher, scavenger and cleaner flotation (Figure 4). The final circuit configuration was selected using a combined assessment of TREO grade, recovery, upgrade ratio and mass rejection. This multi-criterion approach is appropriate for low-grade REE ores because maximum recovery alone can produce an impractically large concentrate mass, whereas maximum grade alone may sacrifice an unacceptable proportion of the contained REEs.

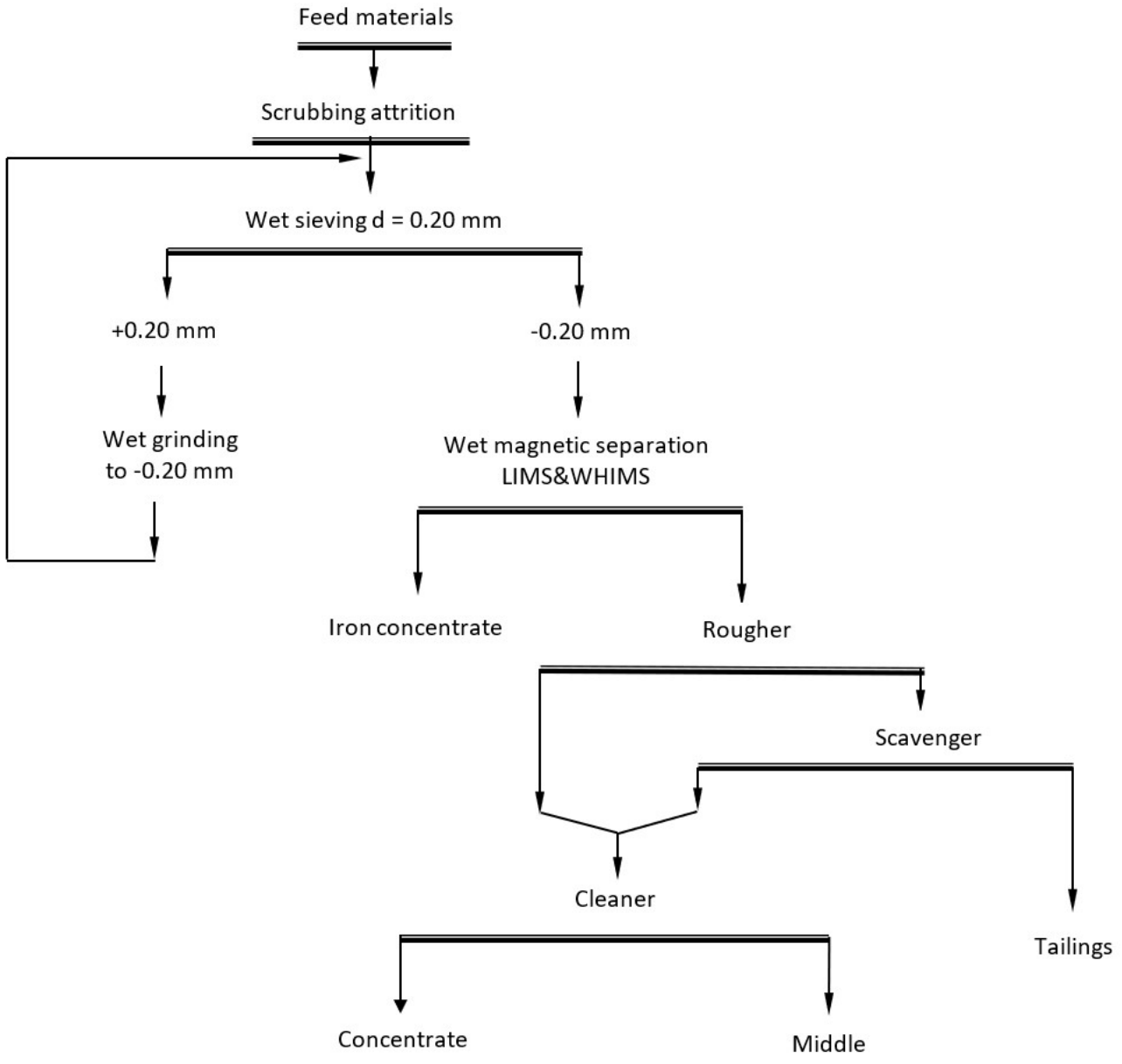


FIG 4 – Simplified beneficiation flow sheet used for the Jupiter programme.

Attrition scrubbing and magnetic separation

Attrition scrubbing was used to disperse clay-rich agglomerates and remove weakly attached coatings from particle surfaces without intentionally reducing the primary particle size. In a fine regolith ore, this distinction is important: the purpose of attrition is surface cleaning and dispersion rather than comminution. Improved dispersion can reduce the physical recovery of clay by entrainment and can expose phosphate mineral surfaces to collectors during the subsequent flotation stage. However, because kaolinite itself is fine and readily suspended, attrition must be accompanied by controlled pulp density, conditioning and froth management to avoid transferring dispersed clay directly into the concentrate.

Wet magnetic separation was evaluated as an early gangue-rejection stage. Goethite and hematite are less strongly magnetic than magnetite, so their response depends on field intensity, particle size, aggregation and mineral association. Nevertheless, even partial removal of iron-rich material can be valuable if it reduces the mass and impurity load presented to flotation and hydrometallurgy. The magnetic product may also have by-product potential where its iron grade and impurity profile are suitable, although this should be evaluated independently from the REE recovery objective.

Flotation strategy

Flotation was the principal REE upgrading stage because the target minerals are predominantly phosphates and the ore is too fine for efficient recovery by conventional gravity separation alone. Flotation is widely used for REE minerals because it can exploit differences in surface chemistry at particle sizes where density-based methods become inefficient (Jordens, Cheng and Waters, 2013; Chelgani *et al,* 2015). However, selectivity is challenging when several REE phosphates occur together with zircon, titanite, apatite, iron oxides and fine silicates.

The reagent programme examined pulp pH, gangue depressants, individual collectors and mixed collector systems (Table 4). Carboxylate collectors such as oleic acid, sodium oleate and tall-oil fatty acids have a long history in REE mineral flotation, although they are often less selective than hydroxamate collectors and can require careful control of pH, temperature and depressant dosage (Marion, Li and Waters, 2020). Their suitability for Jupiter was nevertheless reasonable because the objective was collective recovery of a mixed phosphate-hosted REE assemblage rather than selective separation of individual REE minerals.

TABLE 4

Development of the flotation reagent scheme for the Jupiter beneficiation flow sheet.

Development stage	Objective	Variables evaluated	Key observation	Final outcome
Pulp chemistry optimisation	Establish suitable flotation environment	pH 6–11	Acidic conditions reduced flotation selectivity, whereas alkaline conditions produced cleaner concentrates	Alkaline flotation selected
Collector screening	Compare collector performance	Oleate oleate, TOFA, Fatty acid, mixtures	No single collector consistently outperformed the mixed collector across all representative ore types	Mixed collector adopted
Depressant evaluation	Reduce gangue recovery	Na_2SiO_3, dextrin	Clay entrainment remained significant without sodium silicate	Sodium silicate selected
Circuit development	Improve concentrate quality	Cleaner stages	Cleaner flotation substantially upgraded concentrate grade	Rougher–Cleaner–Scavenger adopted
Locked-cycle verification	Confirm robustness	Closed circuit	Circuit performance remained stable under recycle conditions	Final flow sheet confirmed

Sodium oleate has been widely reported as an effective collector for monazite and xenotime flotation under alkaline conditions (Cheng, Holtham and Tran, 1993). However, flotation performance obtained from pure-mineral studies cannot be directly extrapolated to a complex ore such as Jupiter because mineral associations, particle size distribution, gangue interactions and overall pulp characteristics collectively influence flotation selectivity. Consequently, optimisation of the Jupiter flotation conditions relied primarily on systematic laboratory test work using representative ore samples, while published flotation studies were used as guidance for reagent selection rather than direct operating criteria.

The improved flotation response obtained using mixed collectors is most likely associated with the mineralogical complexity of the Jupiter ore. The concentrate contains several REE-bearing phosphate minerals together with variable proportions of gangue minerals that exhibit different flotation responses. Under these conditions, a mixed collector system provided more consistent flotation performance than any individual collector evaluated. Similar observations have been reported in previous studies, where collector performance depended on mineral assemblage, reagent chemistry and operating conditions rather than on a single flotation mechanism (Chelgani *et al,* 2015; Marion, Li and Waters, 2020).

Open-circuit tests were used to establish the appropriate placement of rougher, cleaner and scavenger stages. The rougher stage prioritised recovery of the fine REE-bearing particles, the cleaner stage reduced entrained and weakly attached gangue, and scavenging recovered residual REEs from the rougher tail. Closed-circuit testing was then used to assess the effect of recycle streams and to confirm whether the selected reagent scheme remained stable when intermediate products were returned to the circuit (GAVAQ, 2025).

Production of an intermediate REE concentrate

The combined beneficiation route produced substantial upgrading from low-grade feed. Across the representative ore types, the selected conditions achieved approximately six- to ten-fold TREO upgrading and rejected up to approximately 96 per cent of the feed mass (Table 5). Concentrates in the range of approximately 1.2–2.0 wt per cent TREO were obtained from feeds containing approximately 1310–2240 ppm TREO (Critica Limited, 2025b). These results demonstrate that a flotation concentrate can be produced despite the fine-grained nature of the REE hosts.

TABLE 5

Summary of the best beneficiation performance for the representative ore types.

Sample	Feed TREO (ppm)	Concentrate TREO (%)	Mass reduction (%)	TREO upgrade
RCLY-fe	2030	1.3	96	6.3x
RSAP-fe	1310	1.2	95	9.4x
RCLY-qz	2240	2.0	95	9.0×
RSAP-qz	1830	1.9	97	10x

Performance should be reported using four linked metrics: concentrate grade, recovery, upgrade ratio and mass rejection. Concentrate grade describes the quality of material sent to hydrometallurgy, while recovery quantifies the proportion of contained REEs retained. Upgrade ratio indicates the effectiveness of concentration, and mass rejection determines the potential reduction in downstream solids throughput. No single metric is sufficient. For example, a high-grade product obtained at very low recovery may not be commercially useful, whereas a high-recovery product containing a large fraction of the feed mass may provide little reduction in downstream processing cost.

The variability between ore types is also scientifically important. Samples richer in kaolinite or containing a larger proportion of the REEs in the finest size fractions can show increased entrainment and reagent demand. Conversely, samples with more feldspar, illite or accessory heavy minerals

may exhibit reduced collector selectivity or co-recovery of non-REE minerals. These differences should be interpreted using the mineralogical data rather than described only as statistical variation between tests.

CONCLUSION

The Jupiter beneficiation programme supports a mineralogy-driven, beneficiation-first flow sheet for a fine-grained phosphate-hosted clay REE deposit. Attrition scrubbing was used to disperse clay and clean particle surfaces; magnetic separation provided early rejection of iron-rich material; and flotation collectively recovered the fine REE-bearing phosphate assemblage. The selected route achieved substantial TREO upgrading and high mass rejection, producing an intermediate concentrate for downstream acid treatment. The results also show that ore variability, clay behaviour and co-recovery of accessory minerals must be interpreted as mineralogical controls on process performance rather than as reagent effects alone.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Critica Limited for providing access to the Jupiter project samples and for permission to publish the results presented in this paper. The authors also thank GAVAQ (Centre for Science and Technology of Mineral and Environment (Vietnam)) for conducting the beneficiation test work and providing technical support throughout the experimental programme.

The authors acknowledge AXT PL for the extensive mineralogical characterisation by TESCAN TIMA, and Curtin University and Resources Technology and Critical Minerals Trailblazer program for research support and access to laboratory and analytical facilities. Constructive discussions with colleagues from Curtin University, Critica Limited and GAVAQ are also gratefully acknowledged.

REFERENCES

Bonnici, N K, Owen, S R, Naithani, R and Martin, A F, 2025. Jupiter Rising: Unearthing Australia's largest Clay-Hosted REE Deposit, in *Proceedings of the Critical Minerals Conference 2025,* pp 23–31 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Chelgani, S C, Rudolph, M, Leistner, T, Gutzmer, J and Peuker, U A, 2015. A review of rare earth minerals flotation: Monazite and xenotime, *International Journal of Mining Science and Technology,* 25:877–883. https://doi.org/10.1016/j.ijmst.2015.09.002

Cheng, T-W, Holtham, P N and Tran, T, 1993. Froth flotation of monazite and xenotime, *Minerals Engineering* 6:341–351. https://doi.org/10.1016/0892-6875(93)90014-E

Critica Limited, 2025a. Jupiter Maiden Resource – Australia's Largest and Highest-Grade Clay-Hosted Rare Earth Deposit, ASX Announcement, 11 February 2025.

Critica Limited, 2025b. Excellent Bulk Sample Results Highlight Jupiter's Consistent Upgrade Potential, ASX Announcement, 29 September 2025.

Foley, N K and Ayuso, R A, 2024. Conventional rare earth element mineral deposits: The global landscape, *Rare Earth Metals and Minerals Industries*: *Status and Prospects* (ed: Y V Murty), pp 17–56 (Springer: Cham). https://doi.org/10.1007/978-3-031-31867-2_2

GAVAQ, 2025. G325 Experimental Results, Internal technical report prepared for the Jupiter REE beneficiation programme, 20 November 2025, Centre for Science and Technology of Mineral and Environment (GAVAQ, Vietnam).

Jeldres, R I, Uribe, L, Cisternas, L A, Gutierrez, L, Leiva, W H and Valenzuela, J, 2019. The effect of clay minerals on the flotation of copper ores: A critical review, *Applied Clay Science,* 170:57–69. https://doi.org/10.1016/j.clay.2019.01.013

Jordens, A, Cheng, Y P and Waters, K E, 2013. A review of the beneficiation of rare earth element-bearing minerals, *Minerals Engineering,* 41:97–114. https://doi.org/10.1016/j.mineng.2012.10.017

Marion, C, Li, R and Waters, K E, 2020. A review of reagents applied to rare-earth mineral flotation, *Advances in Colloid and Interface Science,* 279:102142. https://doi.org/10.1016/j.cis.2020.102142

Ross, D, 2020. Wardiacca Prospect Co-Funded Drilling Report, Department of Mines, Industry Regulation and Safety, Report A12336. 15 pp.

Verplanck, P L, Thompson, J M, Mercer, C M, Bhat, G, Lowers, H A and Boehlke, A, 2025. Formation of the Mount Weld rare earth element deposit, Western Australia: A carbonatite-derived laterite, in *Proceedings of the Third IAGC International Conference*, pp 643–646 (UNICApress).

Distribution and controls on critical minerals at Rosebery, western Tasmania – from deposit to concentrate

C Jago[1], N Fox[2] and A Parbhakar-Fox[3]

1. PhD Candidate, Sustainable Minerals Institute, University of Queensland, Indooroopilly Qld 4067. Email: cjago@uq.edu.au; Superintendent – Geology, MMG Australia Ltd, Southbank Vic 3006.
2. Senior Research Fellow, Sustainable Minerals Institute, University of Queensland, Indooroopilly Qld 4067.
3. Honorary Professor, Sustainable Minerals Institute, University of Queensland, Indooroopilly Qld 4067.

ABSTRACT

The Rosebery deposit in western Tasmania is a world-class, polymetallic volcanic-hosted massive sulfide (VHMS) system with a pre-mining endowment of 86.6 Mt @ 10.3 per cent Zn, 3.1 per cent Pb, 0.4 per cent Cu, 114.4 g/t Ag and 1.7 g/t Au. Continuous operation has occurred since 1936 with sequential flotation processing producing four saleable including Zn, Pb and Cu concentrates and dore. An expanded USGS Critical Minerals list from 2025 demonstrates the strategic significance of Rosebery as a base, precious and critical minerals. Historical research contains significant knowledge gaps in the distribution, variability and deportment of critical minerals at Rosebery.

This study presents preliminary results of a multi-scale characterisation program integrating whole-rock geochemistry, µXRF mapping, TIMA automated mineralogy, MLA and SEM analysis. A total of 65 underground grab samples were collected from the major ore lenses of the Rosebery Lower Mine and satellite prospects including Oak, Bastyan and Jupiter of the broader Read-Rosebery District. It is determined that different sulfide, barite and carbonate ore types throughout the deposit strongly control the distribution of critical minerals such as gallium, indium, cobalt, antimony and bismuth from an inter-lens to intra-lens scale. This signifies potential additional revenue streams to current ore sources.

Grab samples from active stopes in the W- and X- Lenses of the Rosebery Lower Mine were paired with corresponding Cu, Pb and Zn flotation concentrates and gravity circuit samples to understand metal deportment through mineral processing. Preliminary results indicate that Bi and Sb are significantly enriched in the Pb and Cu concentrates, with Sb reaches ~0.5 per cent in the Cu concentrate. Indium reports to the Zn concentrate, while Ga and Li are interpreted to report predominantly to tailings. These results establish a foundation for geometallurgical domaining and highlight Rosebery's broader significance of variable value drivers in the polymetallic deposit.

Critical mineralogy – where client's needs meet real world mineral assemblages

C Laukamp[1]

1. Principal Research Scientist, CSIRO Mineral Resources, Kensington WA 6151.
   Email: carsten.laukamp@csiro.au

ABSTRACT

Australia is endowed with a wide range of critical minerals deposits, such as pegmatite-hosted Li and carbonatite-hosted rare-earth element (REE) deposits. However, a lack of understanding about host and gangue minerals in the respective mineral deposits is limiting the minerals industry from extracting the full value and potentially even stifling investment due to overpromised quality of the respective critical mineral deposits. This is where mineralogy becomes critical.

In the case of pegmatite-hosted Li, a recent comparison of six different pegmatite-hosted Li deposits from across Australia shows that Greenbushes is unique, most notably in regard to: 1) the comparably high amount of spodumene in respect to the gangue minerals; and 2) minor abundance of other Li-bearing mineral phases, such as petalite, eucryptite and montebrasite, which were identified in other case study sites. Li hosted in other minerals than spodumene significantly reduces the amount of recoverable Li, reducing the economic viability of an ore deposit. Furthermore, some Li-bearing pegmatites contain significant amounts of Fe-rich white mica, which are more disruptive than pure muscovite because their breakdown produces Fe-bearing melts and oxides that can modify slag or reaction products and potentially contaminate lithium concentrates.

Accurate characterisation of host and gangue mineralogy is also important for extracting value from other critical minerals deposits, such as carbonatite- or clay-hosted REE deposits. Recent work by CSIRO Mineral Resources has shown that rapid analytical techniques, such as hyperspectral drill core logging, can be used to identify Nd-host mineral groups, such as phosphates or carbonates.

This paper aims to put a spotlight on the complexities and opportunities associated with Li and REE mineral deposits in Australia. For this, mineralogical and geochemical results of example case studies are presented (Laukamp *et al*, 2026a, 2026b). Methods for rapid analysis of critical minerals are discussed, that support decision-making by mineral explorers, mineral processing engineers and downstream industry.

REFERENCES

Laukamp, C, LeGras, M, Didonna, R and Stromberg, J, 2026a. On lithium, alteration and gangue mineral assemblages in Australian Li-pegmatites: hyperspectral mineralogy for orebody characterisation, *Australian Journal of Earth Sciences (AJES) NVCL Special Issue 2026*, pp 1–28. https://doi.org/10.1080/08120099.2026.2661996

Laukamp, C, Hu, S-Y, Chandler, R, Goswami, N, Pejcic, B and Wawryk, M, 2026b. A Comprehensive Understanding of Mineralogy and Geochemistry of the Mt Weld Carbonatite-Hosted REE Deposit: Insights from Hyperspectral and Whole-Rock Geochemical Analysis, *Geochemistry: Exploration, Environment, Analysis*, 26. https://doi.org/10.1144/geochem2025-027

Systematic characterisation of Queensland's mineral deposits and their alteration footprints – insights and tools for critical mineral exploration

V Lisitsin[1], E Belousova[2], A Kontonikas-Charos[3], A Tapu[4] and C Dhnaram[5]

1. Manager Mineral Systems, Geological Survey of Queensland, Brisbane Qld 4000.
   Email: vladimir.lisitsin@nrmmrrd.qld.gov.au
2. Principal Geoscientist, Geological Survey of Queensland, Brisbane Qld 4000.
   Email: elena.belousova@nrmmrrd.qld.gov.au
3. Senior Geoscientist, Geological Survey of Queensland, Brisbane Qld 4000.
   Email: alkiviadis.kontonikascharos@nrmmrrd.qld.gov.au
4. Senior Geoscientist, Geological Survey of Queensland, Brisbane Qld 4000.
   Email: altamini.tapu@nrmmrrd.qld.gov.au
5. CEI Grants Manager, Geological Survey of Queensland, Brisbane Qld 4000.
   Email: courteney.dhnaram@nrmmrrd.qld.gov.au

ABSTRACT

Since 2018, the Geological Survey of Queensland (GSQ) has undertaken a systematic program to characterise significant mineral deposits across Queensland, with a focus on critical and strategic minerals. This initiative aims to build a comprehensive public reference collection of samples and multi-faceted scientific data sets, providing a robust foundation for improving exploration efficiency and enabling new insights into Queensland's mineral systems.

In collaboration with industry, research organisations, and government agencies, GSQ has acquired and analysed over 700 drill cores from more than 110 mineral deposits. The main mineral system and deposit types investigated by this program include: Iron-oxide copper-gold (IOCG) and genetically affiliated deposits (containing elevated critical minerals, including cobalt, rare-earth elements (REE), molybdenum and rhenium); siliciclastic-carbonate ('SEDEX') Zn-Pb-Ag deposits (with elevated Ge); epigenetic sediment-hosted copper deposits (Mt Isa Copper, Capricorn Copper, with elevated Co and In); phosphorites (variably enriched in REE); diverse granite-related rare metal deposits (Sn and W skarns, greisens and veins, Zn skarns, Cu-Sn greisens and polymetallic veins with high In); bauxites (with high Ga); siliciclastic-mafic ('Broken Hill-type') Pb-Ag-Zn deposits; various styles of intrusion-related and epithermal gold deposits. Complementary research by the University of Queensland has characterised mine waste sites, further expanding the data set.

The reference mineral system collection integrates core imagery and hyperspectral data, whole-rock geochemistry, micro-XRF (X-ray fluorescence) and TESCAN Integrated Mineral Analyser (TIMA) maps, mineral chemistry and geochronology, creating a discoverable and accessible resource. This data supports more targeted exploration, reduces discovery risks, and enhances the understanding of Queensland's mineral potential, including opportunities for by-product recovery.

Queensland is the first jurisdiction in Australia to implement a systematic program for characterising mineral deposits, setting a benchmark for innovation in resource exploration. By providing high-quality, standardised data, GSQ's program establishes a critical foundation data set that aids industry exploration decision-making.

Mine waste dumps critical minerals resource characterisation framework for Zimbabwe

P Mugebe[1]

1. Researcher and Mining Consultant, Independent, Brisbane Qld 4520.
   Email: pilot@sikutaholdings.com.au

ABSTRACT

Mine waste dumps across Zimbabwe represent one of the country's most undervalued mineral assets, despite their potential to contribute meaningfully to critical-mineral supply, environmental rehabilitation, and circular-economy objectives. Generated historically from gold, base-metal, chromite, and tin operations, these tailings, slag, and waste-rock deposits contain residual metals that were either unrecovered by earlier processing technologies or never targeted due to limited economic interest at the time. Developing resource characterisation for these legacy dumps provides a systematic framework for quantifying their mineral potential, integrating geological, geochemical, mineralogical, metallurgical, and economic data sets to transform waste into viable secondary orebodies.

Effective resource characterisation requires high-resolution surveying to define dump geometry and tonnage, stratigraphic mapping, targeted sampling to capture spatial grade variability, multi-element geochemical and mineralogical analysis to identify critical minerals and determine liberation characteristics and processing behaviour, geostatistical modelling, and data integration into spatial databases. These data sets support the generation of input data required for the development of metallurgical test work, flow sheets development, and economic evaluation models.

Despite this potential, not much work has been done to characterise mine-waste dumps in Zimbabwe. Existing studies focus predominantly on environmental risks such as acid mine drainage (AMD) and metal contamination, with limited attention to the economic recovery of critical minerals. Most dumps have no surveyed volumes, no systematic sampling, no multi-element assays, and no geostatistical models. Metallurgical knowledge remains limited, and policy frameworks governing tailings ownership, reprocessing rights, and circular-economy incentives are underdeveloped. These gaps constrain investment, technology deployment, and strategic planning.

This paper outlines the role of structured resource characterisation in unlocking the critical-minerals potential of Zimbabwe's mine-waste inventory. By addressing current deficiencies through systematic characterisation, Zimbabwe could quantify the value of its mine-waste resources, support low-impact mineral supply, reduce environmental liabilities, and align national mining policy with global trends in circularity and critical-minerals security.

INTRODUCTION

Zimbabwe's extensive legacy of mining has produced large volumes of tailings, slag, waste rock, and metallurgical residues that remain under characterised despite their potential to host economically significant concentrations of critical minerals. These mine waste dumps represent one of the most under characterised yet potentially transformative sources of critical minerals in Southern Africa. This paper develops an academic analysis of the critical mineral potential of Zimbabwean mine waste, integrating geological assessment, sampling strategy, laboratory analysis, geostatistical modelling, economic evaluation, and policy considerations.

The mining sector of Zimbabwe has historically prioritised primary extraction of gold, platinum group metals (PGMs), chrome, nickel, and base metals, generating substantial waste over more than a century of operations. Much of this material was deposited without modern environmental controls or mineral recovery optimisation, resulting in 'large volumes of under-characterised waste that may contain economically significant concentrations of critical minerals' (Gwaze and Mupaya, 2019). As global demand for critical minerals intensifies, driven by renewable energy technologies, electric vehicles, and digital infrastructure (BGS, 2022; European Commission, 2023), Zimbabwe faces a strategic opportunity to re-evaluate its mine waste as a secondary resource.

However, systematic resource characterisation of mine waste remains limited. Historical operations lacked detailed geochemical characterisation, and few sites have undergone modern sampling or geostatistical modelling (Gwaze and Mupaya, 2019). This gap has constrained investment and hindered environmental rehabilitation. The present study establishes a structured, replicable framework for evaluating the critical-mineral potential of Zimbabwean mine waste using contemporary resource-characterisation techniques. It aligns with global and national critical mineral trends, and highlights the need for a systematic, data driven approach to waste-based resource evaluation. By bridging geological, economic, and policy perspectives, the study aims to support Zimbabwe's transition toward circular mineral development and sustainable resource management.

BACKGROUND AND CONTEXT

Zimbabwe's mining landscape is shaped by long-life operations, artisanal mining, and historical metallurgical inefficiencies. Prior to the 2000s, many mines operated with limited recovery technologies, resulting in significant losses of valuable minerals to tailings and waste rock. For example, early gold operations often achieved recoveries below 60 per cent, while nickel and copper concentrators produced tailings with substantial residual metal content. Chrome and PGM smelters generated slag containing recoverable ferrochrome, PGMs, and base metals. These inefficiencies mirror global trends where legacy waste contains significant residual value (Dold, 2014; Jowitt, Werner and Weng, 2020).

Australia has undertaken some of the world's most advanced mine-waste characterisation programs, culminating in Geoscience Australia's Atlas of Re-Mining Potential, a national-scale geoscientific framework that systematically maps tailings, slag, waste rock, and coal-ash deposits across the country. The Atlas integrates high-resolution geospatial data sets, multi-element geochemistry, mineralogical analysis, and spatial modelling to identify secondary critical-mineral opportunities, demonstrating what is possible when governments invest in structured mine-waste inventories and open-access data sets (Geoscience Australia, 2024). This work builds on decades of Australian research into tailings mineralogy, metallurgical inefficiencies, and circular-economy resource recovery, providing a benchmark for countries seeking to quantify secondary mineral resources within modern critical-mineral strategies (Jowitt, Werner and Weng, 2020). Many nations now recognise that 'legacy waste contains significant residual value' (Dold, 2014; Jowitt, Werner and Weng, 2020) and that systematic characterisation is essential for unlocking this potential. Australia's model shows that coordinated national data sets, rigorous sampling protocols, and transparent publication of mine-waste information can transform historical liabilities into strategic mineral assets.

Australia's leadership has influenced international practice, with the European Union, United States, Canada, China, and several emerging economies adopting similar approaches to mine-waste inventories, critical-mineral mapping, and secondary resource assessment. The EU's Critical Raw Materials Act explicitly references the need for structured tailings characterisation and has led to the development of national mine-waste inventories in Finland, Sweden, and Portugal, mirroring the Atlas framework. The United States Geological Survey (USGS) has expanded its mine-waste geochemical databases following methodologies pioneered in Australia, integrating multi-element assays, mineralogical data sets, and spatial modelling to identify rare earth elements (REE)-rich coal ash, PGM-bearing smelter residues, and base-metal tailings (USGS, 2023). Canada's Mine Waste Library and Chile's tailings-reprocessing initiatives similarly draw on Australian principles, emphasising systematic sampling, geostatistical modelling, and open-data publication to support critical-mineral security and environmental rehabilitation. South Africa has begun developing a national tailings inventory inspired by the Atlas, recognising the potential of gold, PGM, and chromite residues for secondary recovery. Collectively, these global case studies demonstrate that structured mine-waste characterisation is both feasible and transformative, offering Zimbabwe a clear pathway to build a national mine-waste inventory and unlock the secondary mineral value emphasised throughout this paper.

Zimbabwe, with its diverse mineral endowment, is well positioned to benefit from similar initiatives. However, Zimbabwe lacks a national inventory of mine waste dumps, standardised sampling protocols, and a unified policy framework for waste reprocessing (Chamber of Mines Zimbabwe, 2021). The context is further shaped by environmental considerations. Many legacy dumps pose

risks such as AMD, heavy metal leaching, and land degradation. Reprocessing these materials offers dual benefits: recovering valuable minerals while reducing environmental liabilities (Mutemeri and Petersen, 2002). This aligns with Zimbabwe's Vision 2030 goals, which emphasise industrialisation, environmental stewardship, and value addition.

GEOLOGICAL CHARACTERISTICS OF ZIMBABWE MINE WASTE

Zimbabwe's mine waste dumps reflect the country's diverse geological provinces, each with distinct mineralogical signatures. These include the base metal belts, greenstone belts, the Great Dyke, and coal and coal-ash waste deposits. Figure 1 summarises these geological provinces and their characteristic mineralogical signatures.

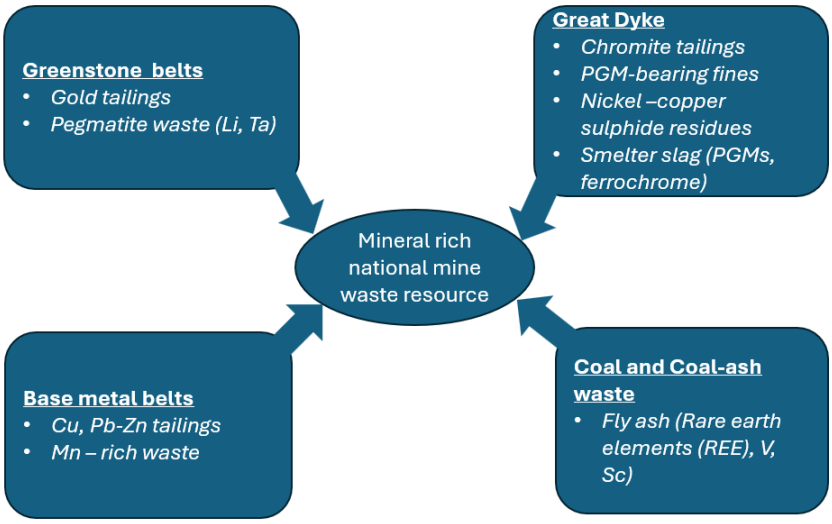


FIG 1 – Zimbabwe geological provinces mineralogy.

Zimbabwe's mine waste inventory reflects the country's major geological provinces, each generating distinct waste streams with significant potential for secondary resource recovery. The Archaean greenstone belts host gold, base metals, and lithium-bearing pegmatites, producing waste types such as gold tailings and pegmatite waste (Li, Ta), Figure 1. Gold tailings commonly retain residual gold locked within sulfide minerals including arsenopyrite and pyrite, as well as trace critical minerals such as antimony, tungsten, and tellurium (Gwaze and Mupaya, 2019; Dold, 2014). Pegmatite waste similarly contains lithium, tantalum, and tin, aligning with recent assessments of Zimbabwe's emerging critical-mineral potential (BGS, 2022; Mtondoro, 2025).

The Great Dyke constitutes another major source of mine waste, hosting chromite, PGMs, nickel, and copper sulfides. Waste materials include chromite tailings, PGM-bearing fines, nickel–copper sulfide residues, and smelter slag (PGMs, ferrochrome) Figure 1. These materials often contain residual chromite (Cr_2O_3), recoverable PGMs, and ferrochrome, reflecting both historical processing inefficiencies and the Dyke's globally significant PGM endowment (Chamber of Mines Zimbabwe, 2021; Jowitt, Werner and Weng, 2020).

Zimbabwe's base metal belts, notably the Magondi and Zambezi belts, contribute copper (Cu), lead-zinc (Pb-Zn) tailings and manganese (Mn)-rich waste, Figure 1. These residues frequently contain accessory cobalt, germanium, and REE, consistent with global observations that base-metal tailings represent important secondary sources of critical minerals (European Commission, 2023; Jones *et al,* 2012). Complementing these hard-rock sources, coal and coal-ash waste from thermal power stations and coalmines generate fly ash, rich in REE, vanadium (V), and scandium (Sc), Figure 1. These are materials increasingly recognised as strategic for the energy transition (USGS, 2023; Magalini, Parbhakar-Fox and Golev, 2025).

Across all geological provinces, Zimbabwean mine waste exhibits considerable mineralogical complexity, being 'heterogeneous, poorly documented, variable in grain size and mineral liberation, and influenced by historical processing inefficiencies' (Denhere, 2021). This complexity underscores the need for systematic characterisation of the mine waste. Structured approaches are essential for

quantifying recoverable value, mitigating environmental risks, and supporting circular-economy strategies in line with emerging global and national policy frameworks (Lebre, Corder and Golev, 2016; Zibret, Mhlongo and Lottermoser, 2020; Mapuvire and Mukonza, 2025). This complexity underscores the need for systematic sampling and mineralogical analysis.

FIELD METHODS AND SAMPLING STRATEGY

Field investigation of Zimbabwean mine waste begins with comprehensive site reconnaissance, combining high-resolution drone imagery, differential GPS surveys, historical mine plans, and visual stratigraphic logging to delineate dump geometry, internal stratification, erosion features, and evidence of historical reworking. Such reconnaissance is essential given the spatial variability and anthropogenic modification characteristic of mine waste deposits (Meck, Love and Mapani, 2006; Lebre, Corder and Golev, 2016). Drone-based photogrammetry and GPS-derived elevation models allow accurate volumetric assessment and identification of sampling transects, while stratigraphic logging supports the recognition of depositional layers, reworked zones, and oxidation fronts, consistent with best practice tailings mapping approaches (Anglo American, 2020).

Based on reconnaissance outputs, a sampling design is developed using a hybrid approach that integrates grid-based surface sampling, vertical auger or sonic drilling, trench sampling, and composite sampling. Sampling density is explicitly linked to geological complexity, as reflected in Table 1. Slag dumps and waste-rock dumps require even higher sampling intensities due to their greater heterogeneity. The indicated density thresholds align with international guidance on sampling anthropogenic mineral deposits, where heterogeneity strongly influences representativeness and confidence in grade continuity (Jones *et al,* 2012; Jowitt, Werner and Weng, 2020). Vertical drilling is used to capture depth variability in tailings profiles, while trenches and pits provide access to coarser waste rock and slag materials.

TABLE 1

Dump recommended sampling density.

Dump type	Geological complexity	Recommended sampling density
Homogeneous tailings	Low	1 sample per 500–1000 m^2
Heterogeneous tailings	Medium	1 sample per 200–300 m^2
Slag dumps	High	1 sample per 150–250 m^2
Waste rock dumps	Very high	1 sample per 100–200 m^2

Sample collection follows strict protocols to ensure representativeness and minimise contamination. Oxidised crusts are removed prior to sampling, consistent depths are maintained across grid points, and non-metallic tools are used to avoid trace-element contamination, particularly important for REE-bearing coal ash and PGM-rich smelter slag (Gwaze and Mupaya, 2019; Dold, 2014). Physical attributes such as moisture content, grain size, colour, compaction, and visible mineralisation are recorded systematically, supporting later geological domaining and metallurgical interpretation. Chain-of-custody procedures are maintained throughout field operations to ensure sample traceability.

A rigorous quality assurance/quality control (QA/QC) programme underpins all sampling activities, incorporating field duplicates, blanks, and certified reference materials to monitor precision, contamination, and analytical accuracy. These procedures follow established QA/QC frameworks for mine waste characterisation (Mhlongo and Amponsah-Dacosta, 2016; Zibret, Mhlongo and Lottermoser, 2020). Field duplicates quantify sampling variability, blanks detect contamination during collection and transport, and certified reference materials ensure laboratory accuracy for critical minerals such as PGMs, REEs, lithium, and cobalt. All QA/QC results are reviewed prior to database entry, ensuring that only validated data inform subsequent geochemical, mineralogical, and resource characterisation workflows.

Collectively, this integrated field methodology provides a defensible foundation for characterising Zimbabwe's mine waste deposits, supporting circular-economy initiatives (Magalini, Parbhakar-Fox and Golev, 2025; Jowitt, Werner and Weng, 2020) and enabling the identification of strategic secondary resources in line with national and international critical-mineral frameworks (European Commission, 2023; USGS, 2023).

LABORATORY ANALYSIS AND DATA PREPARATION

In recent years, global best practice in mine-waste laboratory characterisation has been significantly advanced by the work of Anita Parbhakar-Fox and the MIWATCH (Mine Waste Transformation through Characterisation) program at the Sustainable Minerals Institute, University of Queensland. The work drew considerably from both the applications of hyperspectral mineralogy for geoenvironmental characterisation methodologies (Fox *et al*, 2017), and the techniques for mineralogical mine wastes characterisation for acid rock drainage and metal(loid) leaching (ARDML) potential (Brough *et al*, 2013). MIWATCH provides one of the most comprehensive and structured laboratory workflows for mine-waste analysis, integrating geometallurgical, mineralogical, geochemical, and environmental data sets into unified characterisation pipelines. Parbhakar-Fox's methodology emphasises multi-scale mineralogical analysis, including hyperspectral scanning, automated mineralogy such as quantitative evaluation of minerals by scanning electron or mineral liberation analyser (QEMSCAN/MLA), and detailed deportment studies to determine mineral liberation, associations, and processing behaviour—approaches that directly complement and strengthen the analytical workflow described in Figure 2.

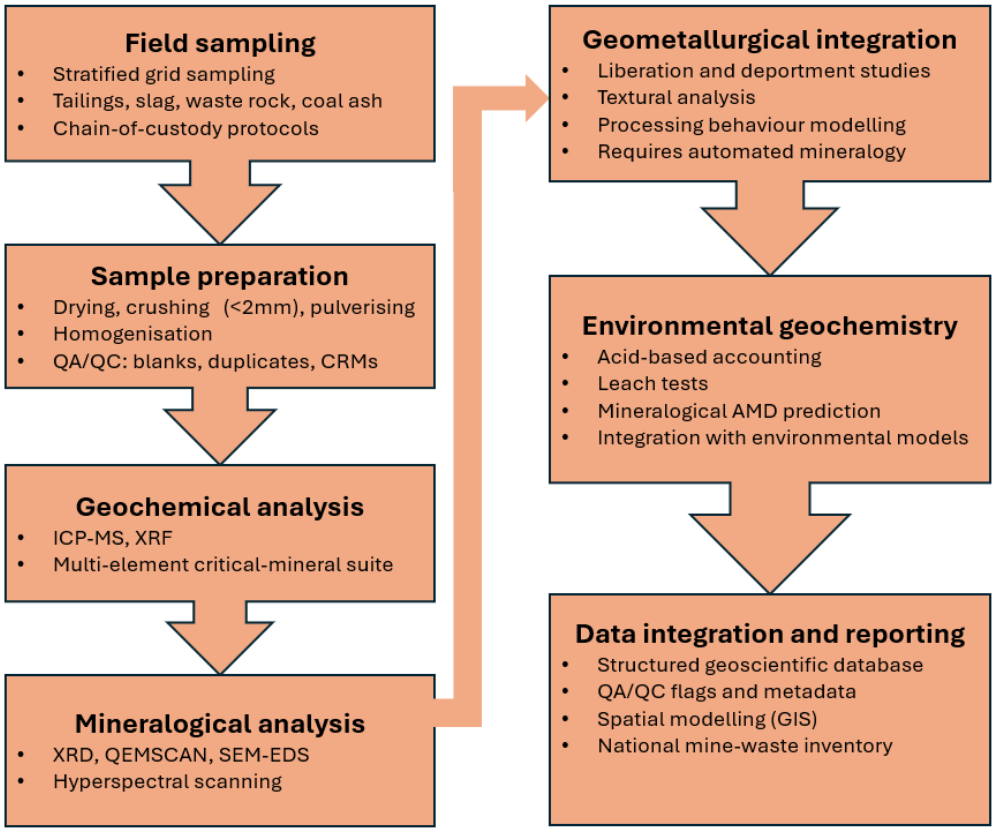


FIG 2 – Zimbabwe mine-waste analytical pipeline (MIWATCH-adapted).

A key contribution of MIWATCH is its rigorous integration of geochemical, mineralogical, and textural data sets into decision-ready geometallurgical models. This includes systematic workflows for identifying critical-mineral signatures in tailings, slag, and waste rock, as demonstrated in MIWATCH case studies across Queensland, Tasmania, and Western Australia. These workflows incorporate advanced analytical techniques such as micro-X-ray fluorescence (XRF) spectrometry mapping, scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) mineral liberation analysis, and multi-element inductively coupled plasma mass spectrometry (ICP-MS) profiling,

enabling high-resolution understanding of mineral deportment and reprocessing potential. MIWATCH's structured laboratory protocols have directly informed national initiatives such as Geoscience Australia's Atlas of Re-Mining Potential, which adopts similar mineralogical and geochemical workflows to characterise Australian mine-waste inventories at scale (Geoscience Australia, 2024). The integration of MIWATCH methodologies into national data sets demonstrates the value of structured laboratory characterisation in supporting critical-mineral strategies, circular-economy objectives, and secondary resource development—providing a clear model for Zimbabwe as it seeks to modernise its mine-waste analytical capabilities.

RESOURCE CHARACTERISATION METHODOLOGY

Resource characterisation of mine-waste dumps requires a structured, multi-disciplinary workflow that integrates geological, geochemical, mineralogical, geometallurgical, spatial, and environmental data sets into a coherent evaluation framework. These data sets support the construction of 3D block models, grade interpolation, and preliminary resource classification, forming the foundation for metallurgical test work, flow sheet development, and economic evaluation. Global best resource characterisation practice is exemplified by Australia's national mine-waste programs, particularly Geoscience Australia's Atlas of Re-Mining Potential, which provides a systematic methodology for identifying, characterising, and publishing mine-waste resources at national scale. The Atlas approach emphasises high-resolution surveying, rigorous sampling, multi-element geochemistry, automated mineralogy, geometallurgical modelling, and spatial integration—principles that form the foundation of modern mine-waste resource characterisation (Geoscience Australia, 2024). These methods align closely with the structured workflows developed by Anita Parbhakar-Fox through the MIWATCH program, which has become a global benchmark for mine-waste characterisation.

The characterisation process begins with geological domaining, where mine-waste dumps are subdivided according to depositional history, material type, grain size, mineralogical zones, oxidation fronts, and evidence of reworking. This step is essential for heterogeneous materials such as gold tailings, chromite residues, slag, and coal ash, where mineral liberation and grade continuity vary significantly. The Atlas of Re-Mining Potential adopts similar domaining principles, using drone photogrammetry, light detection and ranging (LiDAR), and stratigraphic logging to define dump geometry, internal layering, and volumetric attributes. MIWATCH workflows reinforce this approach by integrating mineralogical domains derived from QEMSCAN/MLA, hyperspectral scanning, and SEM-EDS textural analysis, enabling high-resolution understanding of mineral deportment and liberation characteristics.

Following domaining, geochemical and mineralogical characterisation is undertaken using multi-element ICP-MS, inductively coupled plasma optical emission spectrometry (ICP-OES), XRF, and acid digestion, supported by automated mineralogy QEMSCAN/MLA, XRD, SEM-EDS, and hyperspectral mineral mapping. These techniques allow identification of critical-mineral signatures, mineral associations, liberation behaviour, and processing constraints. MIWATCH workflows emphasise the integration of geochemical and mineralogical data sets into unified geometallurgical models, enabling prediction of processing performance, recovery potential, and metallurgical variability. This multi-scale analytical approach has been widely adopted in Australian mine-waste programs and underpins the Atlas methodology, which uses mineralogical and geochemical data sets to classify re-mining potential across thousands of legacy sites.

The next stage involves spatial modelling and data integration, where validated analytical results are compiled into structured geoscientific databases and integrated with spatial data sets. The Atlas of Re-Mining Potential demonstrates the importance of national-scale spatial integration, using geographic information system (GIS) platforms to map mine-waste locations, volumes, mineral potential, infrastructure proximity, and environmental constraints. MIWATCH workflows similarly emphasise database construction, QA/QC flagging, and spatial integration to ensure traceability, reproducibility, and compatibility with national inventories. For Zimbabwe, adopting these practices would enable development of a national mine-waste inventory and support future resource classification.

Although mine-waste deposits are not typically reported under the JORC Code, the principles of transparency, materiality, and competence remain essential. JORC-aligned practices guide data

validation, sampling representativeness, analytical accuracy, geological interpretation, and classification confidence. Early-stage mine-waste characterisation typically aligns with exploration results, while more advanced data sets may support inferred resource-style classifications where geological continuity and grade variability are sufficiently understood. Australian practice demonstrates that mine-waste resources can be classified using JORC principles when sampling density, analytical quality, and spatial continuity meet minimum reporting standards.

Finally, geometallurgical and environmental integration is undertaken to evaluate processing behaviour, recovery potential, and environmental risks. MIWATCH workflows incorporate liberation analysis, deportment studies, textural modelling, acid-base accounting, leach testing, and mineralogical AMD prediction, enabling comprehensive assessment of both economic and environmental performance. The Atlas of Re-Mining Potential adopts similar approaches, integrating metallurgical and environmental data sets to identify re-mining opportunities that support circular-economy objectives and reduce legacy liabilities. For Zimbabwe, adopting these integrated workflows would enable robust evaluation of reprocessing potential, environmental mitigation pathways, and strategic alignment with national critical-mineral goals.

Collectively, these methodologies provide a world-leading framework for resource characterisation of mine-waste dumps. By adopting structured workflows from MIWATCH, the Atlas of Re-Mining Potential, and broader Australian practice, Zimbabwe can generate high-quality data sets, support national critical-mineral strategies, and transform legacy mine-waste deposits into viable secondary resources.

ECONOMIC EVALUATION FRAMEWORK

The economic evaluation of mine-waste reprocessing projects requires a comprehensive assessment of capital and operating costs, revenue potential, metallurgical performance, market dynamics, and project risks. Cost estimation begins with identifying key capital expenditure (CAPEX) components, which include reclamation equipment, processing plants, water and power infrastructure, and environmental controls. These elements correspond directly to what is outlined in Figure 3. CAPEX is typically influenced by the scale of the dump, mineralogical complexity, and the need for specialised circuits for PGMs, REEs, lithium, or chromite (Anglo American, 2020; Lebre, Corder and Golev, 2016). Operating expenditure (OPEX) encompasses excavation, milling, beneficiation, reagents, labour, and tailings re-deposition, reflecting the recurring costs associated with continuous material movement and processing (Mhlongo and Amponsah-Dacosta, 2016).

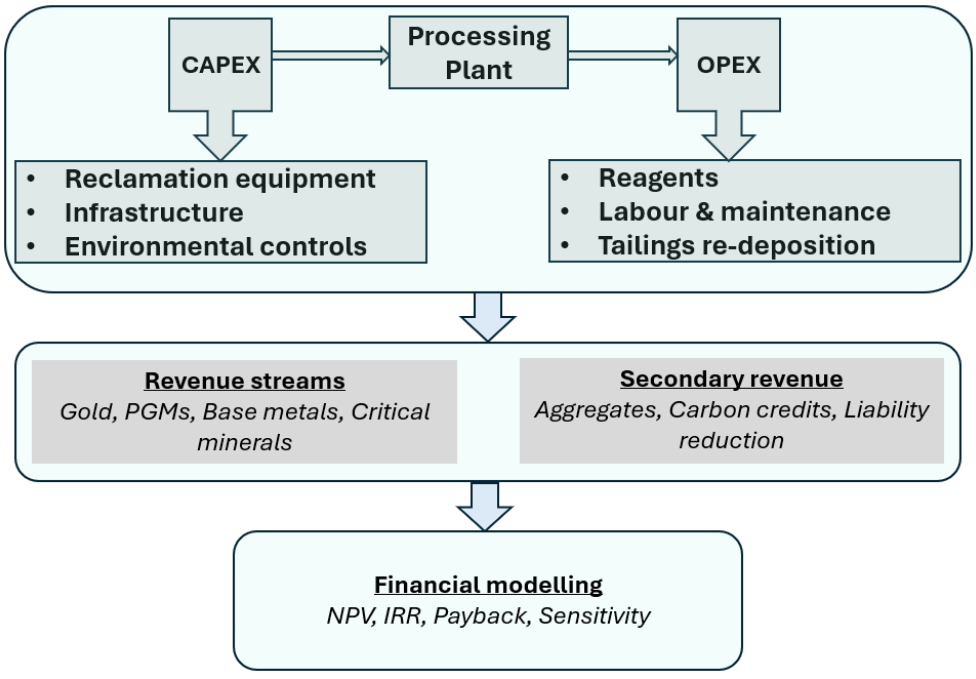


FIG 3 – Economic evaluation framework.

Revenue generation is derived from a diverse suite of commodities present in Zimbabwean mine waste, including gold, PGMs, chrome, nickel, copper, cobalt, lithium, REEs, vanadium, and scandium. These align with Figure 3's revenue streams, which are gold, PGMs, base metals, and critical minerals. Secondary revenue streams, such as aggregates, carbon credits, and reduced environmental liabilities, are increasingly recognised within circular-economy frameworks (Jowitt, Werner and Weng, 2020; Magalini, Parbhakar-Fox and Golev, 2025). Aggregates from waste rock and slag can support construction markets, while carbon credits may arise from reduced land disturbance or improved tailings stability (Manyakaidze, Mhlongo and Petersen, 2025). Liability reduction, including improved water quality and reduced dust emissions, provides additional indirect economic benefits (Meck, Love and Mapani, 2006; Mutemeri and Petersen, 2002).

A critical component of economic evaluation is metallurgical recovery, which determines the proportion of valuable minerals that can be economically extracted. Metallurgical test work assesses mineral liberation, recovery methods, reagent consumption, and reprocessing efficiency, consistent with global best practice for secondary resource evaluation (Dold, 2014; Gwaze and Mupaya, 2019). Recovery performance directly influences revenue projections and processing plant design, particularly for complex materials such as PGM-bearing fines, REE-rich fly ash, and lithium-bearing pegmatite waste (BGS, 2022; European Commission, 2023).

Financial viability is assessed through discounted cash flow (DCF) modelling, incorporating net present value (NPV), internal rate of return (IRR), payback period, and sensitivity analysis, Figure 3. Sensitivity analysis evaluates the impact of fluctuations in grade, recovery, commodity prices, operating costs, and discount rates, ensuring that project economics remain robust under varying market conditions (Chamber of Mines Zimbabwe, 2021; Jones *et al,* 2012).

Market considerations are particularly important for critical minerals, whose prices and demand are shaped by supply chain disruptions, technological shifts, policy incentives, and substitution risks (USGS, 2023; Scot and Eldon, 2025). Zimbabwe's position within global lithium, PGM, and REE supply chains means that geopolitical developments, battery-technology evolution, and regulatory frameworks such as the EU Critical Raw Materials Act (European Commission, 2023) significantly influence project economics.

Finally, a comprehensive risk assessment is essential to ensure project resilience. Key risks include grade variability, metallurgical uncertainty, regulatory delays, community conflicts, and commodity-price volatility. These risks are heightened in mine-waste projects due to heterogeneous material properties and historical processing inefficiencies (Denhere, 2021; Zibret, Mhlongo and Lottermoser, 2020). Regulatory risks are shaped by evolving national legislation such as the Mines and Minerals Act and debates around strategic-mineral governance (Mapuvire and Mukonza, 2025; Murombo, 2025). Social risks may arise from community expectations, land-use conflicts, or legacy environmental issues (Munyoka, 2020; Love, Mapani and Meck, 2006).

Together, these components form a rigorous economic evaluation framework that integrates technical, financial, environmental, and market considerations, enabling informed decision-making for mine-waste reprocessing and supporting Zimbabwe's transition toward a circular and critical-mineral-driven economy.

ENVIRONMENTAL AND POLICY CONSIDERATIONS

Environmental management is central to the reprocessing of Zimbabwe's legacy mine waste, which poses multiple risks including acid mine drainage, heavy-metal leaching, dust emissions, groundwater contamination, and land instability. These risks have been widely documented in Zimbabwean mining districts, where historical dumps have contributed to water pollution, soil degradation, and air-quality deterioration (Meck, Love and Mapani, 2006; Love, Mapani and Meck, 2006). Table 2 highlights the severity of these impacts. Reprocessing offers a direct mitigation pathway by removing sulfidic material, stabilising reactive residues, improving dump geometry, and reducing dust emissions through moisture control and vegetation cover (Dold, 2014; Lebre, Corder and Golev, 2016). Land instability, identified in Table 2 as safety hazards can be significantly reduced through engineered reprofiling and consolidation during reclamation activities.

TABLE 2

Environmental management.

Environmental risk	Impact	Mitigation
Acid mine drainage	Water contamination	Removal of sulfidic material
Heavy-metal leaching	Soil/groundwater pollution	Stabilisation of residues
Dust emissions	Air quality degradation	Moisture control, vegetation
Land instability	Safety hazards	Reprofiling and compaction

Zimbabwe's regulatory framework governing mine-waste management is anchored in the Environmental Management Act (Chapter 20:27; Zimbabwe Government, 2016), the Mines and Minerals Act (Chapter 21:05; Zimbabwe Government, 2006), and statutory instruments regulating environmental impact assessments (EIAs), waste management, and water use. These instruments establish legal obligations for pollution control, land rehabilitation, and responsible mineral extraction (Munyoka, 2020; Mapuvire and Mukonza, 2025). However, enforcement capacity varies across regions, and legacy dumps often predate modern regulatory requirements, creating gaps in compliance and oversight (Mutemeri and Petersen, 2002). The regulatory environment is evolving in response to global critical-mineral demand, with increasing emphasis on sustainable resource utilisation and alignment with international frameworks such as the EU Critical Raw Materials Act (European Commission, 2023).

Despite this regulatory foundation, several policy gaps and opportunities remain. Zimbabwe lacks a comprehensive national mine-waste inventory, limiting strategic planning and investment in secondary resource recovery (Zibret, Mhlongo and Lottermoser, 2020). Incentives for reprocessing such as tax credits, royalty adjustments, or carbon-credit integration, are limited, and circular-economy principles are not yet fully embedded in mining policy (Magalini, Parbhakar-Fox and Golev, 2025; Jowitt, Werner and Weng, 2020). Addressing these gaps aligns with Vision 2030 goals, which emphasise sustainable industrialisation, environmental stewardship, and value addition in the mineral sector (Chamber of Mines Zimbabwe, 2021). Opportunities include integrating mine-waste reprocessing into national critical-mineral strategies, promoting public-private partnerships, and leveraging international climate-finance mechanisms.

Social considerations are equally important, as mine-waste reprocessing intersects with land access, employment creation, artisanal mining activities, and community health and safety. Many dumps are located near settlements or areas used by artisanal miners, creating potential conflicts over land rights, resource access, and benefit sharing (Munyoka, 2020; Murombo, 2025). Reprocessing projects can generate employment and reduce environmental health risks, but they must incorporate inclusive engagement strategies, transparent communication, and community-benefit frameworks to ensure social licence to operate (Manyakaidze, Mhlongo and Petersen, 2025). Health and safety considerations include managing dust exposure, stabilising unstable dump slopes, and preventing contamination of local water sources—issues that have historically affected mining communities across Zimbabwe (Love, Mapani and Meck, 2006).

Together, these environmental, regulatory, policy, and social dimensions form a comprehensive framework for responsible mine-waste reprocessing. Integrating environmental mitigation, regulatory compliance, circular-economy principles, and community engagement is essential for unlocking the strategic value of Zimbabwe's mine-waste resources while ensuring long-term sustainability and social acceptance.

DISCUSSION

The study highlights that Zimbabwe's mine waste dumps constitute a significant, yet under-characterised, secondary resource base for critical minerals. The integrated framework described, spanning geological domaining, systematic sampling, laboratory analysis, geostatistical modelling, economic evaluation, and environmental-policy alignment, shows that mine waste can be assessed with the same rigour applied to primary ore deposits. This is essential given the

mineralogical complexity, heterogeneity, and historical processing inefficiencies documented across Zimbabwe's greenstone belts, the Great Dyke, base-metal belts, and coal-ash environments (Gwaze and Mupaya, 2019; Lebre, Corder and Golev, 2016).

Based on the geology of the mine waste sources and the historical processing techniques, it is highly likely that mine waste streams contain economically relevant concentrations of gold, PGMs, chrome, nickel, copper, cobalt, lithium, REEs, vanadium, and scandium, aligning with global trends in critical-mineral demand (BGS, 2022; European Commission, 2023). The application of structured field methods, including reconnaissance, stratigraphic logging, and density-adjusted sampling strategies, ensures representativeness across diverse dump types. Laboratory workflows, encompassing geochemical, mineralogical, and physical testing provide high-resolution data sets suitable for geostatistical modelling.

Resource characterisation outlined the importance of geological domaining and variography in capturing spatial continuity within heterogeneous anthropogenic deposits. It highlighted the importance of leveraging the already established methodologies in Australia and other countries to achieve world-recognisable results in mine waste characterisation for Zimbabwe.

Economic evaluation overview reveals that reprocessing viability depends on CAPEX/OPEX balance, metallurgical recoveries, commodity prices, and secondary revenue streams such as aggregates, carbon credits, and liability reduction (Jowitt, Werner and Weng, 2020; Magalini, Parbhakar-Fox and Golev, 2025). Sensitivity analyses indicate that price volatility, grade uncertainty, and recovery efficiency are the most influential variables affecting project economics. Environmental and policy considerations underscore the dual role of reprocessing: mitigating legacy risks such as AMD, heavy-metal leaching, dust emissions, and land instability (Meck, Love and Mapani, 2006), while contributing to national development goals under Vision 2030.

Overall, the described framework points that mine-waste resource characterisation is not merely a technical exercise but a multidisciplinary process requiring integration of geology, metallurgy, economics, environmental science, and policy analysis. Zimbabwe's regulatory environment provides a foundation for responsible reprocessing, but gaps remain in national waste inventories, incentive structures, and circular-economy integration (Zibret, Mhlongo and Lottermoser, 2020; Mapuvire and Mukonza, 2025). Addressing these gaps will be essential for unlocking the full strategic value of mine-waste resources.

RECOMMENDATIONS

1. Develop a national mine-waste inventory

   A centralised, georeferenced database of all tailings, slag, waste-rock, and coal-ash dumps should be established. This aligns with international best practice and supports strategic planning, investment attraction, and critical-mineral security (Zibret, Mhlongo and Lottermoser, 2020).

2. Adopt standardised sampling and QA/QC protocols

   Regulatory agencies should require uniform sampling densities, QA/QC procedures, and laboratory standards for mine-waste characterisation to ensure data comparability and reporting transparency.

3. Integrate circular-economy principles into Mining Policy

   Incentives such as tax credits, royalty reductions, and carbon-credit eligibility should be introduced to encourage reprocessing and reduce environmental liabilities (Magalini, Parbhakar-Fox and Golev, 2025).

4. Establish metallurgical test centres for critical minerals

   Zimbabwe should invest in regional metallurgical laboratories capable of testing PGMs, REEs, lithium, cobalt, and vanadium from secondary sources, reducing reliance on foreign facilities.

5. Strengthen environmental and social safeguards

Reprocessing projects must incorporate community engagement, land-access agreements, health-and-safety protocols, and environmental monitoring to ensure social licence to operate (Munyoka, 2020; Murombo, 2025).

6. Promote public-private partnerships (PPPs)

   PPPs can accelerate investment in reprocessing infrastructure, particularly for high-CAPEX components such as processing plants, water systems, and renewable-energy integration.

7. Align mine-waste reprocessing with Vision 2030

   Mine-waste resource development should be integrated into national industrialisation, energy-transition, and export-growth strategies, positioning Zimbabwe as a regional leader in critical-mineral circularity.

CONCLUSION

This study presents a comprehensive resource-characterisation framework for evaluating critical minerals in Zimbabwe's mine-waste dumps. By integrating geological characterisation, systematic sampling, laboratory analysis, geostatistical modelling, economic evaluation, and environmental-policy considerations, the framework suggests that mine waste can be transformed from a legacy liability into a strategic national asset. Since Zimbabwe's diverse geological provinces host significant resources of gold, PGMs, chrome, nickel, copper, cobalt, lithium, REEs, vanadium, and scandium—minerals essential for global clean-energy transitions and advanced manufacturing, it is inferred that the resultant mine waste dumps potentially contain economically viable residues of these minerals.

The framework provides a replicable methodology for quantifying these resources with the same rigour applied to primary deposits, enabling defensible reporting and investment decision-making. Economic analysis would confirm that reprocessing can be financially viable when supported by robust metallurgical recoveries, favourable market conditions, and secondary revenue streams. Environmental assessment would show that reprocessing can mitigate major legacy risks, improving water quality, stabilising landforms, and reducing dust emissions. Policy analysis highlights opportunities for regulatory reform, circular-economy integration, and alignment with Vision 2030. Ultimately, mine-waste reprocessing represents a strategic pathway for Zimbabwe to enhance mineral security, promote sustainable development, reduce environmental liabilities, and participate competitively in global critical-mineral supply chains.

REFERENCES

Anglo American, 2020. *Tailings Management and Reprocessing Strategies* (London: Anglo American plc).

BGS, 2022. *Critical Raw Materials for the Energy Transition* (British Geological Survey, Nottingham).

Brough, C P, Warrender, R, Bowell, R J, Barnes, A and Parbhakar Fox, A, 2013. The process mineralogy of mine wastes, *Minerals Engineering*, 52:125–135.

Chamber of Mines Zimbabwe, 2021. *State of the Mining Industry Report* (Harare: CoMZ).

Denhere, R, 2021. Evaluation of Beneficiation Constraints for Identified Critical Minerals in Zimbabwe, MSc Dissertation, University of the Witwatersrand, Johannesburg.

Dold, B, 2014. Evolution of acid mine drainage formation in sulphidic mine tailings, *Minerals*, 4(3):621–641.

European Commission, 2023. *Critical Raw Materials Act*: *Strategic Raw Materials for Europe* (Brussels: EU Publications).

Fox, N, Parbhakar-Fox, A, Moltzen, J, Feig, S, Goemann, K and Huntington, J, 2017. Applications of hyperspectral mineralogy for geoenvironmental characterisation, *Minerals Engineering*, 107:63–77.

Geoscience Australia, 2024. *Atlas of Re-Mining Potential* (Canberra: Australian Government).

Gwaze, P and Mupaya, B, 2019. Geochemical Characterisation of Gold Tailings in Zimbabwe, *Journal of African Earth Sciences*, 158:103–115.

Jones, H, Parbhakar-Fox, A and Lottermoser, B, 2012. Sampling and characterisation of anthropogenic mineral deposits, *Applied Geochemistry*, 27(5):944–963.

Jowitt, S, Werner, T and Weng, Z, 2020. Critical minerals in mine waste: Global perspectives, *Ore Geology Reviews*, 126:103–140.

Lebre, R, Corder, G and Golev, A, 2016. Sustainable tailings management frameworks, *Resources Policy*, 50:234–245.

Love, D, Mapani, B and Meck, M, 2006. Groundwater contamination from mine waste in Zimbabwe, *Physics and Chemistry of the Earth*, 31(15–16):797–802.

Magalini, F, Parbhakar-Fox, A and Golev, A, 2025. Circular economy opportunities in mine waste reprocessing, *Resources, Conservation and Recycling*, 198:106–118.

Manyakaidze, P, Mhlongo, S and Petersen, F, 2025. Carbon credits and mine-waste rehabilitation, *Journal of Cleaner Production*, 412:137–149.

Mapuvire, V K and Mukonza, R M, 2025. A Critical Analysis of Zimbabwe's Mines and Minerals Bill in Relation to Strategic Minerals, *Journal of Private and Commercial Law,* 9(2):223–248. https://doi.org/10.15294/jpcl.v9i2.32920

Meck, M, Love, D and Mapani, B, 2006. Environmental impacts of mine waste in Zimbabwe, *Mine Water and the Environment*, 25(1):22–27.

Mhlongo, S and Amponsah-Dacosta, F, 2016. QA/QC protocols for mine-waste sampling, *Journal of the Southern African Institute of Mining and Metallurgy*, 116(3):235–244.

Mtondoro, T, 2025. Lithium potential of Zimbabwean pegmatites, *African Mining Review*, 14(2):55–68.

Munyoka, W, 2020. Community impacts of legacy mine waste, *Development Southern Africa*, 37(4):612–630.

Murombo, T, 2025. Strategic mineral governance in Zimbabwe, *Journal of Environmental Law and Policy*, 32(1):88–110.

Mutemeri, N and Petersen, F, 2002. Environmental rehabilitation of mine waste in Zimbabwe, *Journal of Environmental Management*, 65(1):1–12.

Scot, R and Eldon, J, 2025. Critical mineral market volatility and supply chain risk, *Minerals Economics*, 38(2):145–162.

USGS, 2023. *Mineral Commodity Summaries*: *Critical Minerals,* United States Geological Survey, Reston, VA.

Zibret, G, Mhlongo, S and Lottermoser, B, 2020. Mine-waste sampling and environmental risk assessment, *Environmental Monitoring and Assessment*, 192(4):1–18.

Zimbabwe Government, 2006. Mines and Minerals Act, chapter 21:05, Zimbabwe Government: Harare. Available from: <https://www.mines.gov.zw/wp-content/uploads/2025/01/MINES-AND-MINERALS-ACT-1.pdf>

Zimbabwe Government, 2016. Environmental Management Act, chapter 20:27, Zimbabwe Government: Harare. Available from: <https://zimlii.org/akn/zw/act/2002/13/eng@2016-12-31>

Modelling scenarios for future mineral supply considering uncertain exploration outcomes and ESG risks

S A Northey[1], B Mendonca Severiano[2], T G Ryan[3] and E M Dominish[4]

1. Research Director, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW 2007. Email: stephen.northey@uts.edu.au
2. Research Consultant, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW 2007. Email: bernardo.mendoncaseveriano@uts.edu.au
3. PhD Candidate, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW 2007. Email: tara.ryan-1@student.uts.edu.au
4. Research Director, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW 2007. Email: elsa.dominish@uts.edu.au

ABSTRACT

Scenario models for long-term mineral supply struggle to capture important industry dynamics and the uncertainties of mineral exploration. Using the open-source Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) model (Northey *et al,* 2023), we demonstrate an approach for modelling how long-term scenarios for mineral supply may be shifted by incorporating uncertainty in exploration outcomes and regional ESG risks. For instance, the number of new copper mines required to meet mid-century demand for the global energy transition is highly sensitive to rates of brownfield resource expansion at existing mines, which delays their closure in the model runs. Greenfield discovery (or lack thereof) of new large deposits in model runs can also meaningfully shift long-term requirements for new mine developments. When linking mine development probabilities to regional ESG risks, we see how incorporating these types of risk factors may bias mineral supply towards different regions in the scenario model runs. To date, the PEMMSS model has been applied to explore many of the key factors governing the future of copper, nickel, graphite and lithium supply. This is revealing that many of the key results and outputs produced by future mineral supply scenarios are far more uncertain than is commonly reported once additional industry dynamics are incorporated into the scenario models. Importantly, there is a clear need to distinguish between what are predictions and what are exploratory scenarios when looking at studies of future mineral supply. There is also a need to distinguish between the modelling approaches that are appropriate for shorter-time horizon forecasting (eg 5–15 years) versus those appropriate for informing long-term understanding of sustainable development and resource availability (eg 20+ years).

REFERENCES

Northey, S A, 2023. Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) model: Towards a stochastic understanding of the mineral discovery, mine development and co-product recovery requirements to meet demand in a low-carbon future, *Resources, Conservation and Recycling Advances*, 17:200137. https://doi.org/10.1016/j.rcradv.2023.200137

Critical metal inventory of Australia's tailings and mine waste – what's next? From aspiration to delivery

A Parbhakar-Fox[1,2]

1. Technical and Innovation Lead – Geoscience, KCB, Brisbane Qld 4000.
   Email: aparbhakarfox@klohn.com
2. Honorary Professor, University of Queensland, Brisbane Qld 4068.
   Email: a.parbhakarfox@uq.edu.au

ABSTRACT

From 2019 to 2025, several Australian State and Territory Governments and Geoscience Australia commissioned mine waste exploration across Australia to identify potential critical metal resources. In total, 77 mine waste features/sites were investigated by the University of Queensland with a diverse range of material sampled (eg tailings, waste rock, spent heap leach, slag). These were analysed using an integrated geochemistry-mineralogy-mineral chemistry approach. The program highlights included identification of potential Co resources in Qlds NW Minerals Province, Tennant Creek (NT) and Western Tasmania; indium in greisen and VHMS mine waste in Qld; Sb enrichment in Pine Creek (NT) and NSW, REEs in SA and WA, and W in the NE Minerals Province, Qld.

Since the final delivery of this pre-competitive data in 2025, intended to be input into the Geoscience Australia Atlas of Australia's Remining Potential, Regeneration Enterprises and Hillgrove Resources have already established projects at two of these sites (Mt Oxide, Qld and Kanmantoo, SA) to recover critical metals (Cu and Co) and industrial minerals (garnet) from waste rock and tailings respectively. However, many more critical metal business opportunities could be developed due to the nature of the data collected ie mineral texture, metal deportment and mineral associations. Rapid identification of tailored mineral processing pathways for beneficiation and metal recovery is only made possible with these data.

This presentation provides a comprehensive summary of critical metal deportment in Australia's mine waste based on results of this national campaign. It will also highlight how the collected data can be effectively used to: i) guide flow sheet design for critical metal recovery using a combination of established and innovative technologies; and ii) demonstrate how the entire secondary resource can be reused (ie reduction of waste after reprocessing) modelling a blue print for other countries to follow as part of the global push towards circularity in the mining sector.

Geochemical controls on rubidium enrichment and recovery in the Mount Edon pegmatite, Western Australia

A Sarmadi[1], R Didonna[2], B Rashidi[3], E Ramanaidou[4] and A Razmjou[5]

1. PhD Candidate, School of Engineering, Edith Cowan University, Joondalup WA 6027. Email: a.sarmadi@ecu.edu.au
2. Postdoctoral Research Fellow, CSIRO Mineral Resources, Kensington WA 6151. Email: didonna.ro@gmail.com
3. Chief Geologist, Everest Metals Corporation, Perth WA 6000. Email: bahman@everestmetals.au
4. Chief Research Scientist, CSIRO Mineral Resources, Kensington WA 6151. Email: erick.ramanaidou@csiro.au
5. Associate Professor, School of Engineering, Edith Cowan University, Joondalup WA 6027. Email: amir.razmjou@ecu.edu.au

ABSTRACT

Rubidium (Rb) is a reactive alkali critical metal experiencing increasing demand due to its high-tech applications in precision atomic clocks and emerging quantum computing technologies. Historically, Rb has been sourced primarily from Lithium-Caesium-Tantalum (LCT) pegmatites, where it is recovered as a by-product of lithium (Li) and caesium (Cs) extraction. Its enrichment is linked to the extreme differentiation of peraluminous granitic melts, during which incompatible elements are progressively concentrated in residual melts and fluids. However, despite its critical importance, the geological processes responsible for extreme Rb enrichment in pegmatite systems remain poorly understood. In this study, the authors investigated the mechanisms controlling unique high Rb concentrations within the Mount Edon LCT pegmatite system in Western Australia.

By focusing on Rb-enriched mineral phases, including K-feldspar and the mica group minerals, this research investigated the geochemical correlations between Rb and associated elements eg Cs, potassium (K), Li, and fluorine (F). The authors used a multi-analytical approach that goes beyond conventional whole-rock composition methods by integrating microscopic-scale techniques (eg optical microscopy, automated mineralogy, and mass spectrometry analyses) to characterise mineral-scale textures and quantify *in situ* trace element distributions that will support the Rb recovery process. The strong partitioning of Rb into lepidolite highlights mica-rich zones as the most promising targets for both Rb (~3.5 wt per cent) and Cs (~0.9 wt per cent), supporting more selective extraction strategies. Nevertheless, K-feldspar exhibits Rb concentrations with ~0.7 wt per cent, comparable to those of muscovite, suggesting an alternative extraction pathway with fewer interfering ions.

This study establishes a mineralogical–geochemical framework to define Rb hosts, quantify element deportment, and link grain-scale distribution to processing behaviour. The integrated analytical approach constrains metallurgical strategies, providing transferable insights for optimising Rb and Cs recovery from LCT pegmatites globally, beyond Mount Edon, and enhancing the economic potential of critical metal resources.

INTRODUCTION

Rubidium (Rb) is an alkali metal which reacts violently with water and air, and it has been receiving more attention due to its unique properties. Rb is a critical metal with various high-tech applications eg night vision equipment, radiation detection and infrared signals as well as aerospace, healthcare and energy. Rb has been listed as a critical mineral by several countries around the globe including USA, New Zealand and Japan (Everest Metals Corporation, 2026). Surging demand in quantum computing and supply-chain pressures is enhancing Rb's strategic importance. Rb remains the only viable substitute for caesium a mineral that continues to be very difficult to source. The easy filtering of lamplight for atomic clock application is the primary reason that the Rb element cannot be replaced by other alkali metals (Camparo, 2007; US Geological Survey, 2025). The Rb clocks are also cheaper than caesium (Cs) and hydrogen maser clocks, with an acceptable level of stability for

precision time-keeping and global navigation satellite application (Banerjee and Matsakis, 2023). The most recent application for Rb is its usage in quantum-mechanics-based computing devices, which is much faster than traditional computers and may suggest a higher consumption and demand projection of Rb (National Minerals Information Center, 2026).

Sea water brine (0.2 mg/L Rb from Perth Seawater Desalination Plant, Western Australia; Naidu *et al,* 2017; Yelatontsev, Mukhachev and Shevchenko, 2026), geothermal brine and salt lakes (170 mg/L Rb and 20 mg/L Cs from Salton Sea (USA); Yelatontsev, Mukhachev and Shevchenko, 2026) are considered liquid sources of Rb. Nevertheless, historically, Rb from Lithium-Caesium-Tantalum (LCT) pegmatite has been considered the main source of Rb and as a byproduct of Cs and lithium (Li) extraction from pollucite and lepidolite minerals, respectively (National Minerals Information Center, 2026). The LCT pegmatite deposits are an important source of rare and critical elements (Smith *et al,* 2005; Thompson, 2011). Černý and Ercit (2005) classified the pegmatites with high Cs, boron (B), phosphorous (P), sulfur (S), and oxygen-18 isotope ($\delta^{18}O$) with 'LCT-S' pegmatites which are Peraluminous fertile granites and derived pegmatites by anatexis of supracrustal protoliths and subsequent differentiation (Černý and Ercit, 2005). Most pegmatites result from a single intrusive event, with crystallisation controlled by the temperature of the country rock, which governs the cooling rate of the melt (Simmons and Webber, 2008). Crystallisation nucleates at the fine-grained border zone and proceeds inward through the wall zone; textures range from fine-grained, where cooling is rapid and fluxes are scarce, to coarse comb-like/wedge-shaped crystals, where fluxes and volatiles (B, F, P) suppress nucleation and promote directional growth (Simmons and Webber, 2008). Crystallisation proceeds inward from the wall zone through the intermediate zone(s) to the core, with grain size generally increasing toward the core (Simmons and Webber, 2008). The predominant mineral assemblage of granitic pegmatites is quartz, feldspars (mix of potassium (K)-, sodium (Na)-, and calcium (Ca)-feldspars), and accessory mica (Simmons and Webber, 2008). Other typical minerals are spodumene, beryl, tourmaline, lepidolite and accessory minerals such as columbite-tantalite, rutile, pollucite and cassiterite (Černý and Ercit, 2005; Simmons and Webber, 2008; London, 2017).

The LCT pegmatite core mainly consists of the most fractionated portions of pegmatites containing the greatest enrichments Rb and Cs in minerals with the replacement units (Simmons and Webber, 2008). Some Rb-rich minerals have also been reported, such as Rb-feldspar or rubicline ($RbAlSi_3O_8$), containing (5.5–25 wt per cent of Rb_2O), whereas muscovite with 2.6–9.4 wt per cent of Rb_2O. The rubicline formation has been reported to crystallise after pollucite formation. The formation of Rb-rich feldspar is proposed to occur through cation exchange of Rb-rich aqueous fluid with K-feldspar under hydrothermal condition (Pekov and Kononkova, 2010). Moreover, other studies (see Jin *et al,* 2024) reported that the F-rich melt, when undergoing extreme fractional crystallisation, leads to Rb enrichment in the residual melt, forming high Rb minerals such as microcline and mica (phengite) minerals, but Rb is not incorporated in quartz and albite minerals, which are highly incompatible with Rb (Jin *et al,* 2024). Another Rb-mineral is voloshinite ($Rb(Li,Al_{1.5}O_{0.5})[Al_{0.5}Si_{3.5}O_{10}]$) (12.18 wt per cent Rb_2O) but its occurrence has been considered rare (Pekov *et al,* 2010). In the study proposed by Thomas, Davidson and Hahn (2008), they discussed that Cs- and Rb-ramanite—$(Cs,Rb)B_5O_8 \cdot 4H_2O$ may be common, in boron-rich pegmatites (Thomas, Davidson and Hahn, 2008). The phase transformation from muscovite to lepidolite or zinnwaldite occurs together with the presence of Li fixed in the octahedral layer of muscovite via $Al^{vi} \rightarrow 3Li^{vi}$ and $Al^{vi}\ Al^{iv} \rightarrow 2Li^{vi}\ Si^{iv}$ substitution, causing increased lattice spacing (Monier and Robert, 1986).

Rb has previously been reported to be detected in mica and to positively correlate with K-rich feldspar with respect to melt (Were and Keppler, 2021). There is a preferential incorporation of Rb in K-feldspar and Li-rich mica, while Cs is considered highly incompatible with feldspar (Gao *et al,* 2024). The K^+, Rb^+, and barium (Ba^{2+}) ions are mildly compatible in biotite, while Na^+, Cs^+, and strontium (Sr^{2+}) are mildly incompatible (Were and Keppler, 2021). Gao *et al* (2024) suggested that the Li concentration in Na-feldspar is higher than in K-feldspar, whereas Rb and Cs concentrations in Na-rich feldspar are significantly lower than in Na-feldspar and K-feldspar. The Rb partitions slightly more (higher Rb concentration) into K-feldspar when Li concentration is high (Gao *et al,* 2024).

Mount Edon LCT Pegmatite located 420 km north of Perth and 5 km south of Paynes Find in Western Australia. Mount Edon has an indicated and inferred Mineral Resource of 4.3 Mt grading 0.23 per cent Rb_2O and 0.10 per cent Li_2O, reported at a 0.10 per cent Rb_2O cut-off grade (Everest

Metals Corporation, 2026). The Mineral Resource Estimate (MRE) contains more than 9800 t of contained Rb_2O and 4400 t of contained Li_2O. The MRE also includes a high-grade subset of 1.56 Mt at 0.31 per cent Rb_2O and 0.10 per cent Li_2O, reported at 0.25 per cent Rb_2O cut-off grade, representing nearly 49 per cent of the total contained Rb_2O tonnes (Everest Metals Corporation, 2026).

In this study, the authors particularly focused on muscovite minerals, where Li and F^- substitute Al^{3+} and OH^-, respectively (Smith *et al,* 2005). Further, the edge of the muscovite crystals incorporates Rb^+ and Cs^+, indicating structural rearrangements of the original di-octahedral muscovite to produce tri-octaheral zinnwaldite or lepidolite, causing increased interlayer space. According to (Popov*,* 2023), the F-, Rb-, Cs- and Li-rich zones in mica form at the latest step of crystallisation. Therefore, the possibility of finding F-, Rb-, Cs- and Li-rich zones at the grain boundaries and the edges is higher than the centre of the mineral, and there is a positive correlation between these elements (Popov, 2023). Based on the complexity of Rb pegmatite rocks and the poor understanding of the emplacement processes that lead to such high Rb concentration, this study investigates the factors contributing to the high Rb content of the Mount Edon LCT pegmatite, with a particular focus on the Rb-rich mineral phases, including K-feldspar, muscovite and lepidolite. In the analysed samples, only the k-feldspar and mica groups were enriched in Rb. Here the authors used multiple characterisation techniques, exploring positive and negative correlations between Rb and other elements (eg Cs, K, manganese (Mn), iron (Fe) etc). Using Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) instruments have been proposed as effective techniques for quantifying Rb pegmatites (Esparza-Ponce *et al,* 2023). Building on the geological context and critical-metal significance of the Mount Edon pegmatite system, this study investigates the controls on its exceptional Rb enrichment. Specifically, it identifies the mineral phases hosting Rb and associated elements such as Cs, and evaluates the most suitable analytical techniques for characterising high-Rb pegmatites. The resulting mineralogical and geochemical data set provides a basis for understanding Rb partitioning and support future ore processing, refining, and Rb-Cs recovery strategies.

METHODS

Samples and analysis methods

Four surface-collected pegmatite samples (ME-1, ME-2, ME-3 and ME-4 samples) were selected from Mt-Edon deposits for this investigation. Thin sections for each sample were prepared with a thickness of 30 µm. A complementary bulk resin-mounted samples (round blocks) were prepared. A set of advanced characterisation techniques was employed, including polarised light microscopy (petrography), Field Emission Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (FE-SEM-EDS) and the Tescan Integrated Mineral Analyzer (TIMA), and LA-ICP-MS.

The chemical composition of complex solid solutions and the detection of fine-grained minerals cannot be detected with polarised optical microscopy alone (Raith, Raase and Reinhardt, 2012), and requires advanced characterisation methods, such as SEM-EDS (Esparza-Ponce *et al,* 2023).

Whole-rock composition

Whole-rock geochemical analyses of ME-1, ME-2, ME-3 and ME-4 samples were conducted at Nagrom Analytical Services (Perth, Western Australia) to characterise the composition of pegmatites and host rocks and evaluate geochemical variations associated with pegmatite evolution and melt-rock interaction. Major element concentrations were determined by X-ray fluorescence spectrometry (XRF) following lithium borate fusion with a lithium nitrate additive. The fused glass beads were analysed using XRF calibration suites specifically designed for geological materials. Loss on Ignition (LOI) was determined concurrently to quantify volatile components and enable accurate calculation of oxide totals. Trace element concentrations were determined by inductively coupled plasma (ICP) analysis following sodium peroxide fusion and dilute hydrochloric acid digestion. This analytical approach provides near-total dissolution of geological materials and is particularly suitable for refractory mineral assemblages commonly present in rare-element pegmatites.

Polarised-light microscopy

Polarised-light microscopy has been reported a non-destructive way to characterise the geological samples with relatively high spatial resolution. Due to the different interference colour and texture, the approximate chemical composition of the mineral can be estimated, and it can be used as complementary method for phase identification (Raith, Raase and Reinhardt, 2012). Both quartz and feldspar show first-order grey-white interference colours in the thin section sample of 30 micron (Raith, Raase and Reinhardt, 2012). However, twinning is frequent in both feldspars, and the reflection twins for Albite is at (020) crystallographic planes (Nespolo and Souvignier, 2025). K-feldspar (monoclinic sanidine/orthoclase and triclinic microcline) produce the cross-hatched pattern observed under the polarising microscope (Nespolo and Souvignier, 2025).

Tescan Integrated Mineral Analyzer (TIMA)

Both round blocks and polished thin-sections were analysed at the CSIRO microanalytical facility within the Australian Resources Research Centre (ARRC, Perth, Western Australia) using a Tescan Mira 3 field-emission scanning electron microscope (FEG-SEM) equipped with three EDAX Energy Dispersive Spectroscopy (EDS) detectors and a backscattered electron (BSE) detector. Analyses were performed at an accelerating voltage of 25 kV and beam currents ranging from 7–26 nA, using a high-resolution analytical step size of 1 µm. Acquisition times varied between approximately 2 and 3 hrs per sample.

Mineral classification and data processing were carried out using the TIMA software package. Major, minor, and accessory mineral phases were identified through comparison with a customised spectral library developed for this study, comprising approximately 450 mineral compositions. The reference database includes EDS spectra obtained from international standards, published mineral compositions from lithium pegmatite systems, and mineral compositions estimated from semi-quantitative SEM-EDS analyses and stoichiometric compositions available through the Webmineral database (https://www.webmineral.com).

The mineral library also incorporated a range of solid-solution compositions for common primary and alteration minerals, including feldspars, amphiboles, orthopyroxenes, clinopyroxenes, phosphates, garnets, muscovite, biotite, and related phases. Selected uncertain or ambiguous mineral identifications were further verified through targeted SEM-EDS spot analyses and detailed inspection of BSE textures and LA-ICP-MS. Mineral phases were considered valid when the measured spectra matched the expected elemental count ranges at a confidence interval of approximately 99.5 per cent. Pixels with mixed or inconclusive spectra were classified as unclassified (black pixels), producing a final single-phase mineral map for each sample.

Field Emission Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (FE-SEM-EDS)

Representative polished thin sections and round samples were analysed using a Zeiss Ultra Plus Field Emission Scanning Electron Microscope (FE-SEM), with an accelerating voltage of 20 kV at CSIRO. Selected mineral phases (eg lepidolite, muscovite, feldspar) were located using an SEM model fitted with an Oxford Instruments 150 mm^2 energy-dispersive X-ray spectrometer. Backscattered electron (BSE) images were collected and described based on their relative texture, size, and morphology, along with spot analysis and elemental mapping using energy-dispersive X-ray spectroscopy (EDS).

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)

LA-ICP-MS was employed to determine *in situ* trace element concentrations in selected mineral phases, including spodumene, mica, and oxide minerals. Analyses were carried out using a laser ablation system coupled to an ICP-MS, allowing spatially resolved measurements at the micrometre scale. Ablation was performed using spot analyses and rastering to generate elemental maps. Quantification was achieved using external calibration against reference materials, with appropriate internal standards (eg Si, Al, or Ca) based on mineral stoichiometry. Data reduction and calibration were conducted using standard protocols, enabling accurate determination of trace element

distributions and compositional zonation within individual mineral grains (Paton *et al*, 2011; Woodhead *et al*, 2007).

Several X-ray characteristic interferences hindered precise SEM-EDS data acquisition, including overlaps between Rb-Lα and Si-Kα, and between F-Kα and Fe-Lα. Additionally, reliable measurement of light elements such as Li is not feasible with current technology of SEM-EDS detectors.

RESULTS

Whole rock composition

Mount Edon bulk samples (ME-1 through ME-4) represent a suite of silicate minerals characterised by variable Rb concentrations and compositional variation, as shown in Table 1. This investigation presents a detailed geochemical characterisation of these samples through whole rock elemental and oxide analysis, revealing compositional relationships that constrain their mineralogical affinity and trace element partitioning behaviour. Comparative analysis with drill core samples (chipset tray 8–20) provides contextual geochemical data for regional correlation. The analysed samples encompass four bulk mineral separates from Mount Edon (ME-1, ME-2, ME-3, ME-4) and drill core analyses (chipset tray, depths 8–20 m). Compositional data include major oxide concentrations (SiO_2, Al_2O_3, K_2O, Na_2O), trace elements (Rb, yttrium (Y), niobium (Nb)) and calculated elemental ratios.

The SiO_2 concentration ranges from approximately 54 wt per cent (ME-4) to 75 wt per cent (ME-2), defining a compositional trend consistent with feldspar-dominated silicate mineralogy (Table 1). The elevated SiO_2 in ME-1, ME-2, and ME-3 (68–77 wt per cent) indicates substantial quartz and/or alkali feldspar abundance, whereas ME-4 exhibits intermediate SiO_2 content suggestive of aluminosilicate phases. A negative correlation exists between SiO_2 and Al_2O_3 concentrations. Al_2O_3 ranges from 13.8 wt per cent (ME-1) to 24.5 wt per cent (ME-4), exhibiting negative correlation with SiO_2 (Figure 1a). This relationship is the characteristic of Al-enriched phases. Notably, K_2O and SiO_2 show weak correlation, indicating that K partitioning is decoupled from silica activity (Figure 1b). The Na_2O concentrations vary from ~0.5 wt per cent (ME-2, ME-4) to ~1.7 wt per cent (ME-3) and ~4.6 wt per cent (ME-1), showing considerable variation that may reflect plagioclase solid-solution variation. The moderate Na_2O in ME-3 and high Na_2O in ME-1 suggest plagioclase composition (Table 1). The Rb concentrations display strong variation, ranging from 2295 ppm (ME-1) to 24 085 ppm (ME-4). This exceptional Rb enrichment in ME-4 suggests high amount of lepidolite in the sample. A strong negative correlation exists between (Rb, Cs) and SiO_2. As SiO_2 increases from 54 to 74 wt per cent, Rb and Cs decreases from 24 085 to 2295 ppm and from 1292 to 60 ppm, respectively. As the ratio of K/Cs increases, the ratio of K/Rb also increases (Figure 1c). The lowest ratios are seen at ME-4 (K/Cs ≈ 50, K/Rb ≈ 2.5), and they scale upwards to the highest ratios at ME-1 (K/Cs ≈ 650, K/Rb ≈ 17). The highest Y+Nb concentration (146 ppm) occurs in ME-2 with 2695 ppm Rb, the highest Rb concentration (24 085 ppm) occurs in ME-4 with 71 ppm Y+Nb. As the K/Rb ratio increases, the concentration of Li sharply decreases (Figure 1d). At the lowest K/Rb ratio of ~2.5 (ME-4), Li is at its highest at 17 480 ppm. By the time the K/Rb ratio reaches ~17 (ME-1), the Li concentration has dropped to 170 ppm. Figure 1e shows the similar trend for BaO and SrO which is negatively correlated with SiO_2 concentration.

Drill core samples (chipset tray, 8–20 m) provide important compositional context (Table 1). The variations in Rb and Cs contents at different depths of the MD-24 chip tray sample. For example, although the Rb content increases from 955 to 2510 ppm for MD-24 (8–9) and MD-24 (15–16), respectively, it decreases to 1325 ppm in the MD-24 (19–20) sample. The MnO content in the MD-24 samples shows a mild increase from lower to higher depth, with values of 0.09 wt per cent and 0.15 wt per cent for MD-24 (8–9) and MD-24 (19–20), respectively (Table 1).

As the weight percentage of P_2O_5 increases, the concentration of Rb increases significantly, showing a strong correlation of P_2O_5 with Rb. The values range from a low of ~0.023–0.03 wt per cent P_2O_5 corresponding to ~2500 ppm Rb (ME-1 and ME-2), up to a high of 0.30 wt per cent P_2O_5 corresponding to 24 085 ppm Rb (ME-4) (Figure 1f). Similarly, the concentration of Cs increases as

P_2O_5 increases. The data from Table 1 start near 0.02–0.03 wt per cent P_2O_5 with roughly ~60 ppm Cs (ME-1 and ME-2) and rise to 0.30 wt per cent P_2O_5 with 1292 ppm Cs (ME-4).

TABLE 1

The whole rock composition of ME-1, 2, 3 and 4 provided by Nagrom Analytical Services, as well as the composition of the chipset tray provided by Everest Metals Corporation. The numbers in the parentheses indicate the depth (metre) of the drilling.

Formula	SiO_2	Al_2O_3	FeO	MnO	TiO_2	P_2O_5	MgO	CaO	K_2O	Na_2O
Method	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF
Unit	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %
ME-1	74.423	13.869	0.154	0.079	0.005	0.032	0.017	0.056	4.651	4.597
ME-2	75.385	15.003	1.299	0.081	0.053	0.023	0.083	0.014	4.204	0.566
ME-3	68.369	18.083	0.515	0.901	0.017	0.092	0.017	0.028	4.802	1.685
ME-4	54.25	24.564	0.051	1.192	0.012	0.305	0.033	0.013	7.652	0.391
Chipset tray (8–9)	64.2			0.09	0.21		4.58			
Chipset tray (9–10)	72.7			0.07	0.06		1			
Chipset tray (10–11)	74			0.07	0.03		0.27			
Chipset tray (11–12)	74.9			0.05	0.03		0.34			
Chipset tray (12–13)	75.3			0.08	0.03		0.16			
Chipset tray (13–14)	71.7			0.1	0.03		0.13			
Chipset tray (14–15)	74.4			0.11	0.03		0.12			
Chipset tray (15–16)	75.5			0.15	0.03		0.12			
Chipset tray (16–17)	75.7			0.13	0.03		0.11			
Chipset tray (17–18)	75.9			0.12	0.04		0.16			
Chipset tray (18–19)	73.8			0.08	0.02		0.09			
Chipset tray (19–20)	78.1			0.15	0.04		0.12			

Formula	PbO	BaO	SrO	Li	Be	Cs	Nb	Rb	Sn	Ta
Method	XRF	XRF	XRF	ICP	ICP	ICP	ICP	ICP	ICP	ICP
Unit	wt %	wt %	wt %	ppm	ppm	ppm	ppm	ppm	ppm	ppm
ME-1	0.002	0.001	0.004	170	2	60	30	2295	21	9
ME-2	0.005	0.002	0.005	1150	7	58	145	2695	41	32
ME-3	0.009	0.008	0.013	4510	48	340	90	8695	169	59
ME-4	0.016	0.017	0.031	17480	17	1292	55	24 085	332	111
Chipset tray (8–9)	0.01			610		119	23	955	9	8
Chipset tray (9–10)	0.01			470		69	33	1025	8	9
Chipset tray (10–11)	0.01			580		112	47	1990	10	10
Chipset tray (11–12)	0.01			590		100	46	2360	13	11
Chipset tray (12–13)	0.01			590		87	67	2290	13	16
Chipset tray (13–14)	0.01			440		95	43	2370	10	9
Chipset tray (14–15)	0.01			580		78	55	2080	11	11
Chipset tray (15–16)	0.01			840		137	67	2510	16	15
Chipset tray (16–17)	0.01			510		50	68	1700	12	17
Chipset tray (17–18)	0.01			510		52	77	1990	11	14
Chipset tray (18–19)	0.01			280		56	51	2320	6	12
Chipset tray (19–20)	0.01			550		33	83	1325	13	15

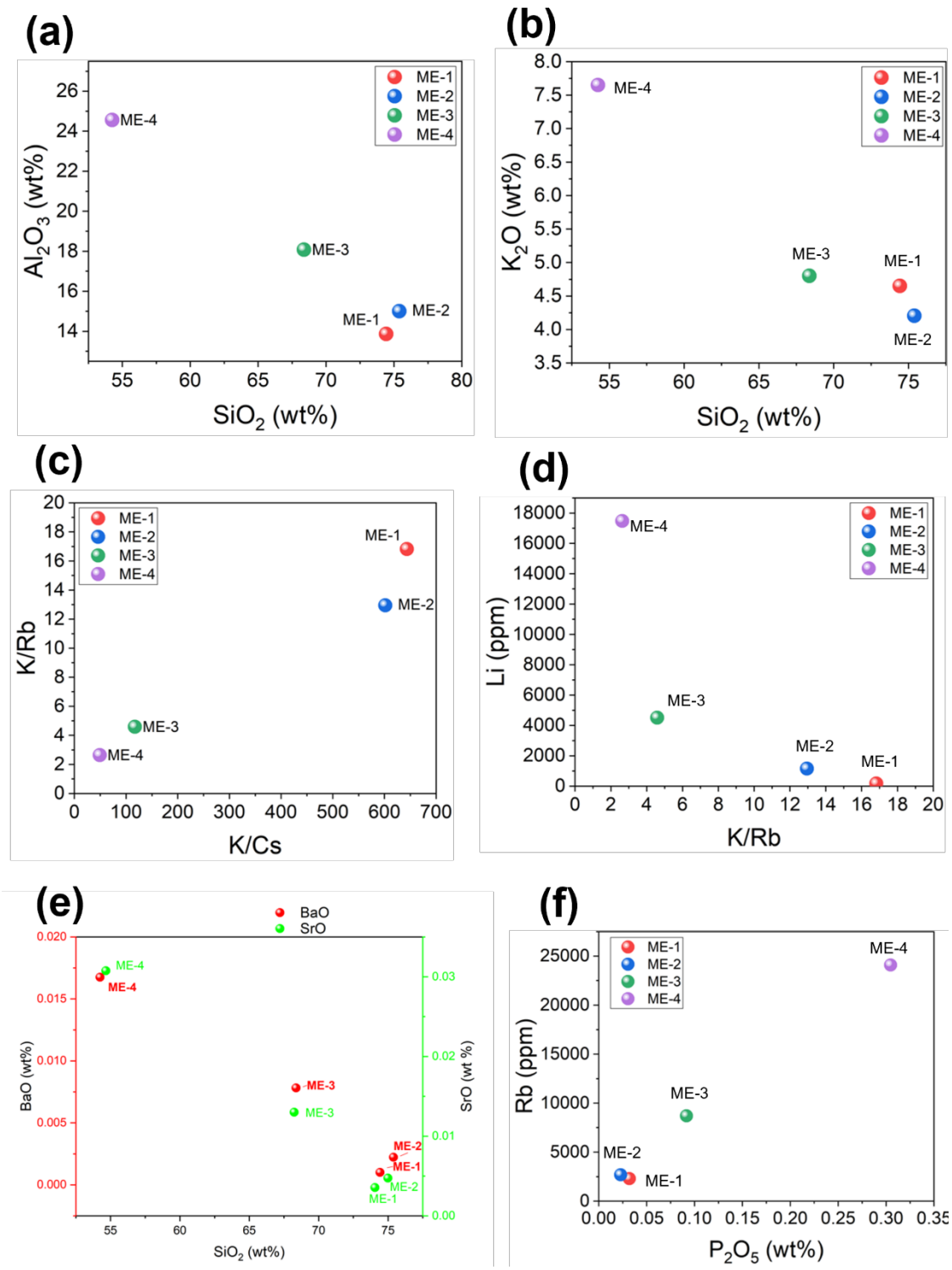


FIG 1 – Relationships among alkali-element ratios and bulk geochemical composition of the ME-1, 2, 3, 4 samples: (a) SiO_2 (wt per cent) versus Al_2O_3 (wt per cent); (b) SiO_2 (wt per cent) versus K_2O (wt per cent); (c) K/Rb versus K/Cs; (d) Li concentration (ppm) versus K/Rb; (e) SiO_2 content (wt per cent) versus BaO content (wt per cent) and SrO content (wt per cent); and (f) Rb concentration (ppm) versus P_2O_5 content (wt per cent).

Petrography

The Petrography analysis of ME-1 shows a variety of different texture for K-feldspar samples. Figure 2a and 2b shows the cross-twinning texture of K-feldspar. However, Figure 2c shows a mixture of Albite (single twinning) and K-feldspar (cross-twining). Granites with two distinct populations of K- and Na-feldspars are referred to as subsolvus granites, which lay within the miscibility gap (Duan *et al,* 2021; Kiselev *et al,* 2021). The mineral below cross twinning in Figure 2b

can be considered Albite due to the formation of simple unidirectional twinning. The mica in both ME-1 and ME-2 have similar size and texture (Figure 2d and 2e). However, the mica from ME-3 (Figure 2f) show a smaller particle size and more zoning area at the edges of the mica grain. However, the texture of mica in sample ME-4 are more complex with zoning areas at multiple directions and irrelevant to its location in the mica crystal (Figure 2g).

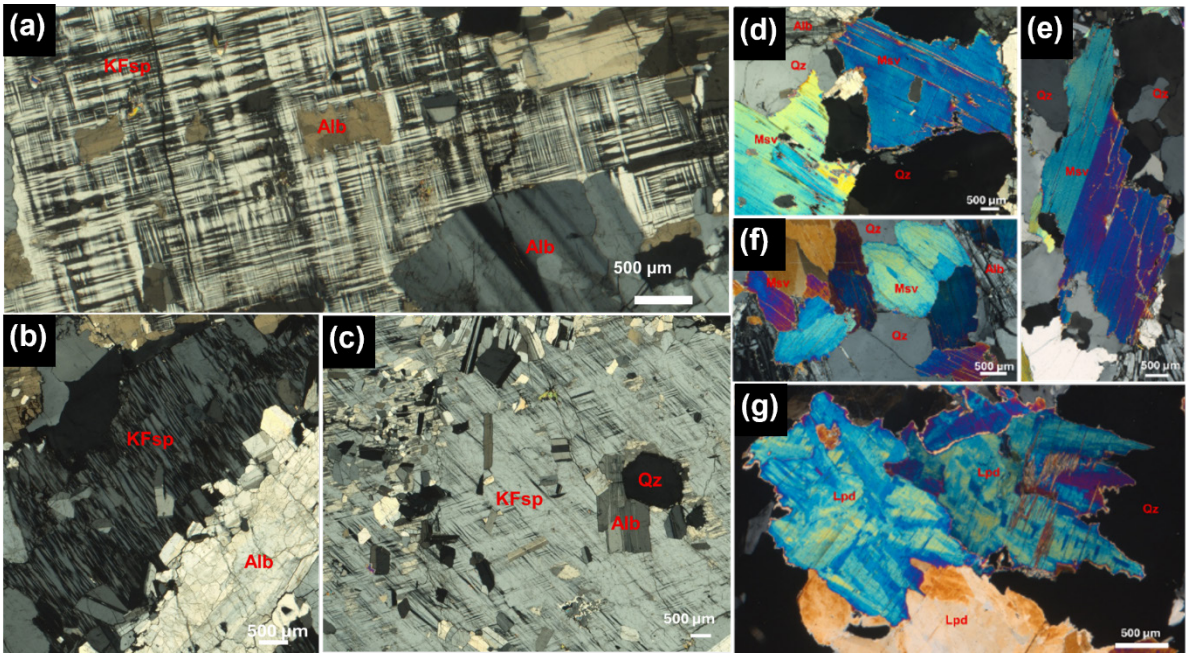


FIG 2 – (a–c) Different type of texture and cross twinning which are the signature texture of K-feldspar (KFsp) has been observed in ME-1 sample. (Albite: Alb; Quartz: Qz). Mica phases of samples: (d) ME-1; (e) ME-2; (f) ME-3; and (g) ME-4. (K-feldspar: KFsp; Albite: Alb; Quartz: Qz; Lepidolite: Lpd).

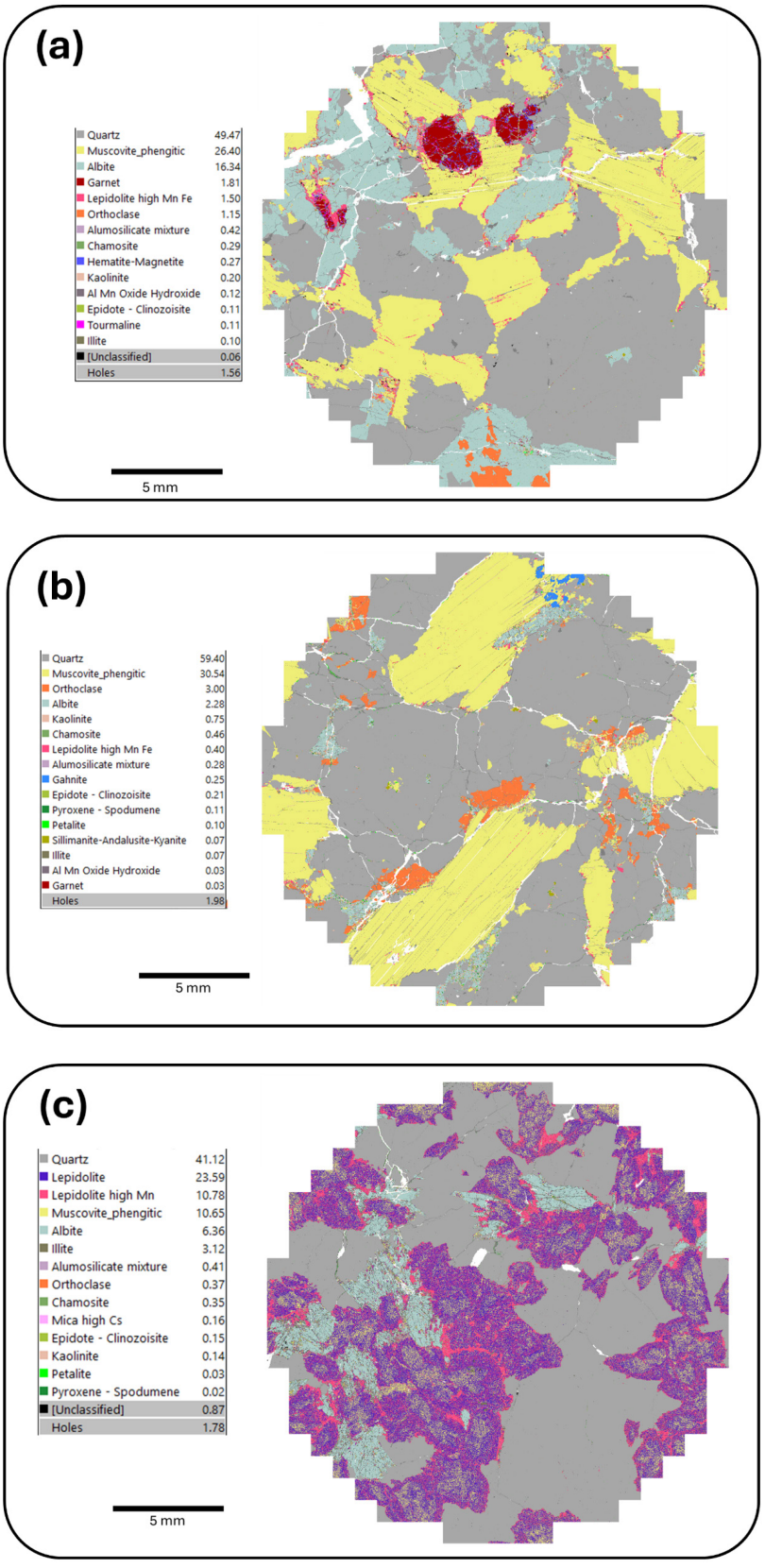
Mineralogy

Figure 3a shows the TIMA map of the ME-1 Round sample. In this sample, quartz has the highest percentage of mineral (49.31 vol per cent). This is also true for ME-1 thin section as well with 37.46 vol per cent (Figure 4a). The difference between these amounts is related to the inherently inhomogeneous formation of minerals in pegmatite, as well as the large grain sizes and minimal weathering. Consequently, the mineral composition can vary even within a metre range. Other major minerals include muscovite (a type of mica), albite (Na-feldspar), and orthoclase/microcline (K-feldspar), the latter of which is primarily found in the ME-1 thin section. ME-1 samples (mainly in the round sample) contain garnet mineral as well in contact with lepidolite with high Mn and Fe. This mineral could also be found near the edges of the muscovite as well in this sample. Other minerals in ME-1 sample, including chamosite, hematite-magnetite, kaolinite, illite, tourmaline, and epidote, are present in minor amounts (below 1 vol per cent).

ME-2 sample also consist of mainly quartz that is 58.69 vol per cent and 65.8 vol per cent for the round and thin section samples, respectively (Figures 3b and 4b). The same as ME-1 sample the second important mineral in the ME-2 samples is phengitic muscovite, big enough that almost stretch from the edges toward the centre of the round sample. The ME-2 round sample also contains gahnite, which is a zinc rich spinel mineral.

Figures 3c and 4c shows the mineral map of ME-3 round and thin-section samples, respectively. Both samples contain quartz, albite, and muscovite. In contrast to sample ME-1,2, chemical fractionation is observed toward the edges of the muscovite grains. While the core is primary muscovite, the composition shifts toward lepidolite with higher Mn content as distance from the centre increases. Furthermore, at the outermost edges, the Cs concentration increases to levels categorised as high-Cs mica. Another distinction lies in the morphology of the albite, which appears more weathered, with grain boundaries filled by chamosite, kaolinite, and illite.

The ME-4 round and thin section samples are mainly lepidolite according to Figures 3d and 4d. The lepidolite samples were divided into three groups: 1) high-Al lepidolite, 2) low-Al lepidolite, and 3) high-F lepidolite, all of which are placed under the category of lepidolite. The main body of the grains is primarily composed of either high-Al or low-Al lepidolite; however, in some grains, the edges exhibit a higher concentration of high-F lepidolite. Additional complementary characterisation techniques are required for accurate Li quantification.



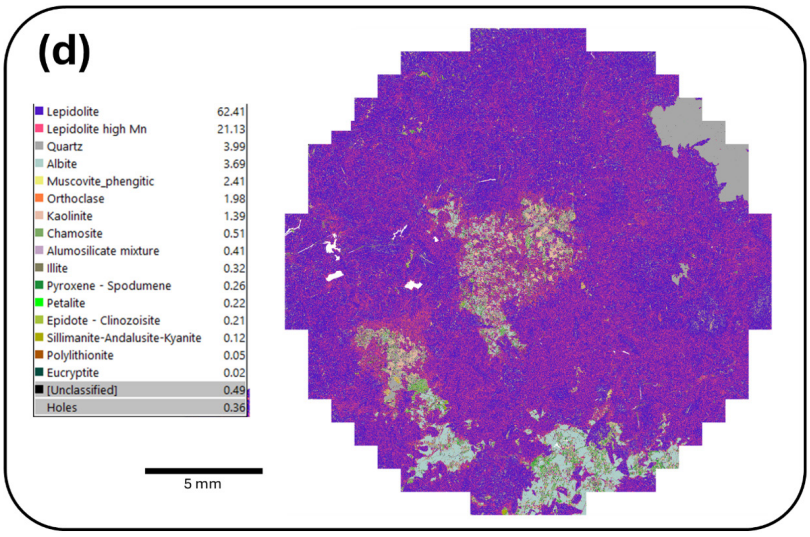


FIG 3 – TIMA maps showing the mineral composition of round samples for: (a) ME-1; (b) ME-2; (c) ME-3; and (d) ME-4.

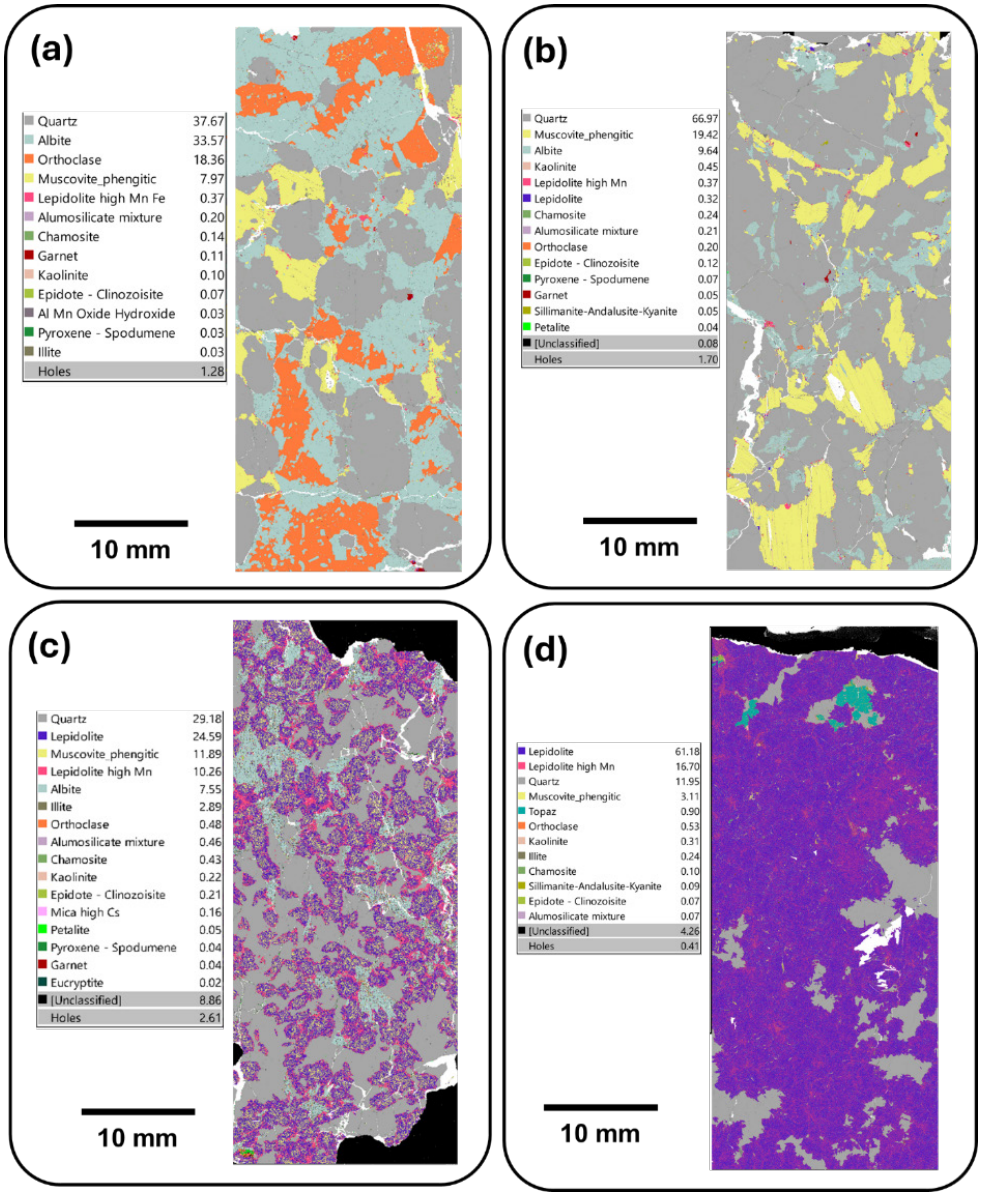


FIG 4 – TIMA maps showing the mineral composition of thin section samples for (a) ME-1; (b) ME-2; (c) ME-3; and (d) ME-4.

Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM-EDS)

Figure 5a and 5b shows the Rb elemental map of the ME-1 thin section sample. It can be observed that Rb concentration is highly correlated with the K enrichment region, which is the K-feldspar region based on the TIMA map (Figures 4a and 5). Another mineral with high Rb correlation is muscovite based on TIMA map (Figures 4a and 5). Rb is also highly correlated with Mn (yellow) in Figures 4a and 5, which is related to garnets. Rb concentration remains insignificant in other areas, which are related to mainly quartz and albite. Figure 5c shows the zoning of in the edges of muscovite which is demonstrated as bright areas in backscattered image. Similar feature has also been seen in other parts of the sample and predominantly at the edges of the muscovite. According to the EDS map (Figure 5c), the bright area is related to the enrichment of Mn and Fe element. This enrichment is accompanied by the lack of aluminium element, which may suggest that Mn and Fe substitute Al in the crystal structure. This area is denoted as point 3 in Figure 5c, and its composition is matching the lepidolite with rather similar Mn, Fe, and Rb content. The Rb content (1.5 wt per cent) in the bright area is higher than the other part of the mineral. The darker islands in between the bright area is associated with quartz due to high silicon concentration (Figure 5c) and EDS point 6 (Table 2). EDS points 4 and 5 are associated with muscovite with Rb concentrations of 1.1 and 0.5 wt per cent, respectively. This indicates an inhomogeneous concentration of Rb in muscovite which toward the edges of the muscovite shows a higher Rb concentration than the centre. The similar formation of muscovite can be seen at the very edge of the muscovite (EDS point 2 in Figure 5c) after the formation of Mn rich area. The Rb content has rather the same amount of Rb the centre of muscovite with 0.4 wt per cent Rb. Further, EDS point 1 in Figure 5c is related to albite.

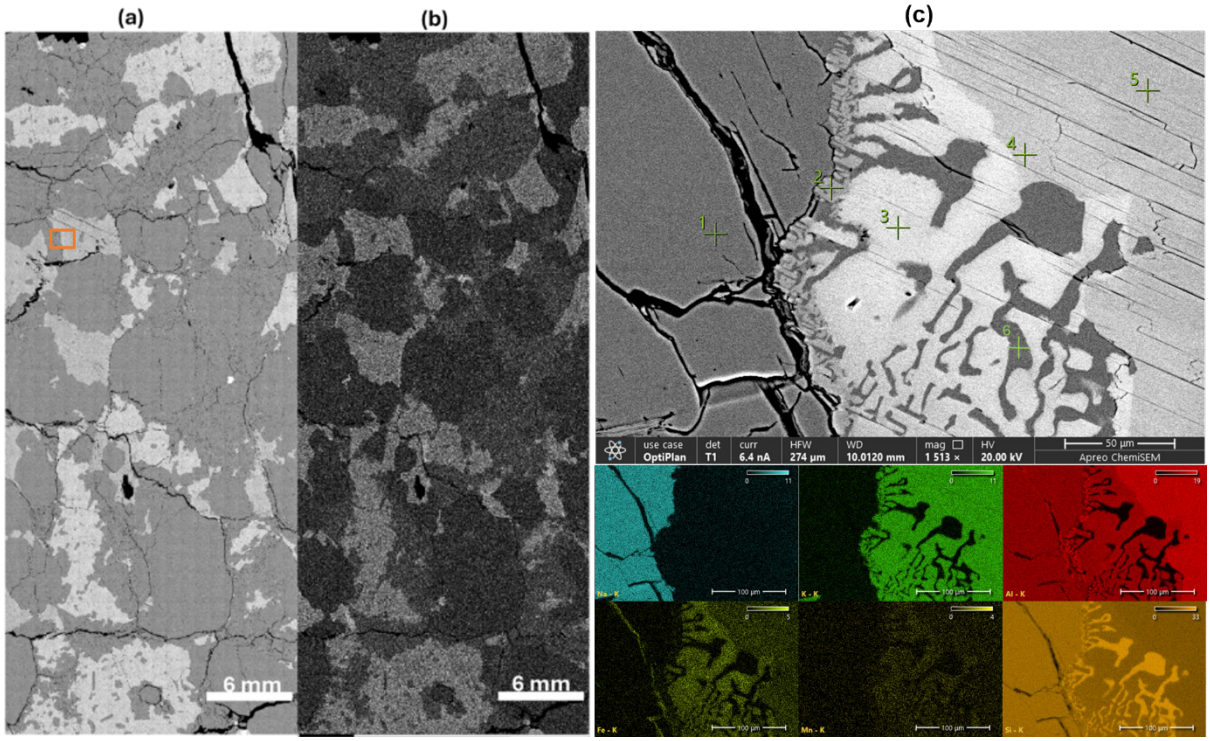


FIG 5 – (a) The backscatter electron image; and (b) the EDS elemental map of ME-1 thin-section for Rb-k wavelength. (c) Backscatter image and elemental maps showing muscovite with Mn and Fe zoning along its edges, and albite occurring on the left-hand side of the image in ME-1 thin section sample.

TABLE 2

EDS point data from Figure 5 (ME-1 thin section) and the references were added for comparison of the EDS point data and the literature.

	Weight %									
	EDS Points						References			
Element	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Point 6**	**Albite** (Mposkos, Baziotis and Proyer, 2012)	**Phengite** (Hoschek, 2001)	**Muscovite** (Webmineral.com, nd)	**Lepidolite** (Stevens, 1938)
Li	-	-	-	-	-	-	-	-	-	1.25
O	51.9	50.8	48.2	47.9	50	67.8	49.48	43.69	47.35	45.71
F	0	0	0	0	0	0	-	-	0.95	4.89
Na	10	0.2	0.2	0.2	0.4	-	8.73	0.19	-	0.57
Ca	-	-	-	-	-	-	1.9	0.05	-	-
Mg	0	0.1	0.3	0.2	0.3	-	-	2.82	-	0.08
Al	11.4	17.1	13.3	17.3	19.3	0.5	10.21	13.15	20.3	16.2
Si	26.7	22.7	21.9	22	18	31.6	32.09	24.24	21.13	21.97
K	0	8	8.8	8.3	8.9	0	-	9.02	9.81	7.9
Mn	0	0.1	0.9	0.5	0.3	-	-	0.04	-	1.58
Fe	0	0.6	4.6	2.4	2.3	0.1	-	2.82	-	0.5
Rb	**0**	**0.4**	**1.5**	**1.1**	**0.5**	-	-	-	-	1.76
Cs	0	0	0.3	0.1	0	-	-	-	-	0.17
Composition	Albite	Muscovite	Phengite or Lepidolite	Muscovite	Muscovite	Quartz				
Substitution			Fe →Al Si → Al Li → Al	Rb → K, Na						

Figure 6a and 6b shows the EDS elemental map of ME-3 thin section sample for Mn-k wavelength. As can be observed, the Mn elemental distribution matches the mica and lepidolite from TIMA map (Figure 4c). The Mn in this sample has zoned in the mica, and there is more Mn toward the edges of the mica compared to the centre. Based on the TIMA map, the centre part of the mica is regarded as muscovite and the edges contain more Mn and Fe which corresponds to lepidolite composition. Similar zoning has been observed by Choi *et al* (2024) from the Uljin-Li deposit. Figure 6c and 6d shows the elemental map of ME-4 thin-section sample for F-k wavelength. Based on the TIMA map, the major phase of the sample is lepidolite. There is a very high fluorine element in this sample as can be observed in the Figure 4d related to topaz mineral. It has been mentioned that that Li and F^- substitute Al^{3+} and OH-, respectively, in the mica mineral (Smith *et al,* 2005). Therefore, the regions in the mica associated with fluorine may indicate a high Li lepidolite which is also called in TIMA map accordingly (Figure 4d).

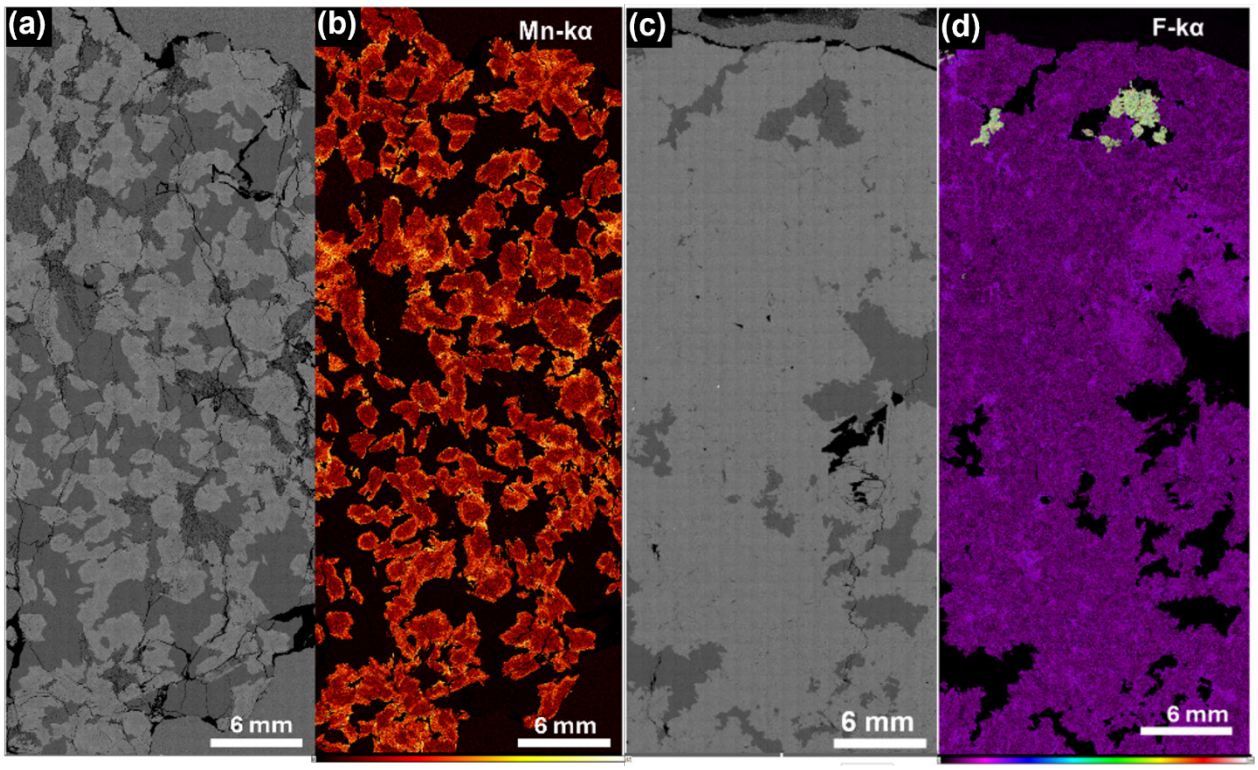


FIG 6 – (a) The backscatter electron image; and (b) the EDS elemental map of ME-3 thin-section for Mn-k wavelength; (c) The elemental map of ME-4 thin-section Al-k, Mn-k, K-k, Si-k; and (d) F-k element.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)

LA-ICP-MS analysis comprised core-to-rim spot traverses across single mica grains (14 points in the ME-3 thin section and 10 points in the ME-4 thin section) together with 2D element maps of the ME-3 round mount. The core-to-rim variation of each element in sample ME-3 is shown in Figure 7. The 2D element maps of the ME-3 round mount reproduced these distributions spatially. K and Rb were bright (indicating higher concentration) and near-uniform across the grain. The Mn and Fe were brightest along the grain edges with comparatively dark cores. Cs was restricted to a thin bright rim. Na was low within the mica; and Li was high throughout the grain body.

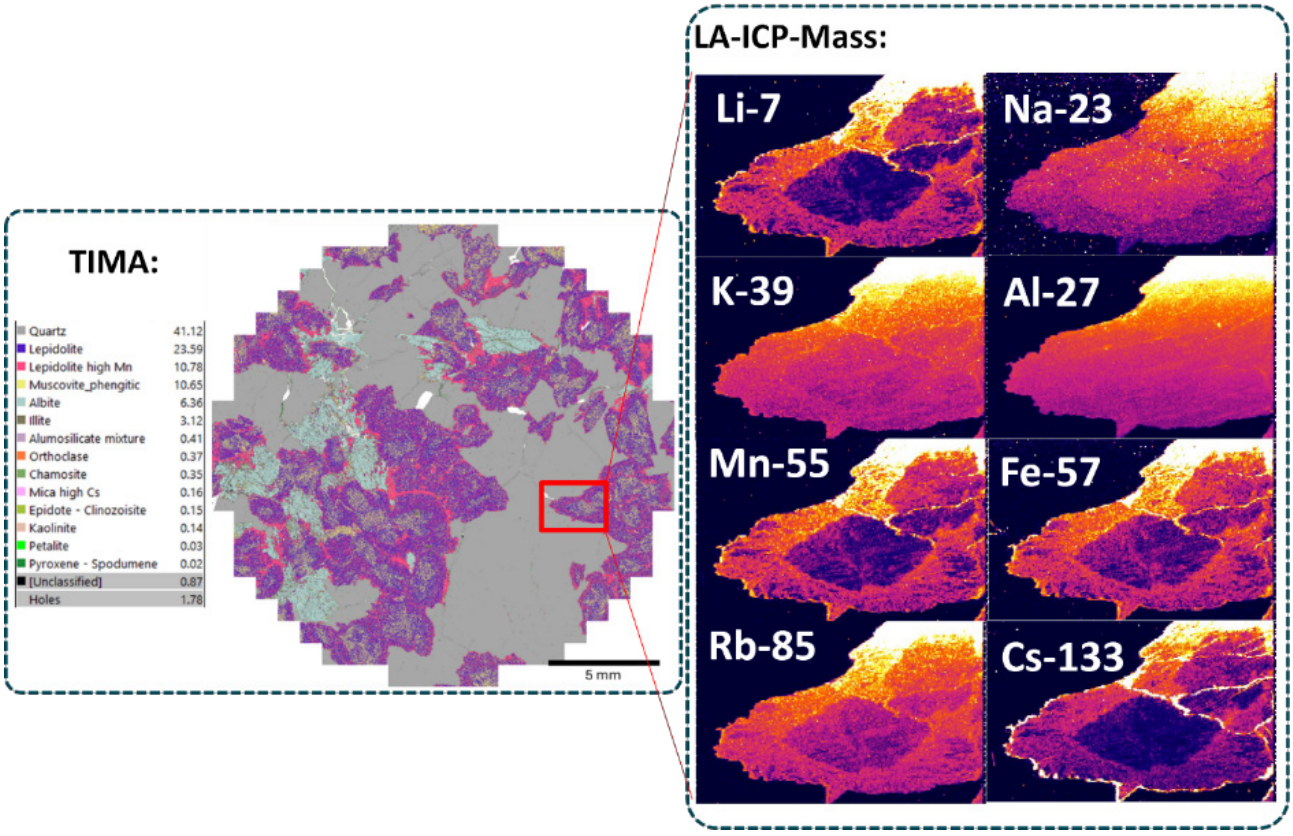


FIG 7 – LA-ICP Mass of the ME-3 round sample for ^{7}Li, ^{23}Na, ^{39}K, ^{27}Al, ^{55}Mn, ^{57}Fe, ^{85}Rb and ^{133}Cs.

The ME-3 LA-ICP-MS data point analysis (Figure 8) extended from core to rim showed an overall increase in Li, Mn and Fe, from 5642 to 20 802 ppm, 10 033 to 28 257 ppm and 4639 to 10 369 ppm, respectively, accompanied by decreases in Al from approximately 198 000 to 138 026 ppm and Na from 3770 to 1826 ppm. K remained relatively stable at approximately 91 000–101 000 ppm through most of the traverse before decreasing to 81 657 ppm at the rim. Rb was enriched throughout the mica, increasing from 18 446 ppm at the core to a maximum of 28 568 ppm at point 10, then decreasing slightly to 24 564 ppm at the rim. In contrast, Cs remained comparatively low across points 1–13, at approximately 343–830 ppm, before increasing sharply to 3440 ppm at the outermost point. Separate SEM–EDS analyses of similar rim regions in ME-3 sample also indicated elevated Cs concentrations of up to approximately 0.9 wt per cent. The LA-ICP-MS Rb range of 18 446–28 568 ppm was consistent with the SEM-EDS range of approximately 18 000–30 000 ppm.

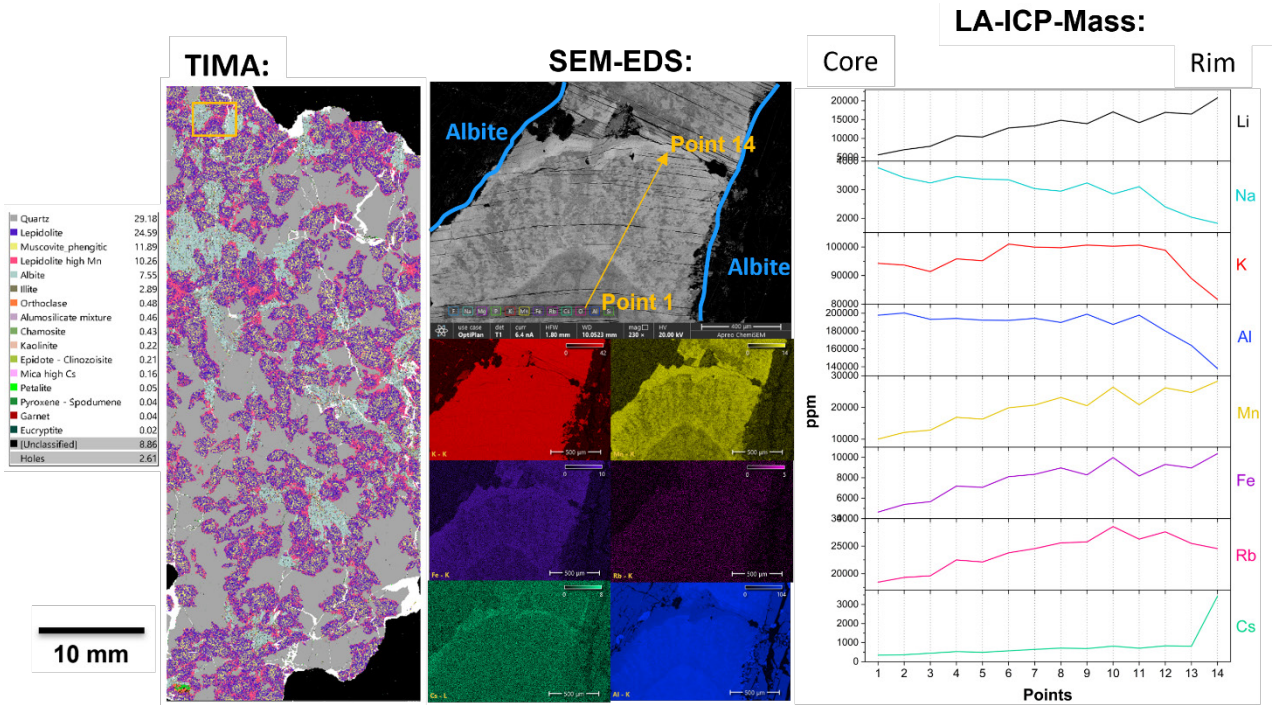


FIG 8 – ME-3 sample LA-ICP-MS characterisation. TIMA mineral map (thin section) showing modal mineralogy dominated by quartz, lepidolite, muscovite-phengite and high-Mn lepidolite, with subordinate albite and illite (see inset legend). The orange box marks the mica grain analysed. SEM-EDS backscattered-electron image of the mica grain bordered by albite, with corresponding K, Mn, Fe, Rb, Cs and Al elemental maps; scale bars 500 µm. Points 1 (core) and 14 (rim) mark the end points of the LA-ICP-MS traverse. LA-ICP-MS core-to-rim trace element profiles (points 1–14, ppm) for Li, Na, K, Al, Mn, Fe, Rb and Cs across the same grain.

The ME-4 LA-ICP-MS (Figure 9) traverse from core to rim showed an overall increase in Li from 16 086 to 25 000 ppm, accompanied by decreases in Al from 134 367 to 63 875 ppm and Na from 2127 to 780 ppm. Be, Ga and Ti also decreased markedly towards the rim, from 20.9 to 1.8 ppm, 175.6 to 29.5 ppm and 67.8 to 11.0 ppm, respectively, whereas Mg increased overall from less than 1 ppm to 34.8 ppm, with a local maximum of 83.3 ppm at point 6. K remained relatively stable in the inner part of the grain before decreasing from 67 599 ppm at the core to 61 608 ppm at the rim. Rb was enriched throughout the mica, increasing locally to a maximum of 26 850 ppm at point 5 before decreasing progressively to 15 270 ppm at the rim. Cs similarly reached its highest concentration at point 5, at 2189 ppm, but remained elevated at 1427 ppm at the rim. The LA-ICP-MS Rb range of approximately 15 270–26 850 ppm broadly overlaps the SEM-EDS range of approximately 18 000–35 000 ppm, although SEM-EDS produced a higher maximum value.

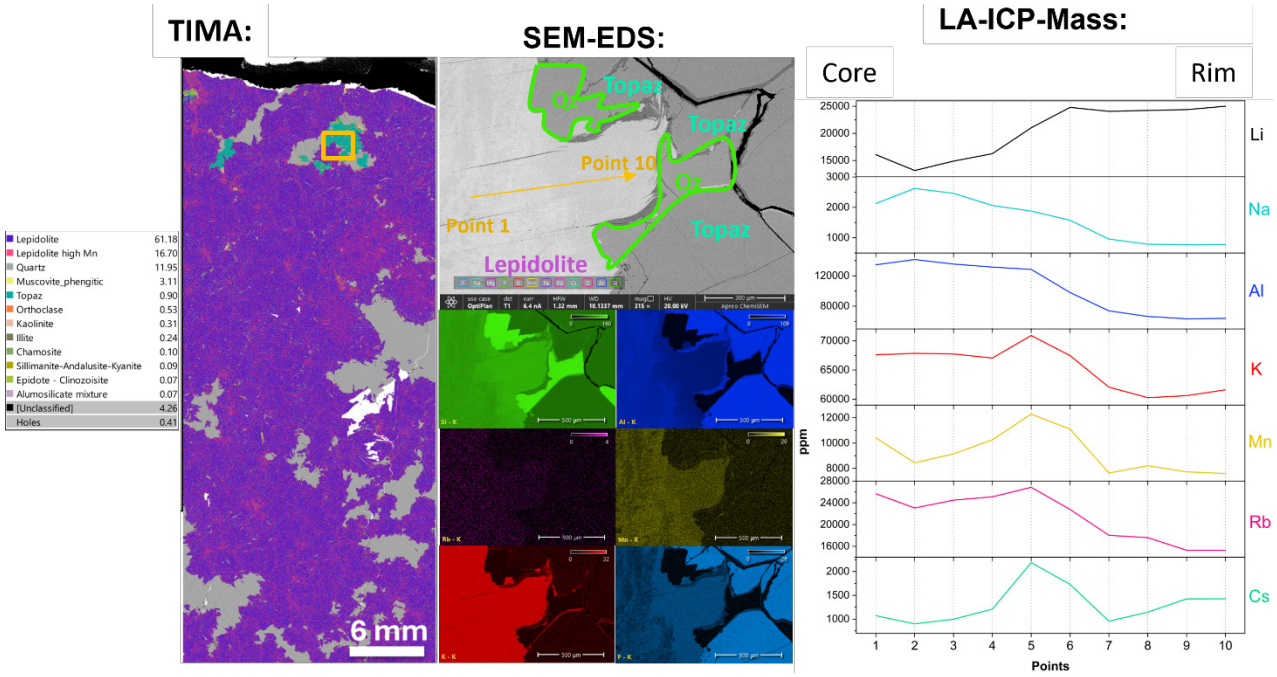


FIG 9 – ME-4 sample characterisation. (a) TIMA mineral map (thin section) showing a lepidolite-dominated assemblage (lepidolite + high-Mn lepidolite) with subordinate quartz, muscovite-phengite and topaz (see inset legend); scale bar 6 mm. The orange box marks the mica grain analysed in (b) and (c). (b) SEM-EDS backscattered-electron image of the lepidolite grain with adjacent topaz, with corresponding Si, Al, Rb, Mn, K and F elemental maps; scale bars 500 µm. Points 1 (core) and 10 (rim) mark the end points of the LA-ICP-MS traverse. (c) LA-ICP-MS core-to-rim trace element profiles (points 1–10, ppm) for Li, Na, Al, K, Mn, Rb and Cs across the same grain.

DISCUSSION

The lower SiO_2 and higher Al_2O_3 of ME-4 suggest a larger proportion of Al-rich silicates, most likely mica and/or feldspar, rather than quartz. ME-1 and ME-2 reflect progressively more silica-rich, possibly pegmatitic compositions (Fiedrich *et al,* 2018; London, 2018). Potassium oxide (K_2O): K_2O ranges from 4.2 to 4.8 wt per cent, with minimal variation across the ME-1, ME-2 and ME-3 samples. The narrow range of K_2O (4.2–4.8 wt per cent) suggests relatively constant K-feldspar participation in the mineral assemblage.

The enrichment of Rb and Cs reflects preferential partitioning into K-bearing minerals and highly evolved residual melts. This partitioning behaviour is consistent with Rb and Cs incorporation into mineral phases (potentially mica (for Cs and Rb) and K-feldspar (for Rb)) other than Na-feldspars. Rb substitutes for K via substitution mechanisms ($Rb^+ \rightarrow K^+$ in the feldspar lattice) in K-feldspar (Smith *et al,* 2005), especially in ME-1, ME-2 and ME-3. The K/Rb ratio provides insight into the degree of fractional crystallisation and elemental partitioning. K/Rb ranges from ~2.63 to ~16.8 (Figure 1c). Low K/Rb ratios in silica-rich samples (ME-1, ME-2, ME-3) is generally interpreted as advance pegmatite differentiation. Notably, ME-4 exhibits the lowest K/Rb ratio (~2.63), indicating extremely Rb-enriched phases and significant fractionation effects.

A slight positive correlation between Na_2O and SiO_2 exists (Table 1), with Na_2O ranging from 0.39 to 4.59 wt per cent across the SiO_2 range 54–74 wt per cent. While the trend is not as pronounced as the Al_2O_3-SiO_2 relationship, it suggests that Na-bearing phases (particularly sodic plagioclase) increase in abundance toward higher-silica compositions. Both sodic plagioclase (albite-rich) and K-feldspar may crystallise together (Duan *et al,* 2021). The extreme enrichment of Rb (24 085 ppm) combined with elevated Li (17 480 ppm) and Cs (1292 ppm) in ME-4 is consistent with pegmatitic fractionation (Table 1 and Figure 1d). Such compositions are characteristic of terminal-stage magmatic crystallisation where incompatible elements partition preferentially into residual melts. The extremely elevated K/Rb of 2.5 (compared to 16.82 and 12.94 in ME-1 and ME-2 samples, respectively) further supports pegmatitic differentiation (London, 2022; Wise, Curry and Harmon,

2024). The extreme Rb values in ME-4, combined with the chemical coherence of the alkali group (Rb, Li, Cs, K) reflect late-stage fluid-assisted redistribution or metasomatic processes (Phelps, Lee and Morton, 2020; Hu *et al,* 2022). As shown in Figure 1d, the extreme Li enrichment suggests preferential Li partitioning into more aluminous phases (Smith *et al,* 2005).

Manzotti *et al* (2024) described a similar feature in ME-1 round sample for fractured garnet (Figure 3a) suggesting that the possibility of Mn chemical diffusion. They also stated that the sealed garnet composed of high spessartine and low almandine, which are Mn-rich and Fe-rich garnets, respectively (Manzotti *et al,* 2024). The presence of gahnite mineral in Figure 3b was also reported in the pegmatite samples from southern Ethiopia (Bekele and Sen, 2020). Fluorine is highly regarded as a co-element with Li; thus, it can be inferred that the high-fluorine areas in Figures 3d and 4d also correlate with higher Li concentrations (Smith *et al,* 2005).

The results in Figures 4a and 5 agree with other authors regarding the incompatibility of quartz and albite with Rb causing Rb enrichment in the residual melt and eventually the enrichment in K-feldspar and phengitic muscovite (Jin *et al,* 2024). The formation of bright area in backscatter electron imaging correlated with Mn and Fe zoning on the edges of the muscovite in ME-1 is associated with the presence of albite at the intersection line of muscovite-albite and not at the intersection line of muscovite-quartz, indicating that lepidolite preferentially develops along muscovite-feldspar boundaries (Figure 5). Similar lepidolite formation has been seen in other intersection area between muscovite-albite and muscovite-orthoclase/microcline (K-feldspar), indicating the formation of lepidolite at the edges of the muscovite occurs when a type of feldspar either Na or K is generally present.

Rb is incompatible in albite relative to K minerals (Jin *et al,* 2024); however, the amount of Rb in albite is not always zero. Neiva (1995) investigated the trace elements in feldspars, and it has been mentioned that the Rb enrichment can occur in albite as well. Nevertheless, further LA-ICP-MS characterisation confirmed that the amount of Rb in albite is around 10 ppm Rb, demonstrating the SEM-EDS analysis (standardless method) may not be reliable for trace analysis of Rb element.

The grain-scale LA-ICP-MS and SEM-EDS data resolve a clear decoupling within the alkali group. Rb tracks K, remaining high and near-uniform across each mica grain, whereas Cs is confined to a thin outermost rim. This reflects ionic-radius control on interlayer substitution: Rb^{+} (~1.72 Å, XII-fold) is only marginally larger than K^{+} (~1.64 Å) and exchanges freely for K throughout crystallisation, while Cs^{+} (~1.88 Å) is too large to be accommodated until the terminal, most-fractionated increment of the crystal. The observation is consistent with the reported preferential incorporation of Rb into K-rich mica and the greater incompatibility of Cs (Were and Keppler, 2021; Gao *et al,* 2024), and with Popov (2023) who found that F-, Rb-, Cs- and Li-rich zones form at the latest crystallisation step and therefore concentrate at grain edges of mica. The late-stage signature is expressed most strongly by Cs, whereas Rb is already pervasive across the mica grain in ME-3.

The coupled Mn/Fe rim enrichment, Al depletion and Li increase revealed by LA-ICP-MS record the crystal-chemical transition from di-octahedral muscovite to tri-octahedral lepidolite/zinnwaldite. As Li and F substitute into the octahedral sheet ($Li^{+} + F^{-} \rightleftharpoons Al^{3+} + OH^{-}$; $Al^{vi} \rightarrow 3Li^{vi}$), Al reduces where Li rises, a negative correlation that only LA-ICP-MS could demonstrate directly in this study, since SEM-EDS cannot detect Li, while Mn and Fe preferentially incorporated into the trioctahedral sheets. This matches the TIMA phase distribution, in which muscovite/phengitic cores pass outward into lepidolite and lepidolite-high-Mn. This octahedral evolution is largely decoupled from interlayer Rb: because Rb resides in the interlayer as a K substitution, its abundance is relatively insensitive to the octahedral Mn/Fe/Li zoning, explaining why Rb enrichment does not follow the Mn zoning in ME-3 even though Cs does.

The close agreement between SEM-EDS and LA-ICP-MS Rb values for Rb in both ME-3 (18 000–30 000 ppm versus 18 446–28 568 ppm, mean 23 593 ppm) and ME-4 (18 000–35 000 ppm versus 15 270–26 850 ppm, mean 21 408 ppm) validates SEM-EDS which is effective for identifying Rb-rich domains, but LA-ICP-MS remains necessary for quantitative method, given the Rb-Lα/Si-Kα overlap of SEM-EDS, standardless SEM-EDS calibration, and SEM-EDS's inability to detect Li. In both samples, core-to-rim traverses show a consistent transition from an Al- and Na-rich core to a Li-, Mn- and Fe-enriched outer domain (Li rising from 5642 to 20 802 ppm in ME-3 and from 16 086 to 25 000 ppm in ME-4, compared to Al reduction), directly confirming the progressive evolution of

muscovite towards a more lepidolitic composition inferred from the Al-poor, F-rich zones mapped by SEM-EDS and the high-Mn lepidolite domains resolved by TIMA.

CONCLUSIONS

SEM–EDS was demonstrated to be an effective technique for the detection and semi-quantitative characterisation of Rb- and Cs-rich domains. Samples with higher lepidolite abundance exhibited elevated concentrations of Rb and Cs. Elemental mapping and point analyses revealed that Rb (~3.5 wt per cent) remains abundant throughout the mica with only minor local rim enrichment and Cs (~0.9 wt per cent) is strongly enriched along the outer rims of lepidolite rims, suggesting late-stage enrichment processes. At the whole-rock scale, the high concentrations of Li, Rb and Cs in ME-4 are consistent with extreme pegmatitic fractionation and the accumulation of incompatible elements in the residual melt. At the mineral scale, however, their distributions are more complex and controlled by mica composition, crystallographic substitution, grain-boundary reactions and local fluid–mineral interaction. The results are consistent with a combined magmatic evolution followed by late-stage hydrothermal or metasomatic model rather than a single uniform crystallisation process. Extreme fractional crystallisation initially enriched the residual melt in Li, Rb, Cs and F, after which late fluids redistributed these elements and modified the primary magmatic mica zoning. From a mineral processing perspective, the widespread distribution of Rb within mica grains indicates that physical separation of Rb-rich mica from quartz and albite is likely represent the most effective initial beneficiation step. However, the localised enrichment of Cs and Li at grain rims of mica and reaction boundaries suggests that mineral liberation and particle size will strongly affect their recovery. The close association of Rb with K-bearing mica further indicates that subsequent hydrometallurgical extraction strategies should account for competition among K^+, Rb^+ and Cs^+ during leaching, purification and adsorption.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Mr Michael Verrall and Dr Louise Schoneveld of CSIRO for their technical assistance, scientific guidance and support during the analytical work. The authors also thank Everest Metals Corporation for providing access to the relevant samples and geological information. The support and facilities provided by Edith Cowan University and CSIRO are sincerely acknowledged.

Declaration of artificial intelligence assisted technologies

During the preparation of this work, the authors used artificial intelligence technologies to assist with editing selected passages and improving the language, clarity, readability and organisation of the manuscript. Following the use of this tool, the authors carefully reviewed, verified and edited the provided content.

REFERENCES

Banerjee, P and Matsakis, D, 2023. Introduction to Atomic Clocks, *An Introduction to Modern Timekeeping and Time Transfer* (eds: P Banerjee and D Matsakis), pp 47–78 (Springer Nature Switzerland: Cham).

Bekele, B and Sen, A K, 2020. The mineral chemistry of gahnite, garnet and columbite-group minerals (CGM): Implications for genesis and evolution of the Kenticha Rare-element granite-pegmatite, Adola, Ethiopia, *Journal of African Earth Sciences*, 162:103691.

Camparo, J, 2007. The rubidium atomic clock and basic research, *Physics Today* [Preprint]. https://doi.org/10.1063/1.2812121

Černý, P and Ercit, T S, 2005. The classification of granitic pegmatites revisited, *The Canadian Mineralogist*, 43(6):2005–2026.

Choi, W, Park, C, Heo, C-H, Yang, S-J, Oh, I-H, Park, K S and Choi, S H, 2024. Magmatic to aqueous phase transition in Li-pegmatite: microtextural and geochemical study of muscovite–lepidolite from Boam mine area, Uljin, South Korea, *Mineralium Deposita*, 59(8):1641–1660.

Duan, G, Ram, R, Xing, Y, Etschmann, B and Brugger, J, 2021. Kinetically driven successive sodic and potassic alteration of feldspar, *Nature Communications*, 12(1):4435.

Esparza-Ponce, H E, Reyes-Rojas, A, Fuentes-Cobas, L E, De la Torre Sáenz, L and Aguilar Elguezabal, A, 2023. Lepidolite characterization using a selection of techniques, *MRS Advances*, 8(20):1144–1149.

Everest Metals Corporation (EMC), 2026. Mineral Resource Upgrade Increases Grade and Tonnage and Underpins Mining Proposal at Mt Edon Critical Minerals Project, WA, EMC ASX announcement.

Fiedrich, A M, Martin, L H J, Storck, J-C, Ulmer, P, Heinrich, C A and Bachmann, O, 2018. The influence of water in silicate melt on aluminium excess in plagioclase as a potential hygrometer, *Scientific Reports*, 8(1):12421.

Gao, X, Michaud, J A-S, Zhou, Z, Horn, I, Almeev, R R, Weyer, S and Holtz, F, 2024. Trace element (Be, Zn, Ga, Rb, Nb, Cs, Ta, W): partitioning between mica and Li-rich granitic melt: Experimental approach and implications for W mineralization, *Geochimica et Cosmochimica Acta*, 375:1–18.

Hoschek, G, 2001. Thermobarometry of metasediments and metabasites from the Eclogite zone of the Hohe Tauern, Eastern Alps, Austria, *Lithos*, 59(3):127–150.

Hu, X, Nan, X, Liu, X and Huang, F, 2022. Rubidium isotope compositions of the average upper continental crust and the Himalayan leucogranites: Implications for magmatic-fluid interaction, *Geochimica et Cosmochimica Acta*, 336:165–176.

Jin, X-W, Lei, R-X, Yuan, H-D, Brzozowski, M J and Wu, C-Z, 2024. Rb enrichment processes in highly evolved granites: Insights from mica and K-feldspar from the Baishitouquan pluton, Eastern Tianshan, *Ore Geology Reviews*, 174:106301.

Kiselev, A A, Keinert, A, Gaedeke, T, Leisner, T, Sutter, C, Petrishcheva, E and Abart, R, 2021. Effect of chemically induced fracturing on the ice nucleation activity of alkali feldspar, *Atmospheric Chemistry and Physics*, 21(15):11801–11814.

London, D, 2017. Reading Pegmatites: Part 3—What Lithium Minerals Say, *Rocks and Minerals*, 92(2):144–157.

London, D, 2018. Ore-forming processes within granitic pegmatites, *Ore Geology Reviews*, 101:349–383.

London, D, 2022. A Rayleigh model of cesium fractionation in granite-pegmatite systems, *American Mineralogist*, 107(1):82–91.

Manzotti, P, Regis, D, Petts, D C, Graziani, R and Polivchuk, M, 2024. Formation of multistage garnet grains by fragmentation and overgrowth constrained by microchemical and microstructural mapping, *Journal of Metamorphic Geology*, 42(4):471–496.

Monier, G and Robert, J-L, 1986. Evolution of the Miscibility Gap Between Muscovite and Biotite Solid Solutions with Increasing Lithium Content: An Experimental Study in the System K2O-Li2O-MgO-FeO-Al2O3-SiO2-H2O-HF at 600°C, 2 kbar P H_2O: Comparison with Natural Lithium Micas. *Mineralogical Magazine,* 50(358):641–651. https://doi.org/10.1180/minmag.1986.050.358.09

Mposkos, E, Baziotis, I and Proyer, A, 2012. Pressure–temperature evolution of eclogites from the Kechros complex in the Eastern Rhodope (NE Greece), *International Journal of Earth Sciences*, 101(4):973–996.

Naidu, G, Jeong, S, Johir, M A H, Fane, A G, Kandasamy, J and Vigneswaran, S, 2017. Rubidium extraction from seawater brine by an integrated membrane distillation-selective sorption system, *Water Research*, 123(16):321–331.

National Minerals Information Center, 2026. Cesium and Rubidium Statistics and Information, US Geological Survey. Available from: <https://www.usgs.gov/centers/national-minerals-information-center/cesium-and-rubidium-statistics-and-information>

Neiva, A M R, 1995. Distribution of trace elements in feldspars of granitic aplites and pegmatites from Alijó-Sanfins, northern Portugal, *Mineralogical Magazine*, 59(394):35–45.

Nespolo, M and Souvignier, B, 2025. Structural analysis of twins in feldspars, II, Albite-pericline twinning and the metric pseudo-symmetry of feldspar lattice, *Mineralogy and Petrology* 120:161–185.

Paton, C, Hellstrom, J, Paul, B, Woodhead, J and Hergt, J, 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data, *Journal of Analytical Atomic Spectrometry*, 26(12):2508–2518.

Pekov, I V and Kononkova, N N, 2010. Rubidium mineralization in rare-element granitic pegmatites of the Voron'i tundras, Kola Peninsula, Russia, *Geochemistry International*, 48(7).

Pekov, I V*,* Kononkova, N N, Agakhanov, A A, Belakovsky, D I, Kazantsev, S S and Zubkova, N V, 2010. Voloshinite, a new rubidium mica from granitic pegmatite of Voron'i Tundras, Kola Peninsula, Russia, *Geology of Ore Deposits*, 52(7):591–598.

Phelps, P R, Lee, C-T A and Morton, D M, 2020. Episodes of fast crystal growth in pegmatites, *Nature Communications*, 11(1):4986.

Popov, D V, 2023. Do pegmatites crystallise fast? A perspective from petrologically-constrained isotopic dating, *Geosciences*, 13(10):297.

Raith, M M, Raase, P and Reinhardt, J, 2012. *Guide To Thin Section Microscopy,* 2nd ed, 127 p. Available from: <https://mineralogy-ima.org/TSM.htm>

Simmons, W B and Webber, K L, 2008. Pegmatite genesis: state of the art, *European Journal of Mineralogy*, 20(4):421–438.

Smith, S R, Kelley, S P, Tindle, A G and Breaks, F W, 2005. Compositional controls on 40Ar/39Ar ages of zoned mica from a rare-element pegmatite, *Contributions to Mineralogy and Petrology*, 149(5):613–626.

Stevens, R E, 1938. New Analyses of Lepidolites and Their Interpretation, *American Mineralogist*, 23(10):607–628.

Thomas, R, Davidson, P and Hahn, A, 2008. Ramanite-(Cs) and ramanite-(Rb): New cesium and rubidium pentaborate tetrahydrate minerals identified with Raman spectroscopy, *American Mineralogist*, 93(7):1034–1042.

Thompson, C A (ed), 2011. *Mineral Commodity Summaries 2011*, 295 p (Nova Science Publishers: Hauppauge, NY).

US Geological Survey, 2025. Rubidium, Mineral Commodity Summaries 2025. https://doi.org/10.3133/mcs2025

Webmineral.com, nd. Muscovite Mineral Data. Available from: <https://www.webmineral.com/data/Muscovite.shtml>

Were, P and Keppler, H, 2021. Trace element fractionation between biotite, allanite and granitic melt, *Contributions to Mineralogy and Petrology*, 176(9):74.

Wise, M A, Curry, A C and Harmon, R S, 2024. Reevaluation of the K/Rb-Li Systematics in Muscovite as a Potential Exploration Tool for Identifying Li Mineralization in Granitic Pegmatites, *Minerals*, 14(1).

Woodhead, J D, Hellstrom, J, Hergt, J M, Greig, A and Maas, R, 2007. Isotopic and elemental imaging of geological materials by laser ablation inductively coupled plasma-mass spectrometry, *Geostandards and Geoanalytical Research*, 31(4):331–343.

Yelatontsev, D, Mukhachev, A and Shevchenko, V, 2026. Comprehensive utilization of mineral resources in produced water from oil and gas industry – A critical review, *Desalination*, 619(3):119558.

Governance and social

From approval to operation – how reform can accelerate Australia's critical minerals pipeline

M J Breitfuss[1]

1. Mining Sector Lead, Onterris, Brisbane Qld 4000. Email: markbreitfuss@onterris.com

ABSTRACT

Australia's critical minerals pipeline is deep, but the number of projects reaching production remains constrained and we are at risk of falling further behind other more nimble and industry-centric jurisdictions. The limiting factor is not geology; it is the ability to rapidly convert statutory approvals into operating mines within commercially viable time frames. In this context, approvals reform is no longer an environmental or regulatory issue, it is a central lever in determining whether projects achieve financial close and are built at all.

Bilateral agreements under the Environment Protection and Biodiversity Conservation Act 1999 were intended to streamline the statutory approvals pathway by enabling State or Territory-led assessments to reduce duplication and provide confidence of an outcome. This was then to transfer to State or Territory-led approvals for Commonwealth matters, yet no Australian jurisdictions have the ability to undertake the process end-to-end. While the bilateral assessment arrangements have delivered efficiencies in some cases, their performance has been inconsistent and remains the critical risk to project success. Variability in State or Territory processes, differing science-based evidentiary thresholds and residual Commonwealth intervention at the approval stage has meant that 'single assessment' has not translated into single, predictable approvals outcomes. Change is needed to enable the full use of bilateral approval powers so that there is a conventional and clear process from application through to receiving conditional approval for mining projects.

Recent reforms to our National environmental legislation introduce a further layer of complexity and uncertainty. The move toward National Environmental Standards, including requirements to avoid 'unacceptable impacts' and deliver 'net gain', reflects a clear and necessary tightening of environmental expectations. However, without corresponding gains in clarity and coordination with States and Territories, there is a risk that higher standards will further extend time frames simply to achieve policy directives rather than improve environmental outcomes.

This presentation will argue that the effort to increase the number of projects reaching operation requires a shift in focus from process to delivery, supported by practical reforms.

First, bilateral agreements between States and Territories and the Commonwealth should evolve into transparent, outcome-based frameworks with nationally consistent standards applied uniformly across jurisdictions, providing greater certainty around approval conditions and expectations. Importantly, the mining industry continues to prove its ability to deliver world-class outcomes for the sector which should then in-turn give regulators confidence that environmental stewardship remains a key outcome for miners.

Second, Governments should enable parallel rather than sequential decision-making by aligning Commonwealth, State, Territory and ancillary approvals, thereby reducing time frames without weakening safeguards. Currently, where Commonwealth approval is required, significant delays and additional conditional requirements are often applied post receipt of State or Territory authorisations. This can impose further financial stress to an already challenging capital raising process, adding unnecessary frustration to all parties, including investors.

Third, early risk resolution pathways should be formalised to address high-impact issues such as biodiversity, social, water, and cultural heritage, at the outset of the process so that miners understand where and how expectations are being set. This collaborative approach would instil confidence and trust between miners and regulators so that all parties understand the rules upon commencing a statutory process so applicants can then accommodate the work needed to meet obligations appropriately.

In a competitive global market, investment is increasingly directed toward jurisdictions offering both strong environmental performance and certainty of execution. The Australian mining industry has continued to innovate and wants to have clear and reasonable guardrails from which to operate within. The challenge is for our regulators to adapt and provide a similar level of clarity that matches community and industry expectations. Closing the gap between the time frames to generate the science necessary to underpin environmental approvals and their assessment and approval through government will be critical to translating Australia's resource potential into operational outcomes.

Beyond the E – the important role of social and governance in critical minerals

M Case[1] and M Saylor[2]

1. Manager of Sustainable Development – Bechtel Mining and Metals, Perth WA 6000. Email: mcase@bechtel.com
2. Communities and Social Performance Lead APAC, Bechtel Mining and Metals, Brisbane Qld 4001. Email: msyalor@bechtel.com

ABSTRACT

The rapid expansion of the critical minerals sector has placed ESG firmly at the centre of project approvals, investment decisions, and supply chain scrutiny. Environmental performance is often the most visible and measurable part of this conversation. Yet across complex mining and infrastructure developments, it is frequently social and governance factors less visible, less quantified, and often addressed later that shape whether projects progress smoothly, stall, or fail altogether.

From the earliest stages of project development, governance structures influence how decisions are made, risks are prioritised, and trade-offs are managed. In Australia, this includes not only regulatory and corporate governance, but also Traditional Owner-led governance and planning frameworks (for example, strategic and community plans, established decision-making structures, and other Traditional Owner instruments). These frameworks should be an explicit and deliberate point of alignment in project delivery.

Experience across critical minerals projects in Australia and internationally highlights how social and governance considerations are woven through every phase of the project life cycle. Traditional Owner frameworks sit alongside and directly inform project ESG/sustainability, cultural heritage management, and 'on Country' activities, and should be treated as integrated delivery inputs rather than a parallel or adjunct stream. Regulatory frameworks, corporate sustainability policies, and project-level execution do not operate in isolation; they intersect daily in decisions about land access, procurement strategies, workforce planning, and engagement approaches.

In practice, EPCM and project delivery engagement is often standardised and process-driven (for example, oriented to approvals, workflows, and discrete deliverables), rather than embedded early through authentic, place-based collaboration. This can limit understanding of local priorities and the opportunity to co-define what 'good' looks like with Traditional Owners and host communities. A common constraint is that implementation is often limited by local Traditional Owner or Indigenous community capability and resourcing, which can inhibit effective collaboration even where intent exists. Where appropriate, projects can support access to capability and resourcing such as specialist support and capacity-building mechanisms to improve the quality of engagement, clarify priorities and focus areas, and build enduring trust across phases.

The legacy of critical minerals projects is shaped well before closure. Without early investment in social performance and specialist Indigenous engagement capability (and sustainability capability), projects risk missing the opportunity to co-define priorities with Traditional Owners and communities weakening an integrated social licence to operate approach and diminishing legacy outcomes. Decisions about land use, governance responsibilities, and stakeholder involvement during development and operations often determine whether post-mining outcomes support long-term community aspirations or become a source of ongoing contention.

By drawing these threads together, the discussion reframes social and governance performance as enabling capabilities rather than compliance functions. Recognising and strengthening these often overlooked dimensions of ESG is increasingly central to navigating complexity, maintaining trust, and delivering resilient outcomes in the critical minerals sector.

Partnerships as enablers of integrated rare earth supply chains – lessons from emerging industry models

A Eames[1]

1. Chief Legal and External Affairs Officer, Australian Strategic Materials Limited, West Perth WA 6005. Email: aeames@asm-au.com

ABSTRACT

The development of resilient, non-China critical minerals supply chains remains a key strategic objective for governments and industry supporting electrification, defence capability and advanced manufacturing. In the rare earths sector, progress has been constrained by the technical complexity and fragmentation of the value chain, which spans mining, beneficiation, separation, metallisation and alloy production. This paper argues that strategic partnerships across the supply chain are essential to overcoming these structural challenges, enabling integration, reducing risk and accelerating development timelines.

The rare earths value chain is characterised by high capital intensity, specialised processing technologies and limited global processing capacity outside China. As a result, individual project developers often face constraints in scaling beyond their core competencies, whether in upstream resource development or downstream processing. In this context, partnerships—across industry participants, governments and end-users—are increasingly critical in aligning incentives and capabilities across the value chain.

This paper examines three key partnership models emerging within the sector. First, industrial partnerships between upstream and downstream participants facilitate vertical integration, allowing alignment between oxide production and metallisation or alloying capacity. Second, government–industry partnerships provide catalytic support through funding, policy frameworks and demand-side initiatives designed to de-risk early-stage projects and encourage domestic processing capability. Third, customer-aligned partnerships, including product qualification programs and offtake agreements, play a central role in underpinning project financing and ensuring alignment with end-market requirements.

To illustrate these dynamics, the paper draws on recent industry developments, including the proposed combination of Australian Strategic Materials Ltd and Energy Fuels Inc, which reflects a broader trend toward linking complementary capabilities across jurisdictions. While subject to approvals (including shareholder and court approval) and completion, this example highlights how upstream and midstream processing capacity can potentially be aligned with downstream metallisation and alloying to form a more integrated ‘mine-to-metals’ platform. Importantly, the case study is used to demonstrate structural themes rather than transaction-specific outcomes.

The analysis considers how such partnership models can address key barriers facing the sector, including feedstock security, technical scale-up risk, financing constraints and limited price transparency. It also explores how coordinated development across jurisdictions may support the emergence of alternative supply chains capable of supplying critical inputs for permanent magnets and other advanced technologies.

The paper concludes that a shift toward ecosystem-based collaboration—anchored by strategic partnerships across industry, government and customers—is fundamental to establishing competitive and sustainable critical minerals supply chains. Without such coordination, efforts to develop alternative supply chains are likely to remain fragmented and slower to achieve commercial scale.

Accelerating regional development through place-based approaches – baseline studies to de-risk critical mineral projects: a Julia Creek/Richmond case study

B Johns[1]

1. Director, Zones and Projects, Critical Minerals Queensland, Brisbane Qld 4000.
   Email: ben.johns@nrmmrrd.qld.gov.au

ABSTRACT

Global demand for critical minerals is increasing rapidly, driven by the energy transition, technological advancement, defence applications and the diversification of strategic supply chains. While Australia possesses globally significant critical mineral resources, many projects face challenges associated with infrastructure constraints, regulatory complexity, workforce availability, environmental considerations and investment risk. Addressing these challenges requires approaches that extend beyond individual project boundaries and consider development at a regional scale.

The Julia Creek/Richmond Critical Minerals Zone (CMZ) in north-west Queensland provides a practical example of how a place-based approach can accelerate regional development while reducing risk for industry, government and communities. The region hosts a cluster of prospective vanadium projects that share common infrastructure requirements, environmental considerations, workforce demands and social opportunities.

Critical Minerals Queensland has adopted a coordinated regional development model that combines baseline studies, stakeholder engagement, infrastructure planning and investment facilitation. This includes the delivery of regional-scale social, groundwater, ecological and First Nations participation studies, alongside planning for common-user infrastructure, transport, energy and water solutions.

The resulting evidence base supports more informed investment decisions, improves understanding of cumulative impacts, reduces duplication of technical studies and assists proponents to navigate environmental and social assessment requirements. The approach also enables government to better coordinate infrastructure investment and community development initiatives while maintaining appropriate environmental, social and governance standards.

The Julia Creek/Richmond experience demonstrates that place-based development can materially de-risk critical mineral project delivery and provide a transferable framework for emerging resource regions. By addressing constraints collectively and focusing on shared regional outcomes, governments and industry can accelerate critical mineral development while creating broader and more sustainable benefits for regional communities.

INTRODUCTION

Critical minerals have emerged as a strategic priority for governments worldwide. Demand forecasts indicate significant growth across a broad suite of commodities that support battery technologies, renewable energy systems, advanced manufacturing, telecommunications, defence capability and emerging industrial technologies. At the same time, governments and investors are increasingly focused on supply chain resilience and reducing reliance on highly concentrated global sources of production.

Queensland possesses substantial critical mineral endowment, including vanadium, graphite, rare earth elements, cobalt, nickel and other minerals essential to emerging industries. The North West Minerals Province, in particular, contains globally significant resources and a long history of mineral development.

Traditional resource project development models have generally focused on assessing projects individually. While appropriate for many circumstances, this approach can result in duplicated studies, fragmented infrastructure planning, inconsistent stakeholder engagement and limited

understanding of regional cumulative impacts. These challenges become increasingly apparent where multiple projects seek development simultaneously within a single geographic region.

Recognising these opportunities and challenges, the Queensland Government established Critical Minerals Queensland (CMQ) and introduced a place-based development model through the creation of Critical Minerals Zones. The Julia Creek/Richmond CMZ has become a pilot example of this approach, bringing together government agencies, industry, local communities, Traditional Owners and regional stakeholders to support coordinated development.

This paper outlines the rationale for the place-based approach, the development of the Julia Creek/Richmond CMZ, the implementation of regional baseline studies, and the role these initiatives play in reducing development risk and accelerating regional growth.

THE CASE FOR A PLACE-BASED APPROACH

Place-based development recognises that resource projects do not operate in isolation. Communities, infrastructure networks, water resources, environmental values and labour markets are shared across regions and frequently influence multiple projects simultaneously.

For emerging critical minerals industries, particularly those located in regional and remote areas, common challenges often include:

- limited infrastructure capacity
- uncertainty regarding water availability
- workforce and housing constraints
- environmental and ecological knowledge gaps
- regulatory complexity
- social licence considerations
- competition for investment capital.

A project-by-project approach can result in each proponent independently attempting to address many of these issues. This often leads to duplication of effort, increased costs and inconsistent outcomes.

A place-based model seeks to address these challenges by establishing a coordinated evidence base and development pathway at the regional scale. This enables government and industry to identify shared opportunities, understand cumulative impacts and prioritise common solutions.

Rather than replacing individual project responsibilities, the approach provides a foundation upon which project-specific studies and approvals can be built, helping proponents progress development activities more efficiently.

Julia Creek/Richmond critical minerals zone – An example

The Julia Creek/Richmond CMZ was established to support development of Queensland's emerging vanadium industry and has subsequently expanded to include graphite opportunities extending towards Croydon.

The region contains a concentration of prospective critical mineral projects, creating a unique opportunity to develop a coordinated industry cluster rather than isolated operations.

The CMZ currently encompasses multiple proposed projects seeking to progress exploration, feasibility and development activities. While each project maintains distinct commercial objectives, they share common requirements for:

- water supply
- energy infrastructure
- transport and logistics

- workforce attraction
- environmental assessment
- community engagement
- processing pathways.

The Queensland Government recognised that addressing these requirements collectively could provide significant efficiency and risk-reduction benefits. Accordingly, the CMZ framework seeks to concentrate government effort and investment where clusters of projects can realise shared value.

This includes coordinated infrastructure planning, regulatory facilitation, baseline data collection and stakeholder engagement, all leading to the ultimate objective of accelerating the development of a regional critical minerals industry while maximising economic and social outcomes for Queensland communities.

Government's enabling role

Critical minerals represent a significant growth opportunity for Queensland, and the state has undertaken a range of initiatives to capitalise on this potential. Key actions include the following.

Establishment of Critical Minerals Queensland: This entity serves as a central gateway for industry, investors and communities, promoting Queensland's critical minerals sector. It facilitates investment in research and development, fosters partnerships and leads government action to support the sector's growth.

Strengthening Stakeholder Relationships: Queensland has adopted a place-based approach to foster collaboration and efficiency by establishing two Critical Minerals Zones – the Julia Creek/Richmond Zone and the Mount Isa/Cloncurry Zone. These zones bring communities and projects closer together, enabling time, resource, engagement and capital efficiencies for a diverse range of stakeholders.

Encouraging Exploration: Since June 2023, Queensland has implemented a no-rent policy for new and existing exploration permits, which has significantly boosted exploration interest. This initiative is complemented by various rounds of the Collaborative Exploration Initiative to encourage discovery and development of critical mineral deposits and the Collaborative Development Program, which has incentivised miners to explore remaining mineralisation in mine waste.

Promoting Investment Opportunities: Queensland has actively profiled and showcased its critical minerals investment opportunities through the release of the *Critical Mineral Prospectus* (State of Queensland, 2026) and participation in international missions. These efforts have targeted investment opportunities and accelerated projects.

Queensland Critical Minerals Fund: This unique fund, being delivered by Queensland Investment Corporation, has been instrumental in investing in critical mineral projects that enhance Queensland's industry capability. It also provides greater access to national and global supply chains in metal refining, minerals processing, and battery technologies.

Research and Development Support: Queensland has prioritised research and development in areas such as the circular economy, recycling, and minerals discovery, extraction, and processing. This includes partnerships with Queensland universities through a mineral's alliance and the construction of vital infrastructure, such as the Queensland Resources Common User Facility in Townsville and the Resources Centre of Excellence in Mackay.

Resources Cabinet Committee: The Resources Cabinet Committee provides strategic oversight and coordination of Queensland's resources sector, including critical minerals. It ensures alignment of government policies and initiatives with industry needs, facilitates cross-sector collaboration, and drives the delivery of key projects and reforms to support sustainable growth in the resources sector.

Mount Isa Transformation Study: Leveraging the joint Queensland-Commonwealth support package for the Mount Isa Copper Smelter and Townsville Copper Refinery announced in October 2025, Queensland stands shoulder to shoulder with the Australian Government to secure a strong future for Mount Isa through the Mount Isa Transformation Study.

Queensland's approach to critical minerals development benefits from the collaborative efforts of several government agencies and their engagement practices with our local communities and mining stakeholders.

Baseline studies as a de-risking mechanism

A central feature of the CMZ model is the development of regional baseline studies. Historically, proponents have generated much of the environmental, social and groundwater information required for project approvals independently. While necessary, this often results in duplication where multiple projects exist in the same region.

Regional baseline studies provide a common evidence base that can support multiple projects while also informing government planning and community engagement.

The CMZ baseline program focuses on four key themes:

1. Social impacts.
2. First Nations participation.
3. Groundwater resources.
4. Ecological values.

Collectively, these studies contribute to a stronger understanding of regional opportunities, constraints and cumulative impacts.

Social baseline study

The social baseline study, completed in 2025, represents one of the most advanced examples of the CMZ approach. It is well understood that major resource developments can create considerable economic opportunities while also generating pressures relating to workforce availability, housing, services and community infrastructure. Understanding these dynamics early is critical to successful project planning.

The study provides a comprehensive regional profile including demographic characteristics, workforce conditions, economic activity, service provision and community aspirations. However, the study does not replace project-specific social impact assessments (SIA), rather, it provides a foundation that significantly reduces the level of new baseline work required. It is estimated that the study can satisfy a substantial portion of the social baseline information typically required for project assessment.

The study provides baseline social and economic data to help project proponents, regulators and community stakeholders better understand potential impacts and opportunities associated with critical minerals development. By reducing duplication and improving planning, the work supports more efficient project delivery, enabling earlier job creation and community benefits within the critical mineral zone and across North-West Queensland.

The findings also assist proponents and local leaders to anticipate social impacts and prepare for future waves of critical minerals investment. The regional perspective also provides value beyond baseline description. By identifying community strengths, vulnerabilities and aspirations, it assists proponents, local governments and other stakeholders to develop more strategic and coordinated mitigation responses. Perhaps most importantly, it improves understanding of cumulative impacts arising from multiple developments occurring concurrently within the region.

The social baseline study has also helped inform other projects in the region such as the draft Gulf Plains bioregional guidance plan. The guidance plan directly references the study to inform the social, cultural and economic values in the plan area, providing better information for proponents to help design projects that support environmental and community priorities and strengthen social licence.

First Nations economic participation

The First Nations Peoples Economic Baseline Program provides a community-driven evidence base on First Nations economic participation across Queensland's two priority CMZs: Mount Isa/Cloncurry and Julia Creek/Richmond.

The program is designed to support meaningful First Nations participation in the economic opportunities generated by growth of the critical minerals sector — through employment, enterprise, procurement and training. The program's purpose is to:

- deliver a culturally grounded, evidence-based account of current First Nations economic participation across the CMZs, drawing on both community engagement and secondary data.
- identify the opportunities, barriers and aspirations that shape First Nations participation in the critical minerals sector.
- record the supports that First Nations Peoples identify as necessary from government and industry, and the outcomes to be avoided.
- function as a proponent-ready reference that provides a more informed starting point for engagement and supports efficient, good-faith social impact assessment.

This program complements and extends the Social Baseline Study referenced above, and when delivered, it will reduce duplication, shorten assessment time frames, and lessen the engagement burden on communities.

Groundwater baseline study

Many critical mineral projects require multiple environmental, planning and resource approvals. Early engagement enables proponents to better understand approval pathways, identify key information requirements and reduce the likelihood of delays associated with incomplete applications.

Completed in late 2025, Phase 1 consolidated existing hydrogeological information across the CMZ and developed a regional understanding of potential groundwater supply pathways. The study:

- compiled existing hydrogeological data sets
- identified potential groundwater sources
- examined groundwater availability opportunities
- considered water quality characteristics
- identified major knowledge gaps.

Importantly, the work highlighted areas of uncertainty associated with groundwater volume, reliability, quality and practical accessibility. These findings established a foundation for further investigation and provided early guidance to project proponents undertaking feasibility assessments.

The second phase of the program focuses on targeted field validation and refinement of regional groundwater understanding. Key objectives include:

- validation of groundwater availability assumptions
- collection of additional field data
- development of regional water quality data sets
- improvement of hydrogeological confidence levels
- provision of information suitable for feasibility and environmental assessment activities.

The resulting data sets are intended to provide proponents with more consistent and robust information for project planning while supporting evidence-based regulatory decision-making. By reducing uncertainty in one of the region's most important enabling factors, the groundwater program contributes directly to project de-risking and investment confidence.

Ecological baseline studies

Environmental values are a critical consideration for any resource development proposal. In the Julia Creek/Richmond region, ecological assessments are being undertaken to improve understanding of key environmental assets and support future assessment processes and offsets, particularly for Matters of National Environmental Significance under Australia's *Environmental Protection and Biodiversity Conservation Act 1999* (Department of Climate Change, Energy, the Environment and Water, 1999.).

Of particular significance is work relating to the Julia Creek Dunnart, a species of recognised conservation importance within parts of the region. Planned outputs include:

- habitat suitability modelling
- updated regional ecosystem mapping
- revised ecosystem descriptions
- new BioCondition benchmarks
- improved understanding of potential offset opportunities.

These products will provide a consistent regional evidence base that can be utilised during environmental impact assessments and support frameworks such as the Gulf Plains Bioregional Guidance plan covering the region. The availability of this publicly accessible ecological information is expected to improve assessment efficiency for proponents and regulators, while maintaining environmental protection outcomes and strengthening social licence.

Infrastructure as a regional enabler

While baseline studies address information gaps, infrastructure investment addresses physical constraints. The Julia Creek/Richmond region requires coordinated consideration of several critical enabling inputs, including:

- energy
- water
- transport
- communications
- workforce accommodation.

A key example is power supply planning associated with the CopperString transmission network. Improved electricity infrastructure has the potential to significantly influence project economics while supporting future processing opportunities.

Similarly, transport infrastructure investment can enhance export pathways and improve regional connectivity. The CMZ approach allows these requirements to be considered collectively rather than through isolated project assessments. This approach enables government and industry to explore common-user solutions that may provide superior outcomes compared with multiple standalone investments.

Supporting processing and value adding

Queensland's critical minerals strategy extends beyond resource extraction. A major objective is the development of sovereign processing capability capable of retaining greater value within Queensland and Australia.

The Julia Creek/Richmond CMZ provides opportunities to support this objective through collaborative approaches to technology demonstration and processing development. A clear example of this is through Queensland Government support for common-user processing facilities which can assist proponents to demonstrate processing flow sheets, reduce technical risk and accelerate commercialisation pathways.

These initiatives are particularly important in emerging critical mineral sectors where processing technologies continue to evolve and where individual projects may face challenges funding pilot-scale activities independently. The development of shared processing capability can therefore contribute to both industry growth and regional economic diversification.

Building community confidence and social licence

Projects ultimately operate within communities and for this reason, stakeholder engagement sits at the centre of the place-based approach. The CMZ model encourages ongoing engagement with:

- local governments
- Traditional Owners
- landholders
- community organisations
- industry representatives
- service providers.

Engagement at the regional scale enables broader discussions regarding cumulative impacts, infrastructure priorities, workforce needs and legacy opportunities. It also provides a mechanism for incorporating local knowledge into technical studies and planning processes.

By aligning technical assessments with community priorities, the approach strengthens social licence and supports more durable development outcomes.

Lessons for future critical minerals development

Several key lessons have emerged from implementation of the Julia Creek/Richmond CMZ, including:

- regional-scale information can substantially reduce uncertainty for both proponents and regulators.
- baseline studies can improve efficiency without diminishing project-specific accountability, where proponents still need to undertake project-level assessments, but can do so from a stronger evidence base.
- infrastructure planning is more effective when undertaken across a regional development corridor rather than on an individual project basis.
- cumulative impacts and shared opportunities are often better understood when examined at the scale at which communities experience them.
- collaboration among government, industry, communities and Traditional Owners is essential for achieving long-term development outcomes and contribute to improved social licence.

These lessons provide a foundation for potential replication of the model in other emerging critical minerals regions throughout Queensland and potentially Australia.

CONCLUSIONS

The Julia Creek/Richmond Critical Minerals Zone demonstrates how place-based development can accelerate critical mineral project delivery while supporting broader regional development objectives.

The novel approach moves beyond traditional project-by-project assessment by establishing a coordinated regional framework that integrates infrastructure planning, stakeholder engagement and baseline data collection.

Regional baseline studies addressing social conditions, groundwater resources, ecological values and First Nations participation are reducing information gaps, improving investment confidence and supporting more efficient project assessment processes.

At the same time, coordinated planning for water, power, transport and processing infrastructure is helping to address fundamental barriers to development and encouraging industry clustering.

The experience to date suggests that place-based approaches can materially de-risk critical mineral development by providing shared evidence, supporting regulatory efficiency and enabling more effective regional collaboration.

As demand for critical minerals continues to grow, the Julia Creek/Richmond model offers a practical framework for unlocking regional opportunities while delivering sustainable economic, environmental and social outcomes.

ACKNOWLEDGEMENTS

The author acknowledges the contributions of Critical Minerals Queensland, the Office of the Coordinator-General, Queensland Government partner agencies, local governments, Traditional Owner groups, industry participants and community stakeholders involved in the development of the Julia Creek/Richmond Critical Minerals Zone.

The author also acknowledges the specialist consultants and technical working groups that contributed to the social, groundwater, ecological and First Nations baseline studies referenced in this paper.

Approval to publish was provided by the Queensland Government.

REFERENCES

Department of Climate Change, Energy, the Environment and Water, 1999. Environment Protection and Biodiversity Conservation Act 1999, No. 91, Department of Climate Change, Energy, the Environment and Water, Australian Government, August 2026. Available from: <https://www.legislation.gov.au/C2004A00485/latest/text>

State of Queensland, 2026. Queensland Critical Mineral Prospectus, Department of Natural Resources and Mines, Manufacturing and Regional and Rural Development, Queensland, State of Queensland, February 2026. Available from: <https://www.nrmmrrd.qld.gov.au/__data/assets/pdf_file/0005/1895090/critical-minerals-prospectus.pdf>

Critical minerals Queensland – First Nations economic participation

B Johns[1]

1. Director Zones and Projects, Critical Minerals Queensland, Townsville Qld 4800.
   Email: ben.johns@nrmmrrd.qld.gov.au

ABSTRACT

As the critical minerals sector expands to support the global energy transition, there is a growing imperative to ensure development delivers meaningful, long-term benefits for First Nations Peoples. Understanding how First Nations communities may choose to engage with and leverage economic opportunities in the critical minerals sector is essential to achieving equitable, sustainable, and socially responsible outcomes.

The recent body of work undertaken by Critical Minerals Queensland to better understand First Nations perspectives on economic participation in the critical minerals sector, identifies community-driven aspirations and priorities that influence decisions about economic engagement.

The abstract will share lessons learnt about how First Nations Peoples may seek to leverage opportunities across the critical minerals value chain, from exploration and development through to operations, services, and downstream activities.

Beyond social licence – First Nations partnership as critical project infrastructure

J Lawton[1]

1. CEO, Aboriginal Enterprises in Mining, Energy and Exploration (AEMEE), Brisbane Qld 4007. Email: ceo@aemee.org.au

ABSTRACT

Australia's critical minerals opportunity is being driven by urgency, with governments, investors and industry seeking to accelerate exploration, approvals, financing and development to secure Australia's position in rapidly changing global supply chains. In this environment, project certainty, time and cost matter, yet the relationship with First Nations people whose Country, rights and interests intersect with resource development is still too often considered separately from the core commercial and technical factors that determine whether a project is successful.

This presentation challenges the conventional framing of 'social licence to operate' and considers what changes when genuine First Nations partnership is treated as part of the core infrastructure of a project and a fundamental component of project risk. Resource projects routinely assess geological, technical, regulatory, financial and construction risks, while the consequences of poorly established First Nations relationships can include approval challenges, cultural heritage disputes, damaged trust, project delays, additional costs and investment uncertainty. Establishing strong relationships early should therefore not be viewed only through the lens of corporate responsibility or as simply the right thing to do. It is also in the commercial interests of proponents, investors, governments and communities seeking successful and timely project delivery.

The emerging critical minerals sector provides a significant opportunity to approach this differently. Many Australian critical minerals projects remain in exploration, feasibility or early development, creating an opportunity to establish relationships, participation and commercial arrangements while projects are still being shaped rather than attempting to retrofit them once key decisions have already been made.

This does not mean that 'de-risking' should become another way of describing more efficient consultation or securing First Nations acceptance of predetermined projects. If the sector is to genuinely change the relationship, the conversation needs to extend beyond consultation and transactional benefit agreements to consider First Nations decision-making, Indigenous enterprise participation, procurement, equity, ownership and enduring economic interests in the projects being developed on Country.

There is also a clear investment dimension to this discussion. As governments and investors seek to accelerate Australia's critical minerals pipeline, the quality and maturity of First Nations relationships should be considered alongside geology, approvals, infrastructure, capital and project economics when assessing project readiness and risk. Early alignment of interests has the potential to provide greater certainty through exploration, approvals, construction and operations while creating stronger foundations for long-term relationships between projects and communities.

These decisions also need to consider what remains after mining. Lessons from mine closure demonstrate that decisions made during exploration and project development can shape outcomes on Country decades later. The social licence available to the next generation of resource projects will inevitably be influenced by the experience and legacy of previous development, including whether mining created enduring capability, businesses, ownership and economic opportunities or left communities managing unrealised commitments and post-mining liabilities.

Drawing on AEMEE's work across Australia's resources sector, emerging work on First Nations participation in critical minerals and recent research examining Indigenous participation in mine closure and post-mining economies, this presentation considers how the critical minerals sector can establish a different approach while much of the industry is still being shaped.

Rather than viewing First Nations engagement as a social consideration alongside project development, there is an opportunity to recognise strong First Nations partnerships as part of the commercial architecture required to develop successful projects. This requires moving the conversation beyond whether First Nations communities support the next generation of Australian mines and towards how First Nations people participate in their design, development and ownership, how value is shared throughout the life of a project, and what economic opportunities and legacy remain on Country when mining is over.

Social licence and critical minerals – comparative insights from Australian and Canadian public attitude surveys

K Moffat[1] and M-O Fortin[2]

1. CEO, Voconiq, Brisbane Qld 4000. Email: kieren.moffat@voconiq.com
2. Partnership Development Director, Transfert Environnement et Société, Montreal, Quebec, Canada. Email: mofortin@transfertconsult.ca

ABSTRACT

Global decarbonisation pathways depend on secure supplies of critical minerals, yet the expansion of mining activity increasingly hinges on societal acceptance and the maintenance of a social licence to operate. This paper synthesises findings from two large-scale national studies, the *Australian Attitudes to Mining Survey 2024* (Moffat *et al*, 2024) and the *Canadian Social Acceptability Barometer for the Mining Sector* (Moffat *et al*, 2025), to examine public attitudes toward mining and their implications for critical minerals development in resource-rich democracies. Together, the surveys capture societal sentiment from more than 11 000 respondents and provide a rare, comparable evidence base across jurisdictions with significant critical minerals endowments. Both studies demonstrate strong strategic-level support for mining, particularly for critical minerals underpinning the energy transition. Majorities in Australia and Canada view such minerals as essential to national prosperity and the achievement of net-zero objectives, and generally prefer secure domestic supply. However, this support is explicitly conditional. Persistent concerns regarding environmental impacts, benefit-sharing, procedural fairness, and trust in mining companies continue to constrain social licence, particularly at the local and project scales. In both countries, trust consistently lags acceptance, underscoring that broad societal approval of critical minerals extraction does not translate automatically into consent for specific developments. Beyond the substantive findings, this paper highlights the value of systematically measuring, analysing and hence understanding societal sentiment across jurisdictions key to critical minerals production. Replicable engagement science methodologies enable benchmarking of trust, legitimacy and acceptability, providing early warning of social risk and opportunities for adaptive governance. Securing long-term access to critical minerals will therefore require sustained investment in social performance and evidence-based engagement informed by continuous sentiment monitoring.

REFERENCES

Moffat, K, Fortin, M-O, Pretorius, N, Zhou, J, Cyrzon, and McIlroy, T, 2025. Social Acceptability Barometer: Canadian Mining Sector (2025 Report), Transfert Environment et Societe & Voconiq, Canada. Available from: <https://voconiq.com/en-us/blog/2026/03/local-and-national-social-license-are-connected>

Moffat, K, McCrea, R, Pitcaithly, A, Unger, I, Bailey, C, Boughen, N and Parr, J, 2024. Australian attitudes toward mining: Citizen survey – 2024 Results, CSIRO, Australia [EP2024-4783]. Available from: <https://www.csiro.au/en/work-with-us/industries/mining-resources/social-and-environmental-performance/attitudes-to-mining-survey-report-2024>

Licensing the social licence – identifying legitimacy-based SLO issues in Victoria's critical minerals industry

R Noor[1], M Farrelly[2] and L Lester[3]

1. PhD researcher (Geography), School of Social Sciences, Monash University, Melbourne Vic 3800. Email: mohd.noor@monash.edu
2. Professor and Associate Dean Graduate Research, Faculty of Arts, Human Geography, School of Social Sciences, Monash University, Melbourne Vic 3800. Email: megan.farrelly@monash.edu
3. Professor (Research) and Director, Monash Climate Change Communication Research Hub, Faculty of Arts, School of Media, Film, and Journalism, Monash University, Melbourne Vic 3800. Email: elizabeth.lester@monash.edu

ABSTRACT

Australia's critical minerals sector is central to the country's decarbonisation agenda, yet its social legitimacy remains highly contested. In Victoria, where proposed and operating mineral sands projects overlap with farmland and environmentally sensitive regions, tensions over social licence to operate (SLO) have become especially acute. This study examines how communities and project proponents perceive SLO in Victoria's emerging critical minerals sector and what these perceptions reveal about legitimacy in just energy transitions. The study uses a qualitative multiple case study design of five projects across the Wimmera–Mallee and East Gippsland regions of Victoria. Evidence from ten semi-structured interviews with community, government, industry, and advocacy stakeholders was analysed for perceptions of consultation, governance, and project legitimacy. Findings show SLO is understood as a relational, place-based process shaped by trust, institutional credibility and lived experience. The data also signalled four emergent themes: relational legitimacy, cumulative transition pressures, path-dependent engagement, and place- and legacy-based legitimacy. Consultation was frequently regarded as tokenistic, while trust in mining projects was tied to trust in government. Of note, overlapping renewable energy, transmission, and mining developments intensified local fatigue and seeded greater resistance. Historical mining identities in some places supported greater acceptance, whereas agricultural and environmentally sensitive regions saw extraction as incompatible with local values.

This paper argues these legitimacy gaps reflect a trust deficit caused by institutionalised procedural consultation, public apathy in critical minerals compounded by the rapid rise of renewables and transmission projects, and perceptions of SLO as a compliance tool, fuelling scepticism toward the broader energy transition agenda. To make concerted progress in advancing legitimate critical minerals mining operations in regional Australia, further attention is required to assess the impact of current SLO practices on Australia's national transition agenda, investigating actor interactions in decision-making, and cumulative effect assessment of current status and future scenarios.

INTRODUCTION

Australia's critical minerals sector underpins its decarbonisation agenda, yet its social legitimacy remains unsettled. Mineral sands, and other transition minerals are viewed as essential to renewable energy and low-carbon infrastructure, but their extraction often occurs where agriculture, environmental sensitivity, and land use pressures intersect. Although non-exclusive to many infrastructure projects that shape public opinion and sentiment, the concept of social licence to operate (SLO) in Australia refers to the ongoing relationship of trust, acceptance, and legitimacy negotiated between companies and communities (Lacey, 2021; Laurence, 2021). 'Community' in this work is referred to as the overlapping groups of residents (in shire councils, Indigenous First Nation lands, and regional towns) with diverse interests, identities, and levels of influence who are directly (through living or livelihood) or indirectly (eg business ownership) affected by mining project activities across environmental, social, and economic dimensions. However, the concept and practice of 'community' remains contested, inconsistently practiced, and lacks clear governance and enforcement frameworks. Resource governance scholarship recognises intersecting challenges in creating, maintaining, and repairing SLO (Dumbrell *et al*, 2021; Santiago *et al*, 2021; Mercer-

Mapstone, 2018). Yet, it remains unclear how SLO is conceptualised within just energy transition research. Existing studies on critical minerals highlight growing environmental, social, and governance risks, with social risks relating to extractive legitimacy including trust, inclusion, and recognitional justice. Yet, limited attention is given to how legitimacy is co-produced across overlapping transition infrastructures and place-based justice claims. This gap is evident in Australia's expanding critical minerals sector, where mining lies at the intersection of decarbonisation and development imperatives, generating new social, environmental, and governance conflicts.

This study examines how communities and proponents perceive SLO in Australia, especially Victoria's critical minerals projects. Among the Australian states, Victoria's uniqueness lies in its mineral sand projects that coincide with its rich heritage of productive farmlands, creating conflict between agriculture and resource extraction. This highlights the need for social science research to understand stakeholder perceptions, land-use conflict, and the governance conditions under which these projects may gain legitimacy, particularly in the Wimmera–Mallee region, which is emerging as a major hub for mineral sands and rare earth projects. Focusing on five mineral sands projects across two Victorian regions, the study provides qualitative insights drawn from ten semi-structured interviews with community representatives, local governments, proponents, advocacy partners and environmental lawyers.

Insights from the interviews indicate divergent community attitudes and sentiment regarding critical mineral mining in Victoria, which are often shaped by proximity to mining, perceived benefits and socio-environmental impacts linked to environmental sensitivity, cultural heritage, agricultural identities, economic outcomes, and presence of legacy industries. These factors reflect competing priorities and unavoidable trade-offs. Moreover, communities and proponents often diametrically oppose in how they perceive and understand mining's social, environmental, and economic implications. While these issues require more nuanced understanding in Victoria's emerging critical mining sector, this study offers one of the first integrated empirical analyses for understanding place-based perceptions, expectations and engagement in Victoria's critical minerals sector.

LEGITIMACY AND SOCIAL LICENCE – AN OVERVIEW

Legitimacy-based social licence in mining governance

Social licence to operate (SLO) has become increasingly central to mining governance as legal approval alone cannot secure public acceptance of extractive projects. Although widely used across mining and infrastructure sectors, SLO remains contested and inconsistently defined. Existing scholarship conceptualises SLO variously as community acceptance, operational legitimacy, stakeholder engagement, or corporate risk management (Stuart *et al*, 2023; Curran, 2017; Moffat *et al*, 2016; Dare*,* Schirmer and Vanclay, 2014; Owen and Kemp, 2013). Early industry approaches framed SLO as a mechanism to reduce conflict and maintain operational continuity (Fraser, 2021). Recent scholarship, however, positions SLO within broader debates on legitimacy, justice, and trust (Breakey, Wood and Sampford, 2025; Lehtonen *et al*, 2022; Meesters *et al*, 2021; Gehman, Lefsrud and Fast, 2017).

Scholars argue SLO cannot be reduced to procedural consultation or public relations strategies alone, and signal the important role long-term relational legitimacy has between companies and communities (Parsons, Lacey and Moffat, 2014; Owen and Kemp, 2013; Prno and Slocombe, 2012). Scholars have argued that mining consultations often become symbolic exercises focused on 'one-off' procedural compliance (Hall *et al*, 2015; Dare*,* Schirmer and Vanclay, 2014; Owen and Kemp, 2013). Communities may participate formally while remaining excluded from substantive decisions. Hence, community input often fails to shape final project outcomes, generating frustration, distrust, and perceptions of tokenism (Parsons, Lacey and Moffat, 2014). Moffat and Zhang (2014) identify trust, procedural fairness, and confidence in institutions as central factors shaping community acceptance of mining operations. Parsons and Moffat (2014) conceptualise SLO as relational legitimacy, where acceptance depends on companies being perceived as transparent, responsive, and accountable to community concerns. From both of their arguments, trust functions as both a social and political condition enabling extractive projects to maintain legitimacy beyond legal approval. Beyond economic benefits and environmental impacts, communities often evaluate mining projects through perceptions of honesty, fairness, and institutional reputation (Oh, Shin and Ho,

2023; Wang *et al*, 2016). Hence, legitimacy is relationally negotiated, challenging earlier industry approaches that treated SLO primarily as communications or reputation management.

These critiques are particularly relevant to Australia's critical minerals industry as mining companies increasingly operate within ESG-oriented (environmental, social and governance) environments that emphasise transparency, sustainability, and ethical sourcing. While ESG frameworks encourage corporate accountability, they also managerialise SLO by framing legitimacy as a measurable outcome rather than a democratic process based on trust and shared decision-making (Cash, 2025; Glückler and Gutiérrez, 2025). Hence, trust becomes difficult to achieve where communities perceive consultation as a mechanism for securing predetermined approvals.

Such concerns are evident in practice, with growing criticism of how SLO is operationalised. Hall *et al* (2015), Dare, Schirmer and Vanclay (2014) and Owen and Kemp (2013) suggest that many engagement processes prioritise project certainty and regulatory compliance over meaningful participation and shared decision-making, in part because deeper engagement can increase time, costs and operational uncertainty for proponents (Thomson and Boutilier, 2011). Consequently, trust deficits persist even within highly institutionalised governance systems. CSIRO's (2024) nationwide survey on people's attitudes towards mining indicated trust was the dominant factor in achieving SLO (Figure 1). Yet, other legitimacy factors, including distributional fairness, procedural fairness, external regulations contribute to trust (Grimmelikhuijsen, de Vries and Bouwman, 2024; Schnaudt, Hahn and Heppner, 2021).

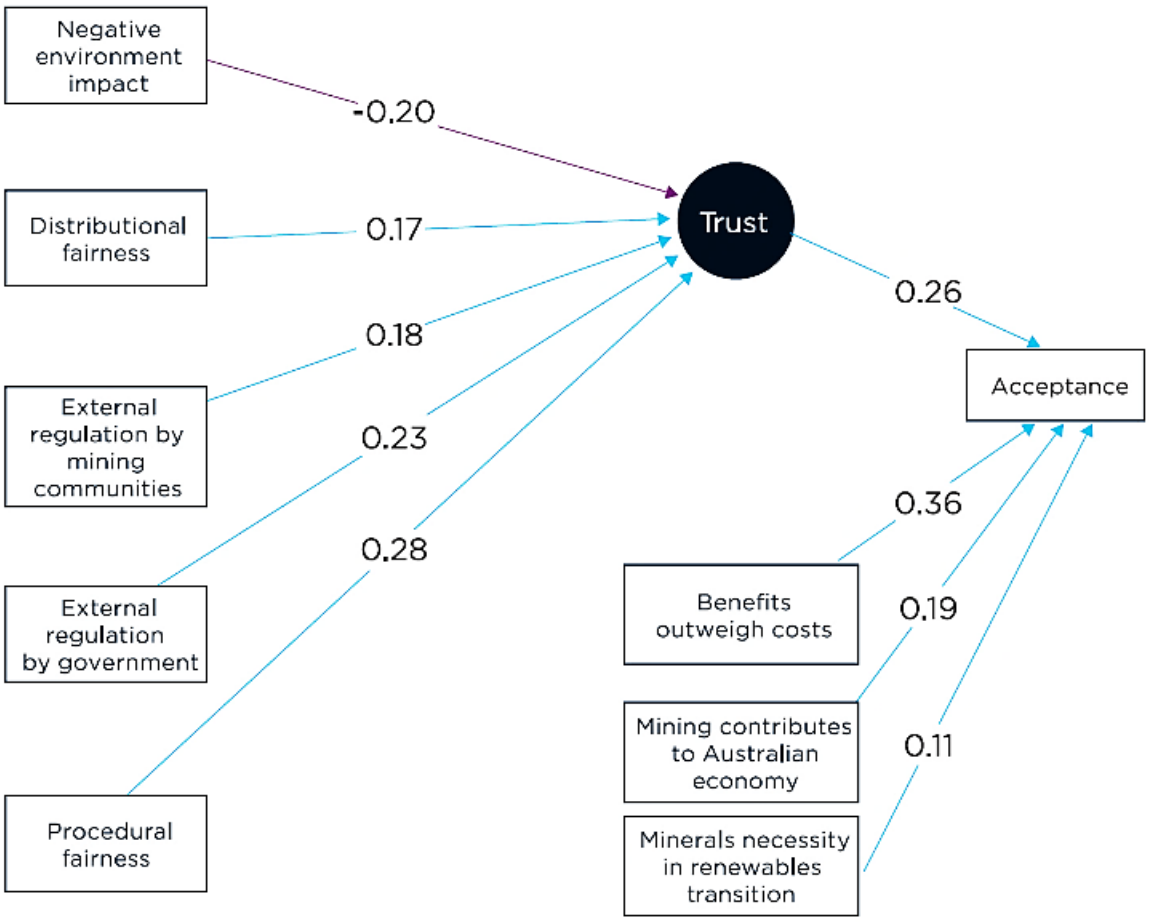


FIG 1 – Australian attitude towards mining (CSIRO, 2024:31).

Legitimacy tensions around energy transition

The global push for low-carbon transition has intensified demand for critical minerals used in renewable energy technologies, electrification, and battery storage. This is a part of just transition which, according to the UN International Labor Organization, is a 'conceptual framework in which the labour movement captures the complexities of the transition towards a low-carbon and climate-

resilient economy, highlighting public policy needs and aiming to maximize benefits and minimize hardships for workers and their communities in this transformation' (Rosemberg, 2010:141). Within the field of [just] energy transitions, that involves addressing 'distributional issues of who gains and who pays the cost' (of energy transition) (Healy and Barry, 2017:457), trust becomes more critical as communities are asked to support extractive projects justified through climate and decarbonisation narratives. This tension is evident in Australia's attitude towards mining, where only 11 per cent believe minerals are necessary for the renewable transition (CSIRO, 2024:31).

This is because although Australia positions itself as a 'clean and ethical supplier' of mineral resources (Geoscience Australia, 2025), its mining activities continue to raise concerns over biodiversity loss, social impacts, and uneven economic benefits. Consequently, the energy transition risks reproducing many of the same socio-environmental inequalities historically associated with extractive industries. This tension has increased emphasis on justice- and legitimacy-based transitions.

Just transition and energy justice scholarship argue decarbonisation pathways must equitably distribute benefits and burdens while ensuring procedural inclusion, recognition, and democratic participation (see Gurčinaitė and Barbrook-Johnson, 2026; van der Kooij, 2025; de Fontenelle and Heffron, 2023; Astola *et al*, 2022). Yet critical minerals governance often prioritises national economic interests, supply chain security, and accelerated approvals over local justice concerns (Owen *et al*, 2022; Heffron, 2020). Communities experience environmental and infrastructural burdens of extraction locally, while broader transition benefits are framed nationally or globally. Consequently, legitimacy within critical minerals governance is shaped by cumulative and place-based pressures which can lead to complete indifference in the overall extractive industry. This concern is reflected in Australian citizen attitudes, where 32 per cent prefer reducing mining activities 'even if it delays the net-zero transition' (CSIRO, 2024:34).

Moreover, existing SLO frameworks (ie Thomson and Boutilier's 'Pyramid' Model (2011); Moffat and Zhang's Integrative Model (2014) and Prno and Slocombe's Community-Social Licence-Insurance Equilibrium (CoSLIE) Model (2012)) often evaluate legitimacy at the project scale, focusing on local community acceptance and site-specific impacts. This aligns closely with recognitional justice, which emphasises diverse social realities and place-specific understandings of justice in transition governance (Fischer *et al*, 2024). Concurrently, unresolved pollution, abandoned mines, and inadequate rehabilitation legacies continue to shape contemporary distrust toward mining companies and governments (Table 1). These dynamics show legitimacy is relationally embedded across time and place.

TABLE 1

Dimensions contributing to legitimacy tensions in critical minerals development.

Dimension of legitimacy tension	Representative issues
Environmental pressures	Biodiversity, water, land use, dust impacts
Social and cultural pressures	Place identity, heritage, historical attachment, community values, legacy experiences
Governance pressures	Trust, regulation, participation, transparency

Overall, despite growing scholarship on the convergence of SLO and just energy transition, important gaps remain. Existing studies often focus on individual mining projects and overlook how legitimacy is cumulatively shaped across overlapping transition infrastructures. Similarly, legitimacy is widely recognised as central to SLO (Breakey, Wood and Sampford, 2025; Eabrasu, Brueckner and Spencer, 2021; Meesters *et al*, 2021; Gehman, Lefsrud and Fast, 2017; Jijelava and Vanclay, 2017), but its application beyond recognition and procedural justice is less developed and rarely explored in-depth, especially restorative or reparative justice in minerals governance (Heffron, 2020). Restorative or reparative justice is used where historical wrongs require remediation. Similar term 'transitional justice' exists in adjacent literatures, which refers to how societies address systematic past wrongs (conflict, repression, colonial dispossession) through trials, truth commissions,

reparations, and institutional reform (see Scholz and Schuppert, 2025; Van Uffelen, Taebi and Pesch, 2024; de Fontenelle and Heffron, 2023). Moreover, limited empirical research has examined these dynamics within Australia's emerging critical minerals sector, particularly in regions experiencing legacy-based social issues across traditional mining (eg gold mining, brown coal, and base metals as by-products of gold mining in Victoria), renewable energy, and transmission developments.

METHODS

Research design

To address the research gaps on legitimacy-induced SLO, this study adopts a qualitative, multiple case study design to examine how SLO is perceived and negotiated in Australia's critical minerals sector. This paper aims to characterise how critical mineral mining stakeholders perceive and influence the SLO process in Victoria, Australia. In exploring this question, this study seeks to uncover important dynamics of managing the social licence in Australia's critical minerals industry.

The study focused on mineral sands projects in Victoria using data from ten semi-structured interviews with critical mineral mining stakeholders including local government officials, community members, industry proponents, and researchers. Purposive sampling was used to capture perspectives from stakeholders who occupy different positions with the identified projects and experience project legitimacy, consultation, and impact in distinct ways. To protect confidentiality, interview data are anonymised and participants are identified using generic identifiers.

Case selection and participant recruitment

The research focused on five mineral sands projects across the north-western Wimmera–Mallee region and the East Gippsland area in Victoria, Australia. These projects coexist with productive farming land in Victoria, leading to public debate over environmental governance, agricultural land use, and community consultation issues (see Table 2). The selected projects include developments at varying stages of exploration, planning, approval, and operation, allowing the study to capture differing experiences of engagement across mining life cycle.

TABLE 2

Social, governance and environmental challenges in Victorian mineral sands projects (Resources Victoria, 2026, 2025; Astron, 2025; Gippsland Critical Minerals, 2025; Planning Victoria, 2025; VMH, 2025; Planning Panels Victoria, 2023; Planning Victoria 2024a, 2024b; The Weekly Times, 2024; Victorian Farmers Association, 2024; Kennedy, 2023).

Projects	Social and governance dynamics	Environmental challenges
Avonbank Mineral Sands Project	• Loss of productive Wimmera agricultural land. • Uncertainty over post-mining rehabilitation. • Concerns over dust, radiation, noise, traffic, and impacts on rural amenity. • Division between farming and regional economic benefits. • Opposition despite environmental approval.	• Extensive land disturbance requiring long-term rehabilitation to restore agricultural capability.
Donald Mineral Sands Project	• Community upset over lack of consultation. • Large project to reshape land use and regional life. • Power, water, and road upgrades are not project-ready. • Strong farmer opposition over soil, water, and dust impacts.	• High water demand. • Soil rehabilitation on prime cropping land. • Radiological risks from monazite concentrate.

Fingerboards Mineral Sands Project	• Threats to waterways and Ramsar ecosystems (Mitchell River). • Loss of Lindenow Valley farmland and 700+ mature trees. • Risks of erosion, toxins, and water scarcity. • High-profile SLO scenario where community opposition nearly derailed the project.	• Water use, soil loss, radioactive tailings, biodiversity. • Heightened near sensitive farming areas.
Goschen Rare Earth and Mineral Sands Project	• Only 40 days to review 3244-page EES. • Pushback from farming groups on dust, noise, traffic, and radioactivity issues; effects on crops, groundwater, land access and reliability of rehabilitation.	• Located in highly sensitive irrigation-heavy farming region in Loddon–Mallee.
Wimmera Project	• Complex multi-agency governance, ie EES Technical Reference Group (EPA Victoria, GWM Water, Wimmera Catchment Management Authority, First Peoples–State Relations, Horsham Rural City Council, DEECA). • Tensions with Wimmera's agricultural and rural communities.	• Impacts on groundwater in a water-limited agricultural region. • Uncertainty around long-term rehabilitation of mined land.

Participants were recruited through publicly accessible email invitations to Victoria-based stakeholders. The ten semi-structured interviews took place between February and March 2026 (Table 3). To protect confidentiality, each interviewee was assigned a project-specific code (eg R1-DON, R2-FIN), used when reporting results. Participants without direct project affiliation were coded as R7-CM1, R9-CM2, etc.

TABLE 3

List of interviewees (DON = Donald Mineral Sands Project; FIN = Fingerboards Mineral Sands Project; GOS = Goschen Rare Earth and Mineral Sands Project; CM = critical minerals).

SI	Interviewee code	Stakeholder type	Location
1	R1-DON	Proponent	VIC
2	R2-FIN	Community and advocacy	VIC
3	R3-DON	LGA	VIC
4	R4-FIN	Community and advocacy	VIC
5	R5-DON	LGA	VIC
6	R6-GOS	Community and advocacy	VIC
7	R7-CM1	Industry	VIC
8	R8-FIN	Community and advocacy	VIC
9	R9-CM2	RDA	WA
10	R10-CM3	Academia	VIC

Data collection and analysis

By using semi-structured interviews, this study generated in-depth data on participants' perceptions, experiences, and lived realities. Following qualitative best practices (Longhurst and Johnston, 2023), an interview guide was designed around broad themes to encourage flexible discussion rather than

structured questioning. The interview guide followed a common prompt with stakeholder-specific questions. Interviews were conducted face-to-face or via Zoom or telephone and lasted about one hr. We prioritised face-to-face interviews because remote interviews can limit building rapport and miss non-verbal cues (Self, 2021). These limitations were mitigated by beginning interviews with informal chats to build rapport and paying close attention to tone and pauses (Khan and MacEachen, 2022; Saarijärvi and Bratt, 2021). Virtual interviews also enabled participation from distant regions, including one interstate participant, broadening the study's contextual range (de Villiers, Farooq and Molinari, 2022; Saarijärvi and Bratt, 2021). While the study focuses on Victoria, this interstate perspective provided a modest comparative reference point for understanding whether interview themes were unique to Victoria or also evident in other states.

Using reflexive thematic analysis (Braun and Clarke, 2006), we iteratively identified, interpreted, and compared recurring patterns in (i) how SLO was understood and enacted by companies, communities, regulators, and other actors; (ii) where and how tensions or shifts in legitimacy emerged; and (iii) what dynamics enable or constrain the overall SLO in Australian critical minerals industry. First, interview transcripts were reviewed to gain familiarity with the data and identify initial patterns. Second, initial codes were assigned capturing recurring concepts, conflicts, experiences, and perceptions relevant to SLO and critical minerals governance (Table 4). Third, these codes were grouped into broader themes reflecting shared patterns in interview responses. Twelve themes were first generated which were continuously refined through comparison across interviews and literature to ensure analytical coherence. Finally, four overarching main themes were identified. We also used reflexive practices to rectify assumptions and potential biases (Braun and Clarke, 2021). This included writing summaries and reflective notes after interviews and holding team debriefings to discuss data interpretations, saturation point, and alternative explanations.

TABLE 4

Codes, sub-themes and themes generated in this study.

Codes	Sub-themes	Themes
Trust/mutual confidence	Trust as the core of legitimacy	Relational legitimacy
Deep distrust (community-company-government)		
SLO as vague concept	Transparency and information sharing	
Misinformation and media sensationalism		
Lack of education/understanding about mining		
SLO as community buy-in/absence of discontent	Reciprocity (mutual recognition)	
Value proposition/delivering promises on time		
Risk communication and negotiations		
Cumulative impacts ('triple threat')	Overlapping projects	Cumulative transition pressures
Government/company as 'repeat players'		
Dust, arsenic, pollution, lacking safety monitoring	Compounding environmental issues	
Impacts on agricultural, heritage, vegetation, rivers		
Land-use conflict: mining versus agriculture		

Housing crisis FIFO/DIDO workforce versus local employment	Impact on shared infrastructure (housing, roads, labour, local services)	
Procedural/‘drop-in’ consultations Online-only consultations in low-connectivity areas Consultations as ‘sham’/‘dodgy’/‘lip service’	Consultation as procedural compliance	Path-dependent engagement
Government not seen as intermediary/captured by industry Community trauma (eg bushfires) shaping distrust	Early mistrust shaping later engagement	
Government fast-track approval Lack of local government funding, expertise, resources Regional/rural inequity versus city/main projects	Fast-tracking	
Legacy mining culture (pro-mining towns)	Mining identities and regional history	Place- and legacy-based evaluation
Impacts on agricultural, heritage, vegetation, rivers	Place attachment	
Land-use conflict: mining versus agriculture versus housing	Competing land uses	
SLO measured by reactions to aftermath Benefit-sharing and royalty distribution Community ‘bought with money’ CSR as ‘woke culture’/‘being seen’	Post-approval legitimacy	

FINDINGS AND DISCUSSION

The interviews revealed SLO in Victoria’s critical minerals sector is understood as a contested and fragile relationship shaped by history, power, and repeated interactions among companies, regulators, Traditional Owners, and communities. Four major themes emerged from the interpretive synthesis: (1) relational legitimacy; (2) cumulative transition pressures across mining and renewable infrastructure; (3) path-dependent engagement and consultation deficits; and (4) place- and legacy-based evaluation, historical mining identities and post-approval legitimacy. These themes form the basis of the findings and discussion section.

Relational legitimacy

A dominant theme emerging from the interviews suggests communities do not assess social licence through procedural completion alone, but through relational trust and perceived fairness. Respondents repeatedly rejected the assumption that consultation itself produces legitimacy. Instead, legitimacy was evaluated through whether mining companies and governments were viewed as transparent, responsive, accountable, and trustworthy over time. R2-FIN, for example, argued that their project did not possess a genuine social licence because it had effectively *‘bought support’* by *‘bribing local political figures’* and *‘not earning community trust through meaningful*

engagement'. Similarly, R3-DON described consultations as a *'sham'* and linked *'community confidence in mining directly to confidence in government institutions'*. These findings strongly reinforce existing SLO scholarship which identifies trust as the central mediating factor underpinning legitimacy and acceptance (Stronge, Kannemeyer and Edwards, 2024; Dare, Schirmer and Vanclay, 2014; Moffat and Zhang, 2014).

Of note, participants' reactions to mining were seen as hidden cues that need extraction by observing both retrospective and reactive attitudes. For example, R1-DON suggested viewing SLO as a *'best alternative to negotiate agreement and measuring it by understanding community's 'absence of discontent' or non-compliance in community feedback and taking that feedback in the form of representative democracy'.* A contrasting but complementary response from R10-CM3 argued that SLO should be *'measured by not how people give clearance to a project*, *but how they react to the aftermath'.*

The interviews suggest that procedural consultation in Australia increasingly functions as a managerial exercise and not a trust-building process. R6-GOS described regulator responses as *'lip service'* and argued that *'agencies appeared institutionally aligned with mining interests over community concerns'*. Such claim was confirmed by R9-CM2 who views *'CSR activities by mining companies are a way of 'being seen by the community''.* The gap between SLO and ESG is further reinforced by R7-CM1 who recalled from their experience that *'the 1980s saw a big gap between community expectation and company performance and faced early signs of SLO in the form of 'public policy,' 'social community issue,' 'reputation management,' but not ESG'*. The findings therefore show a critical legitimacy gap between institutional perceptions of consultation success and community's perception of procedural exclusion. Although proponents may meet formal consultation obligations, communities continue to evaluate SLO through long-term relational conduct and demonstrated accountability throughout project life cycle. This disconnect is particularly significant for Australia's just energy transition because transition legitimacy depends on accelerating project approvals without sacrificing public trust or disregarding meaningful participation (Radtke, 2025; Radtke and Renn, 2024).

Additionally, social licence was not viewed solely as a relationship between mining companies and communities, but as deeply mediated by the perceived legitimacy of governments and regulatory institutions. Many respondents expressed the view that regulators were either ineffective, politically constrained, or aligned with industry interests. For example, R3-DON argued *'community trust in mining depends on whether communities trust the government itself'*. Likewise, R6-GOS claimed regulators are *'captured by the mining companies'* and try to *'make the companies happy.'* These findings suggest perceived legitimacy is strongly state-mediated and communities judge mining projects not only by corporate behaviour, but also by the credibility, independence, and transparency of the institutions responsible for regulating them. This closely aligns with literature on governance theory and participatory legitimacy, particularly Prno and Slocombe's (2012) argument that SLO is co-produced through governance structures and institutional norms.

Several respondents highlighted structural weaknesses in current governance systems. R4-FIN described local governments as 'lacking sufficient technical expertise, resources, and funding to effectively monitor mining impacts despite being expected to manage many implementation responsibilities'. R8-FIN similarly observed that project proponents often enter communities as highly resourced 'repeat players,' while residents 'must navigate thousands of pages of technical environmental documentation within limited consultation window'. Critically, the interviews suggest that governments increasingly function not as neutral intermediaries but as facilitators of transition acceleration. Respondents frequently associated fast-tracked approvals and consultation processes with growing domestic and international political pressure to rapidly advance renewable and critical minerals development. This can pose major tensions between procedural fairness and accelerated 'fast-track' approvals under Australia's 'Future Made in Australia' transition agenda (The Treasury, 2024).

Cumulative transition pressures

It is important to recognise that communities rarely experience mining projects in isolation. Respondents repeatedly described overlapping pressures from critical minerals mining, renewable

energy infrastructure, and electrical transmission developments occurring simultaneously in the same region. R3-DON characterised this as a *'triple threat'* involving mining, wind energy, and transmission line projects, arguing that *'none of these developments currently have meaningful social licence'* within the community. This finding suggests that communities evaluate mining impacts from combined socio-economic and environmental points of view. Respondents identified concerns relating to land-use conflict, agricultural disruption, biodiversity and water loss, housing shortages, and workforce pressures. R5-DON highlighted that *'regional road systems*, *housing capacity*, *and local services were already under pressure from renewable developments before mining proposals emerged'*. This interview shows that communities frequently perceive decarbonisation projects as cumulative industrialisation in the extractive industries. R1-DON, suggested viewing SLO from other infrastructure industries such as renewables, where *'community attitude transfers significantly in the form of broader resource curse'*. These findings resonate strongly with the earlier discussion of the paradoxes embedded in energy transition – while renewable technologies are promoted as environmentally sustainable, their material dependence on critical minerals introduces new forms of socio-environmental conflict and extraction pressure and uneven distributional impacts regarding energy justice.

Moreover, cumulative transition pressures appear to intensify legitimacy fatigue within regional communities. Several respondents suggested that repeated exposure to overlapping consultations, planning, and project proposals creates frustration, exhaustion, and scepticism that can obscure the energy transition agendas. For instance, R10-CM3 viewed Victoria's 'duty-based regulatory model' as a way of *'pivoting away'* responsibilities. This contributes to broader distrust not only toward mining companies but also toward renewable energy development itself. Consequently, the interview data suggest that achieving a just energy transition requires moving beyond project-by-project legitimacy models toward integrated regional governance approaches capable of assessing cumulative socio-environmental and infrastructural pressures. This aligns with long-standing critiques of environmental impact assessment that highlight the difficulty of capturing cumulative impacts when each mine is assessed in isolation, even in regions with multiple co-located projects (Tulve *et al*, 2024; Jenkins, 2018; Franks, Brereton and Moran, 2010).

Path-dependent engagement

Interview data also revealed the path-dependent nature of social licence formation. Respondents emphasised how early interactions between mining proponents and communities shape long-term legitimacy trajectories, often in ways that become difficult or impossible to reverse. For example, R8-FIN suggested *'perceived arrogance*, *poor communication*, *and dismissive first-contact consultation led to a bad foundation'*, producing distrust which is *'almost always irrecoverable.'* Additionally, R10-CM3 mentioned *'deploying third parties for managing remediation processes and financial handling'* for *'killing the bad blood'*. Similarly, R2-FIN described *'community resentment toward online-only consultation processes in low-connectivity regional areas*, *where many residents lacked digital access or technical literacy'*. R4-FIN also mentioned *'informing communities through the right channel'* to avoid generating *'ignorance'* or *'apathy'*.

These findings strongly align with the framing of SLO as a dynamic, relational, and continuously negotiated process that evolves in response to changing community expectations, trust, and legitimacy perceptions (Glückler and Gutiérrez, 2025; Mercer-Mapstone, 2018; Moffat *et al*, 2016; Dare*,* Schirmer and Vanclay, 2014; Moffat and Zhang, 2014; Parsons and Moffat, 2014). However, the interviews extend this understanding by demonstrating that legitimacy is also temporally and historically cumulative. Early procedural failures become institutional memories, shaping future interpretations of company behaviour. This finding extends existing literature on procedural justice and stakeholder engagement. While early engagements are seen as good practice (Dare*,* Schirmer and Vanclay, 2014), the interviews reveal that even if conducted at early stages, tokenistic or poorly designed engagements can create enduring distrust that later corporate social responsibility (CSR) and compensatory measures struggle to repair. This was echoed by R6-GOS, who described early mining consultation in their areas as *'lip service only,'* supporting Dare*,* Schirmer and Vanclay (2014) and Owen and Kemp (2013), who argue that consultation often becomes procedural compliance that lacks meaningful participation.

From an energy justice perspective, procedural justice is undermined not only when communities are excluded outright, but when they are formally included through consultation structures that remain inaccessible, technically overwhelming, or already constrained by predetermined project pathways (Shejale *et al*, 2025; Heffron and de Fontenelle, 2023). R7-CM1's discussion of *'Development by Consent'* provides an important contrast here, arguing that *'meaningful legitimacy requires engagement before engineering*, *financing*, *and contractual decisions become fixed'*. This suggests that legitimacy deficits emerge when community feedback is not incorporated in project phases and consultation occurs after substantive decisions have already been made. Such pattern suggests that SLO in critical minerals is strongly path-dependent. Transition infrastructure is particularly vulnerable to this dynamic as legitimacy failures in one project can spill over into broader opposition toward renewable energy and associated infrastructure development (Wibisono *et al*, 2024; Ikejemba *et al*, 2017). Victoria shows this dynamic clearly that cumulative transition infrastructures are already pressuring its communities to view critical minerals activities through a lens of scepticism.

Place- and legacy-based legitimacy

Finally, across the ten interviews, the data revealed social licence is profoundly shaped by place-based histories, cultural identities, and regional experiences with extractive industries. Communities do not evaluate mining abstractly or uniformly. Rather, legitimacy is filtered through historical memory, economic dependence, and environmental and local attachment. For example, R6-GOS observed communities in Bendigo and Ballarat remain comparatively pro-mining because of '*longstanding cultural and economic ties to gold mining history'*. Similarly, R9-CM2 described mining as *'the soul'* of Western Australia's Kalgoorlie region and that *'if it dies*, *the whole region will collapse'*. Similar perspectives emerged independently in both states (Victoria and Western Australia) suggest that 'pro-mining' legitimacy may be shaped by historical memory, local investment and recognition of mining identity.

Conversely, community respondents who were from predominantly agricultural communities typically perceive critical mineral mining (and most mining operations) as incompatible with farming and environmental identities. Such pattern was found in Wimmera and East Gippsland, where communities oppose mining projects due to clashes with agricultural land, impacts on water resources, and issues related to dust and radioactivity. R2-FIN emphasised emotional attachment to place, explaining that residents *'chose to live in the region'* because they *'love this beautiful place.'* Similarly, 70 per cent of respondents explicitly framed mining as threatening to agricultural productivity, water and soil systems, tourism, and ecological integrity.

These findings strongly support the notion that SLO is inherently place-based and socially constructed through locally lived experiences and values. However, locally constructed legitimacy does not necessarily align with legitimacy assessed at a broader societal or national scale, where support may be shaped less by direct lived experience and more by commitments to broader energy transition and climate policy (Dare*,* Schirmer and Vanclay, 2014). This way, stakeholders who do not live, work, or directly benefit from a project's immediate locality can observe a form of legitimacy which is disconnected from local lived experience. What is acceptable in a single location may not be acceptable at other localities or at a broader societal scale (Pollard and Rose, 2019). The study findings also align with recognitional justice scholarship, which argues that legitimacy depends on acknowledging culturally specific relationships to land, heritage and livelihood (Whyte, 2017; Walker, 2012). Communities with long histories of mining exposure (ie in Ballarat) often evaluate risks differently from regions (ie in Wimmera) where extraction is perceived as externally imposed industrial disruption.

A major theme parallel to place-based legitimacy found is that communities assess social licence not only during approval processes, but through long-term evaluations of project legacies and delivered outcomes. Respondents emphasised that long-term mining legitimacy depends on whether promised benefits are materialised and socio-environmental impacts are managed over time. R5-DON argued that community trust depends on proponents *'delivering the promise on time'* of local infrastructure, employment and economic development. R4-FIN similarly criticised the *'absence of long-term health monitoring and baseline environmental data despite ongoing concerns about pollution exposure'*.

Importantly, many respondents expressed scepticism toward corporate promises relating to employment and economic growth. R5-DON criticised fly-in-fly-out (FIFO) and drive-in-drive-out (DIDO) workforce models for failing to deliver meaningful local economic participation while simultaneously intensifying housing and infrastructure pressures. R6-GOS similarly noted that *'modern mining technologies often reduce opportunities for local labour participation'*. This finding of 'promise delivery' strongly aligns with academic findings that SLO is a dynamic and continuously renegotiated process (Maonaigh, Fitzgerald and Reilly, 2025; Stronge, Kannemeyer and Edwards, 2024; Stuart *et al*, 2023). However, reservation to FIFO-DIDO workforce reveal a new finding that although employment benefits are a major incentive for mining approval, external workforce operating in local mining operations are not always welcomed.

The interviews also demonstrate that environmental legacies remain central to legitimacy evaluation. Respondents referred to concerns over water contamination, biodiversity loss, tailings management, and uncertainty in rehabilitation. Even where rehabilitation occurs, communities often perceive impacts on farmlands as irreversible which reflects broader concerns within just transition literature that sustainability narratives can externalise long-term ecological and social costs onto regional communities (Avelino *et al*, 2024; Stark, Gale and Murphy-Gregory, 2023).

CONCLUSION AND WAY FORWARD

As a parallel construct to legitimacy in energy and mining industries (Gehman, Lefsrud and Fast, 2017; Moffat and Zhang, 2014), SLO is often expected to follow the same legitimacy principles in critical mineral mining. However, the patterns identified in this study suggest SLO legitimacy is more complex where communities judge projects through relational trust, fairness and accountability instead of procedural consultation institutionalised as evidence for legitimacy. This disconnect shows a deeper legitimacy deficit in the way of energy transition: 'critical minerals' narrative is used to justify accelerated approvals due to its 'critical' nature, but its public consultation practices keep following the same procedural approach which has been creating tensions and community apathy in the form of 'not in my backyard' movement, especially in the renewables sector. Rather than licensing a genuine social licence, such approaches attempt to 'manage' community consent by treating SLO as a compliance artefact within ESG and CSR repertoires, fuelling public scepticism and indifference to both mining and the broader transition agenda. Consequently, the critical minerals industry will be another link in the chain of cumulative transition pressures. Rather than solving legacy issues and welcoming transition-led resource extraction, the industry is likely to contribute yet another bottleneck in the form of fossil fuels' path dependency and extractivism logics.

While this was a small sample, the insights signal tensions in addressing SLO in the future. This positions the need for research to examine the impact of current and future social licence practices in the critical minerals industry on Australia's transition landscapes and 2050 net-zero targets. While this paper gives a glimpse of how communities perceive and influence social licence in critical minerals, more nuanced studies could investigate how stakeholder engagement influences decision-making and benefit-sharing through SLO and how key actors interact in shaping it. To assess cumulative transition impacts, future research could also undertake a cumulative effects assessment (CEA) to assess the total potential impact of mining, renewables and transmission development using retrospective analyses to understand the *status quo* and prospective analysis to predict the potential future cumulative effects under different scenarios. While prospective CEA analysis can support future planning and decision-making, retrospective analysis can also examine how cumulative impacts emerged. That way, future critical mineral pathways could avoid reproducing the same governance tensions and public resistance that the transition seeks to overcome and instead offer a legitimacy-aware transition in Australia.

ACKNOWLEDGEMENTS

The study is part of an ongoing larger doctoral research project with ongoing data collection that examines the themes and dynamics of SLO in Australia's critical mineral industries for driving just energy transition. The doctoral research project also includes secondary analysis of parliament enquiry documents and industry reports.

FUNDING AND COMPETING INTERESTS

No external funding was sought or received for this work. There are no affiliations with or involvement in any organisation or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

REFERENCES

Astola, M, Laes, E, Bombaerts, G, Ryszawska, B, Rozwadowska, M, Szymanski, P, Ruess, A, Nyborg, S and Hansen, M, 2022. Community Heroes and Sleeping Members: Interdependency of the Tenets of Energy Justice, *Science and Engineering Ethics*, 28(5). https://doi.org/10.1007/s11948-022-00384-3

Astron, 2025. *The Donald Project*, Astron Corporation. Available from: <https://www.thedonaldproject.com.au/> [Accessed: 22 June 2025].

Avelino, F, Wijsman, K, van Steenbergen, F, Jhagroe, S, Wittmayer, J, Akerboom, S, Bogner, K, Jansen, E F, Frantzeskaki, N and Kalfagianni, A, 2024. Just Sustainability Transitions: Politics, Power and Prefiguration in Transformative Change Toward Justice and Sustainability, *Annual Review of Environment and Resources*, 49(1):519–547. https://doi.org/10.1146/annurev-environ-112321-081722

Braun, V and Clarke, V, 2006. Using thematic analysis in psychology, *Qualitative Research in Psychology*, 3(2):77–101. https://doi.org/10.1191/1478088706qp063oa

Braun, V and Clarke, V, 2021. One size fits all? What counts as quality practice in (reflexive) thematic analysis?, *Qualitative Research in Psychology*, 18(3):328–352. https://doi.org/10.1080/14780887.2020.1769238

Breakey, H, Wood, G and Sampford, C, 2025. Understanding and defining the social license to operate: Social acceptance, local values, overall moral legitimacy and 'moral authority', *Resources Policy*, vol 102. https://doi.org/10.1016/j.resourpol.2025.105488

Cash, D, 2025. ESG Ratings and the Social License to Operate: The Potential for the Misallocation of Trust, in *The Palgrave Handbook of Social License to Operate and Energy Transitions* (eds: J Górski and G Mete), Palgrave Studies in Energy Transitions, (Palgrave Macmillan: Cham). https://doi.org/10.1007/978-3-030-74725-1_16-1

CSIRO, 2024. *Australian attitudes toward mining*, Commonwealth Scientific and Industrial Research Organisation (CSIRO). Available from: <https://www.csiro.au/en/work-with-us/industries/mining-resources/social-and-environmental-performance/attitudes-to-mining-survey-report-2024> [Accessed: 31 August 2026].

Curran, G, 2017. Social licence, corporate social responsibility and coal seam gas: framing the new political dynamics of contestation, *Energy Policy*, 101:427–435. https://doi.org/10.1016/j.enpol.2016.10.042

Dare, M (Lain), Schirmer, J and Vanclay, F, 2014. Community engagement and social licence to operate, *Impact Assessment and Project Appraisal*, 32(3):188–197. https://doi.org/10.1080/14615517.2014.927108

de Fontenelle, L and Heffron, R J, 2023. The Power of Energy Justice for Rural Communities, *The Power of Energy Justice and the Social Contract* (Palgrave Macmillan: Switzerland).

de Villiers, C, Farooq, M B and Molinari, M, 2022. Qualitative research interviews using online video technology – challenges and opportunities, *Meditari Accountancy Research*, 30(6):1764–1782. https://doi.org/10.1108/MEDAR-03-2021-1252

Dumbrell, N P, Adamson, D, Zuo, A and Wheeler, S A, 2021. How do natural resource dependent firms gain and lose a social licence?, *Global Environmental Change*, 70. https://doi.org/10.1016/j.gloenvcha.2021.102355

Eabrasu, M, Brueckner, M and Spencer, R, 2021. A social licence to operate legitimacy test: Enhancing sustainability through contact quality, *Journal of Cleaner Production*, 293. https://doi.org/10.1016/j.jclepro.2021.126080

Fischer, A, Joosse, S, Strandell, J, Söderberg, N, Johansson, K and Boonstra, W J, 2024. How justice shapes transition governance – a discourse analysis of Swedish policy debates, *Journal of Environmental Planning and Management*, 67(9):1998–2016. https://doi.org/10.1080/09640568.2023.2177842

Franks, D M, Brereton, D and Moran, C J, 2010. Managing the cumulative impacts of coal mining on regional communities and environments in Australia, *Impact assessment and project appraisal*, 28(4):299–312. https://doi.org/10.3152/146155110X12838715793129

Fraser, J, 2021. Mining companies and communities: Collaborative approaches to reduce social risk and advance sustainable development, *Resources Policy*, 74. https://doi.org/10.1016/j.resourpol.2018.02.003

Gehman, J, Lefsrud, L M and Fast, S, 2017. Social license to operate: Legitimacy by another name?, *Canadian Public Administration*, 60(2):293–317. https://doi.org/10.1111/capa.12218

Geoscience Australia, 2025. *Critical Minerals at Geoscience Australia*, Geoscience Australia. Available from: <https://www.ga.gov.au/scientific-topics/minerals/critical-minerals> [Accessed: 15 July 2026].

Gippsland Critical Minerals, 2025. *GCM provides an update on Fingerboards Project rescoping including 12 initial design changes*, VMH Limited. Available from: <https://www.gippslandcriticalminerals.com/post/gcm-provides-an-update-on-fingerboards-project-rescoping-including-12-initial-design-changes> [Accessed: 22 July 2025].

Glückler, J and Gutiérrez, D, 2025. Social license to operate: an institutional critique and research framework, *Resources Policy*, 107. https://doi.org/10.1016/j.resourpol.2025.105657

Grimmelikhuijsen, S, de Vries, F and Bouwman, R, 2024. Regulators as Guardians of Trust? The Contingent and Modest Positive Effect of Targeted Transparency on Citizen Trust in Regulated Sectors, *Journal of Public Administration Research and Theory*, 34(1):136–149. https://doi.org/10.1093/jopart/muad010

Gurčinaitė, G and Barbrook-Johnson, P, 2026. From just transition pledges to policy practice: A participatory case study applying the Energy Justice Framework in early-stage transition planning in Vilnius, Lithuania, *Energy Research and Social Science*, 134. https://doi.org/10.1016/j.erss.2026.104618

Hall, N, Lacey, J, Carr-Cornish, S and Dowd, A M, 2015. Social licence to operate: understanding how a concept has been translated into practice in energy industries, *Journal of Cleaner Production*, 86:301–310. https://doi:10.1016/j.jclepro.2014.08.020

Healy, N and Barry, J, 2017. Politicizing energy justice and energy system transitions: Fossil fuel divestment and a 'just transition', *Energy Policy*, 108:451–459. https://doi.org/10.1016/j.enpol.2017.06.014

Heffron, R J and de Fontenelle, L, 2023. The Power of Procedural Justice in the Planning of Energy Projects, in *The Power of Energy Justice and the Social Contract* (Palgrave Macmillan: Switzerland).

Heffron, R J, 2020. The role of justice in developing critical minerals, *The Extractive Industries and Society*, 7(3):855–863. https://doi.org/10.1016/j.exis.2020.06.018

Ikejemba, E C X, Mpuan, P B, Schuur, P C and Van Hillegersberg, J, 2017. The empirical reality and sustainable management failures of renewable energy projects in Sub-Saharan Africa (part 1 of 2), *Renewable Energy*, 102:234–240. https://doi.org/10.1016/j.renene.2016.10.037

Jenkins, B R, 2018. Challenges in Cumulative Impact Assessment: Case Studies from canterbury, New Zealand, *WIT Transactions on Ecology and the Environment*, 215:25. https://doi.org/10.2495/EID180031

Jijelava, D and Vanclay, F, 2017. Legitimacy, credibility and trust as the key components of a social licence to operate: An analysis of BP's projects in Georgia, *Journal of Cleaner Production*, 140:1077–1086. https://doi.org/10.1016/j.jclepro.2016.10.070

Kennedy, E, 2023. *Swan Hill farmers raise concerns about impacts of VHM's Goschen mineral sands min*. Available from: <https://www.abc.net.au/news/2023-11-29/swan-hill-farmers-concerns-impact-vhm-goschen-mineral-sands-mine/103079646> [Accessed: 22 June 2025].

Khan, T H and MacEachen, E, 2022. An Alternative Method of Interviewing: Critical Reflections on Videoconference Interviews for Qualitative Data Collection, *International Journal of Qualitative Methods*, 21. https://doi.org/10.1177/16094069221090063

Lacey, J, 2021. *How social licence is driving innovation in the mining industry*, CSIRO. Available from: <https://www.csiro.au/en/news/all/articles/2021/february/how-social-licence-is-driving-innovation-in-the-mining-industry> [Accessed: 16 July 2026].

Laurence, D, 2021. The devolution of the social licence to operate in the Australian mining industry, *The Extractive Industries and Society*, 8(2). https://doi.org/10.1016/j.exis.2020.05.021

Lehtonen, M, Kojo, M, Kari, M, Jartti, T and Litmanen, T, 2022. Trust, mistrust and distrust as blind spots of Social Licence to Operate: illustration via three forerunner countries in nuclear waste management, *Journal of Risk Research*, 25(5):577–593. https://doi.org/10.1080/13669877.2021.1957987

Longhurst, R and Johnston, L, 2023. Semi-structured interviews and focus groups, in *Key Methods in Geography* (eds: N Clifford, M Cope, T Gillespie and S French), 4th edition, Thousand Oaks: Sage:168–183. https://hdl.handle.net/10289/15973

Maonaigh, C Ó, Fitzgerald, L M and Reilly, L, 2025. Revisiting the social licence to operate in the energy transition: An intersectional agenda for research and practice, *Energy Research and Social Science*, 126. https://doi.org/10.1016/j.erss.2025.104139

Meesters, M, Wostyn, P, van Leeuwen, J, Behagel, J H and Turnhout, E, 2021. The Social Licence to Operate and the legitimacy of resource extraction, *Current Opinion in Environmental Sustainability*, 49:7–11. https://doi.org/10.1016/j.cosust.2020.11.002

Mercer-Mapstone, L D, 2018. The role of dialogue in social licence to operate in the extractives sector, PhD thesis, Sustainable Minerals Institute, The University of Queensland. https://doi.org/10.14264/uql.2018.544

Moffat, K and Zhang, A, 2014. The paths to social licence to operate: An integrative model explaining community acceptance of mining, *Resources Policy*, 39:61–70. https://doi.org/10.1016/j.resourpol.2013.11.003

Moffat, K, Lacey, J, Zhang, A and Leipold, S, 2016. The social licence to operate: a critical review, *Forestry (London)*, 89(5):477–488. https://doi.org/10.1093/forestry/cpv044

Oh, C H, Shin, J and Ho, S S H, 2023. Conflicts between mining companies and communities: Institutional environments and conflict resolution approaches, *Business Ethics, the Environment and Responsibility (Print)*, 32(2):638–656. https://doi.org/10.1111/beer.12522

Owen, J R and Kemp, D, 2013. Social licence and mining: A critical perspective, *Resources Policy*, 38(1):29–35. https://doi.org/10.1016/j.resourpol.2012.06.016

Owen, J R, Kemp, D, Harris, J, Lechner, A M and Lèbre, É, 2022. Fast track to failure? Energy transition minerals and the future of consultation and consent, *Energy Research and Social Science*, 89. https://doi.org/10.1016/j.erss.2022.102665

Parsons, R and Moffat, K, 2014. Integrating impact and relational dimensions of social licence and social impact assessment, *Impact Assessment and Project Appraisal*, 32(4):273–282. https://doi.org/10.1080/14615517.2014.936107

Parsons, R, Lacey, J and Moffat, K, 2014. Maintaining legitimacy of a contested practice: How the minerals industry understands its 'social licence to operate', *Resources Policy*, 41:83–90. https://doi.org/10.1016/j.resourpol.2014.04.002

Planning Panels Victoria, 2023. *Avonbank Mineral Sands Project*. Available from: <https://www.planningpanels.vic.gov.au/__data/assets/pdf_file/0030/728382/Avonbank-Mineral-Sands-EES-IAC-Report.pdf> [Accessed: 23 July 2026].

Planning Victoria, 2024a. *Avonbank Mineral Sands*. Available from: <https://www.planning.vic.gov.au/environmental-assessments/browse-projects/avonbank-mineral-sands> [Accessed: 23 July 2026].

Planning Victoria, 2024b. *Stakeholder Consultation Plan Wimmera Project*. Available from: <https://www.planning.vic.gov.au/__data/assets/pdf_file/0035/719288/Wimmera-Project-EMM-S180481-EES-Consultation-Plan-Jul-2024-Rev5-Re-issued-for-Use.pdf> [Accessed: 23 July 2026].

Planning Victoria, 2025. *Wimmera mineral sands*. Available from: <https://www.planning.vic.gov.au/environmental-assessments/browse-projects/wimmera-mineral-sands> [Accessed: 23 July 2026].

Pollard, J A and Rose, D C, 2019. Lightning Rods, Earthquakes and Regional Identities: Towards a Multi-Scale Framework of Assessing Fracking Risk Perception, *Risk Analysis*, 39(2):473–487. https://doi.org/10.1111/risa.13167

Prno, J and Slocombe, S D, 2012. Exploring the origins of 'social license to operate' in the mining sector: Perspectives from governance and sustainability theories, *Resources Policy*, 37(3):346–357. https://doi.org/10.1016/j.resourpol.2012.04.002

Radtke, J and Renn, O, 2024. Participation in Energy Transitions: A Comparison of Policy Styles, *Energy Research and Social Science*, 118. https://doi.org/10.1016/j.erss.2024.103743

Radtke, J, 2025. E-participation in energy transitions: What does it mean? Chances and challenges within Germany's Energiewende, *Technological Forecasting and Social Change*, 210. https://doi.org/10.1016/j.techfore.2024.123839

Resources Victoria, 2025. *Fingerboards Mineral Sands Project*. Available from: <https://resources.vic.gov.au/community-and-land-use/key-site-updates/fingerboards-mineral-sands-project> [Accessed: 21 August 2025].

Resources Victoria, 2026. *Avonbank Mineral Sands Project*. Available from: <https://resources.vic.gov.au/landholders-and-community/key-site-updates/avonbank-mineral-sands-project> [Accessed: 23 July 2026].

Rosemberg, A, 2010. Building a Just Transition: The linkages between climate change and employment, *International Journal of Labour Research*, 2(2):125–161.

Saarijärvi, M and Bratt, E-L, 2021. When face-to-face interviews are not possible: tips and tricks for video, telephone, online chat and email interviews in qualitative research, *European Journal of Cardiovascular Nursing* : *Journal of the Working Group on Cardiovascular Nursing of the European Society of Cardiology*, 20(4):392–396. https://doi.org/10.1093/eurjcn/zvab038

Santiago, A L, Demajorovic, J, Rossetto, D E and Luke, H, 2021. Understanding the fundamentals of the Social Licence to Operate: Its evolution, current state of development and future avenues for research, *Resources Policy*, 70(March 2021). https://doi.org/10.1016/j.resourpol.2020.101941

Schnaudt, C, Hahn, C and Heppner, E, 2021. Distributive and Procedural Justice and Political Trust in Europe, *Political Science*, *Institut d'études politiques de paris - Sciences Po*, 3:642232. https://doi.org/10.3389/fpos.2021.642232

Scholz, R and Schuppert, F, 2025. Energy Justice: Caught Between a Lack of Clarity and Overloading?, *Ethics, Policy and Environment*, 18 p. https://doi.org/10.1080/21550085.2025.2517297

Self, B, 2021. Conducting interviews during the COVID-19 pandemic and beyond, *Forum*, *Qualitative Social Research*, 22(3):18–22:3<18. https://doi.org/10.17169/fqs-22.3.3741

Shejale, S, Zhan, M X, Sahakian, M, Aleksieva, R, Biresselioglu, M E, Bogdanova, V, Cardone, B, Epp, J, Kirchler, B, Kollmann, A, Liste, L, Massullo, C and Schibel, K-L, 2025. Participation as a pathway to procedural justice: A review of energy initiatives across eight European countries, *Energy Research and Social science*, 122. https://doi.org/10.1016/j.erss.2025.103982

Stark, A, Gale, F and Murphy-Gregory, H, 2023. Just Transitions' Meanings: A Systematic Review, *Society and Natural Resources*, 36(10):1277–1297. https://doi.org/10.1080/08941920.2023.2207166

Stronge, D C, Kannemeyer, R L and Edwards, P, 2024. Building social licence to operate: A framework for gaining and maintaining meaningful, trustworthy relationships, *Resources Policy*, 89. https://doi.org/10.1016/j.resourpol.2023.104586

Stuart, A, Bond, A, Franco, A M A, Baker, J, Gerrard, C, Danino, V and Jones, K, 2023. Conceptualising social licence to operate, *Resources Policy*, 85. https://doi.org/10.1016/j.resourpol.2023.103962

The Treasury, 2024. *Future Made in Australia*, Australian Government. Available from: <https://treasury.gov.au/policy-topics/future-made-australia> [Accessed: 14 July 2026].

The Weekly Times, 2024. *State minister gives wheatbelt mines a green light.* Available from: <https://www.weeklytimesnow.com.au/news/victoria/state-minister-gives-wheatbelt-mines-a-green-light/news-story/bb44883ae7190c1ffe052f2c286d157b> [Accessed: 23 July 2026].

Thomson, I and Boutilier, R G, 2011. Social License to Operate, in *SME Mining Engineering Handbook* (ed: P Darling), pp 673–690 (Engelwood: Society for Mining, Metallurgy and Exploration).

Tulve, N S, Geller, A M, Hagerthey, S, Julius, S H, Lavoie, E T, Mazur, S L, Paul, S J and Frey, H C, 2024. Challenges and opportunities for research supporting cumulative impact assessments at the United States environmental protection agency's office of research and development, *Lancet Regional Health – Americas (Online)*, 30. https://doi.org/10.1016/j.lana.2023.100666

van der Kooij, P, 2025. Putting the three-tenets energy justice framework into policy practice: A case study in the Netherlands, *Energy Research and Social Science*, 127. https://doi.org/10.1016/j.erss.2025.104300

Van Uffelen, N, Taebi, B and Pesch, U, 2024. Revisiting the energy justice framework: Doing justice to normative uncertainties, *Renewable and Sustainable Energy Reviews*, vol 189. https://doi:10.1016/j.rser.2023.113974

Victorian Farmers Association, 2024. *Goschen sand mine development highlights broken EES*. Available from: <https://www.vff.org.au/goschen-sand-mine-development-highlights-broken-ees/> [Accessed: 22 July 2025].

VMH, 2025. *The Goschen Project*: *A Critical Minerals Asset Shaping Tomorrow*, VMH Limited. Available from: <https://www.vhmltd.com.au/projects/the-goschen-project/> [Accessed: 22 July 2025].

Walker, G, 2012. *Environmental Justice*: *Concepts*, *Evidence and Politics* (Routledge: London). https://doi.org/10.4324/9780203610671

Wang, L, Awuah-Offei, K, Que, S and Yang, W, 2016. Eliciting Drivers of Community Perceptions of Mining Projects through Effective Community Engagement, *Sustainability*, 8(7):658. https://doi.org/10.3390/su8070658

Whyte, K, 2017. Indigenous Climate Change Studies: Indigenizing Futures, Decolonizing the Anthropocene, *English Language Notes*, 55(1–2):153–162. https://doi.org/10.1215/00138282-55.1-2.153

Wibisono, H, Lovett, J, Chairani, M S and Suryani, S, 2024. The ideational impacts of Indonesia's renewable energy project failures, *Energy for Sustainable Development*, 83. https://doi.org/10.1016/j.esd.2024.101587

Deep sea tailings placement – regulatory trends, evolving environmental, social and governance practices and financing implications

L Rollin[1] and K Vershinina[2]

1. Principal Consultant (ESG), SRK Consulting (Australasia) Pty Ltd, Perth WA 6005. Email: lrollin@srk.com.au
2. Principal Consultant (ESG), SRK Consulting (Australasia) Pty Ltd, Brisbane Qld 4000. Email: kvershinina@srk.com.au

ABSTRACT

Marine tailings disposal, including Deep Sea Tailings Placement (DSTP) and shallow-water submarine tailings disposal, is used as an alternative to land-based tailings storage where onshore options are constrained by climate, topography, land availability, biodiversity, or social impacts. For some critical minerals' projects, DSTP is considered a technically feasible option. However, DSTP is increasingly contested by regulators, investors, non-government organisations, communities, and downstream supply chains due to uncertainties about deep-sea ecosystems, long-term impacts and the difficulty of monitoring and remediation once waste is placed on the sea floor.

This paper synthesises recent international experience from current and proposed DSTP operations in Papua New Guinea, Indonesia, Turkey and Norway, alongside global policy developments such as the London Protocol, regional guidance in the Pacific and the European Union's Best Available Techniques reference documents, and the 2016 International Union for Conservation of Nature (IUCN) resolution calling for an end to sea disposal of extractive waste. It examines how lender, industry, and supply chain standards (including International Finance Corporation / World Bank Group (IFC/WBG), International Council on Mining and Metals (ICMM), Global Industry Standard on Tailings Management (GISTM), Mining Association of Canada / Towards Sustainable Mining (MAC/TSM), Initiative for Responsible Mining Assurance (IRMA), the Copper Mark, the World Gold Council, and the Responsible Jewellery Council) are reshaping the acceptability and financing of marine tailings disposal.

The analysis highlights rising legal, environmental, social, and reputational risks for new DSTP projects, including litigation, permitting challenges, community opposition, and potential constraints on access to capital and premium markets. In response, the paper proposes a practical framework for DSTP built around eight pillars: alignment with good international industry practice, structured stakeholder engagement, rigorous comparative environmental and social impact assessment of all tailings options, robust environmental and social management planning, comprehensive monitoring and reporting, clear closure and post-closure strategies, independent expert review and regulatory compliance. The paper concludes that marine tailings disposal should only be used where it demonstrably presents a lower overall risk profile than terrestrial alternatives and is implemented with high levels of transparency and accountability.

Digital frontiers – the impact of artificial intelligence and machine learning on Indigenous participation, economic success, sovereignty and knowledge protection

M Saylor[1] and M Case[2]

1. Community and Social Performance Lead APAC, Bechtel Mining and Metals, Fortitude Valley Qld 4006. Email: msaylor@bechtel.com
2. Manager of Sustainable Development, Bechtel Mining and Metals, Guildford WA 6055. Email: mcase@bechtel.com

ABSTRACT

The rapid advancement of artificial intelligence (AI) and machine learning (ML) is reshaping industries, economies and societies. For Indigenous peoples, these technologies offer new opportunities alongside significant risks. This paper examines how AI and ML affect Indigenous participation in the digital economy, economic pathways, sovereignty, and the protection of Indigenous cultural and intellectual property (ICIP). It considers benefits including new forms of enterprise, language revitalisation, and data-informed decision-making in areas such as mining, resource management and cultural heritage protection.

In the mining industry, where Bechtel operates globally, AI-enabled tools are increasingly influencing project delivery, operational efficiency and sustainability outcomes. Linking Indigenous considerations to this context is essential so innovation aligns with equity and cultural respect. At the same time, AI and ML can entrench harm through data sovereignty breaches, algorithmic bias, and misappropriation or commodification of traditional knowledge. Without robust governance and meaningful Indigenous involvement, these technologies may perpetuate historical inequities and undermine rights.

Drawing on case studies from Australia and the Asia-Pacific, the paper analyses how Indigenous communities are engaging with AI and ML, the barriers they face, and emerging strategies to assert control over data, algorithms and knowledge systems. It emphasises culturally informed governance, ethical AI design and Indigenous-led participation in technology development. The analysis also considers international and emerging frameworks, including the United Nations Declaration on the Rights of Indigenous Peoples, relevant WIPO instruments on intellectual property, genetic resources and associated traditional knowledge, and digital rights approaches.

The paper argues that responsible application of AI and ML grounded in Indigenous values and rights is essential to achieve equitable, sustainable and culturally respectful outcomes in the digital age.

Markets and finance

An investor perspective on critical minerals opportunities

R Breaden[1]

1. Investment Director, Critical Minerals Queensland, Brisbane Qld 4002.
   Email: ralph.breaden@nrmmrrd.qld.gov.au

ABSTRACT

Critical minerals investment in 2026 is being reshaped by geopolitics, supply chain concentration, price volatility and intensified competition for secure supply. For project proponents, capital is no longer attracted by resource quality alone. Investors and offtakers increasingly require credible pathways to development, clear risk mitigation, strong environmental and social credentials, and a compelling investment proposition tailored to their mandate.

This paper examines the changing investor landscape for critical minerals, distinguishing between offtakers, financial investors and hybrid strategic partners. It argues that successful projects will be those that translate geological opportunity into bankable investment narratives, supported by practical development roadmaps, transparent funding requirements and evidence of jurisdictional certainty.

Drawing on Queensland's critical minerals context, the paper highlights the role of government in reducing pre-investment uncertainty, improving project readiness and helping proponents engage targeted investors in a crowded global market. The central proposition is simple: capital flows to confidence. Projects that can demonstrate value, credibility and delivery capability are best placed to progress from exploration and development towards final investment decision.

INTRODUCTION

Critical minerals have moved from a specialist mining and processing opportunity to a strategic and sovereign concern for governments, manufacturers and investors.

Their role in clean energy technologies, defence capability, digital infrastructure and advanced manufacturing has made reliable access a matter of economic security. At the same time, the investment environment has become more complex. Supply chains are concentrated, governments are introducing new export measures and strategic partnerships, and investors are seeking projects that can demonstrate both technical merit and a credible path to market.

INVESTING IN A GEOPOLITICALLY CHANGED WORLD

In 2026, critical minerals are at the centre of global investment strategies, driven by their essential role in advanced technologies, including decarbonisation programs. The geopolitical landscape has shifted significantly, with nations and corporations prioritising the diversification of supply chains and securing access to these vital resources amidst rising tensions and resource nationalism.

Geopolitical risks have increased significantly and are now a core consideration, with supply chains being complicated by export restrictions in key producing countries. These tensions between major powers are creating uncertainty in global markets and driving support for projects in trusted jurisdictions.

Investors are also impacted by shifts in the environmental and social landscapes, where mining projects must demonstrate community acceptance, responsible development pathways, regulatory readiness and capability to manager social licence risk.

Mining projects are also increasingly facing supply chain bottlenecks due to processing capacity for critical minerals being highly concentrated in a few countries. Investors, who have a choice on where they place their funds, need to be assured that these vulnerabilities, as well as the price volatility they generate, can be mitigated.

WHO IS INVESTING IN 2026

Investing in 2026 is influenced by the current geopolitical landscape, which is shaped by a range of global challenges, including economic uncertainty, geopolitical tensions, climate change, and technological advancements.

Investment interest is increasingly coming from three overlapping groups:

1. Offtakers seeking secure supply.
2. Pure financial investors seeking long-term exposure to strategic commodities.
3. Hybrid partners that combine capital with supply chain participation.

Offtaker

Is a guaranteed buyer of the critical minerals produced by a mining project. In a geopolitically charged world, offtakers aim to secure a stable and reliable supply of critical minerals to mitigate risks such as geopolitical tensions, trade restrictions, and supply chain disruptions.

An offtake agreement is a legally binding contract between the mining company and the offtaker. It specifies the quantity, quality, price, and delivery schedule of the critical minerals.

Types of offtakers include end-users who need critical minerals for their products, traders and intermediaries that resell commodities to end-users or other markets and governments who often secure strategic reserves of critical minerals for national security and economic resilience.

Pure investors

A pure investor is seeking long-term growth or potential future revenue streams. In the past investors typically only invested in late-stage projects, however given the race to secure critical minerals supply chains, over the last 18 months, there is an increasing focused effort to pick early-stage players that will deliver longer term results.

In 2026 the investment is predominantly coming from:

- *Sovereign Wealth Funds (SWFs):* countries with significant natural resource wealth, such as Norway, Saudi Arabia, and the UAE, continue to use their SWFs to diversify their economies and invest in global markets. Focus areas include renewable energy, technology, and infrastructure projects.
- *Institutional Investors:* pension funds, insurance companies, and endowments remain major players, seeking long-term, stable returns. They are increasingly prioritising Environmental, Social, and Governance (ESG) criteria in their investment decisions.
- *Private Equity and Venture Capital Firms:* targeting emerging technologies such as artificial intelligence, quantum computing, biotechnology, and clean energy. Start-ups in regions like Southeast Asia, Africa, and Latin America are attracting attention due to growth potential.
- *Retail Investors:* with the rise of digital platforms and democratisation of finance, retail investors are more active than ever. Many are exploring cryptocurrencies, decentralised finance (DeFi), and thematic ETFs (eg climate tech, space exploration).
- *Government and Multilateral Organisations:* investing heavily in infrastructure, defence, and renewable energy to address climate change and geopolitical risks. Multilateral organisations like the World Bank and Asian Development Bank are funding sustainable development projects.

Offtakers and strategic partnerships

In 2026 many large global corporate groups are directly negotiating to secure their future offtaker needs and hybrid investment models are becoming more common. Some of the majors are expressing interest to secure off take commitments many years into the future, given the current and projected geopolitical instability that is causing major global manufacturing companies to self-secure critical minerals needs.

More often, offtakers and investors are engaging earlier, increasingly entering into early-stage offtake agreements or providing upfront funding to mining companies, securing supply before production begins. These prepayment agreements provide upfront capital to mining companies that helps cover exploration, feasibility studies, and initial development costs.

Offtakers are also forming joint ventures or strategic alliances with mining companies to co-develop projects, ensuring a direct stake in the project and its output. Some companies, particularly automakers and battery manufacturers, are vertically integrating by acquiring stakes in mining companies or developing their own mining operations. This reflects a broader shift from passive investment to active supply chain participation, where investors seek not only financial return but also security of supply, downstream optionality and strategic influence.

Investment companies, including private equity firms, venture capital funds, and sovereign wealth funds, are increasingly investing in early-stage exploration and development projects. The investment takes many forms including equity investors who are taking equity stakes in junior mining companies or early-stage projects, private-public partnerships where investment firms collaborate with governments to co-fund critical mineral projects, particularly in regions with untapped resources.

Notably, investors are still prioritising projects that adhere to ESG standards, recognising that sustainable mining practices are critical for long-term profitability and regulatory compliance. Of course this said, the governing factor remaining tis hat that high cost ESG projects may not secure finding unless a substantial subsidy keeps the overall cost competitive.

WHAT A PROJECT NEEDS TO DO IN 2026 TO SECURE INVESTMENT

What a project needs to do to secure investment depends heavily on which stage of the mining life cycle the project is at.

There are often no shortage of investors or money for key in-demand projects that are close to production. When a project is close to Final Investment Decision, full investment options are aplenty because technical, permitting and market risks are better understood.

The closer you are to production the easier it is to choose and secure investment. Earlier-stage projects face narrower pool of capital and must therefore present a sharper investment proposition.

At the earlier stage, success depends on differentiating your project. Investors need to understand why the project matters, why it is developable, why the jurisdiction is competitive and why the proponent has the capability to move from exploration to delivery. A strong investment story must be grounded in evidence, not aspiration.

Investors want to see mining operations that have a clear pathway in an acceptable time frame. Here in Queensland, the government can help reduce pre-investment uncertainty by supporting project readiness and improving access to baseline data to shorten development time frames and accelerate the pathway for projects in our Critical Mineral Zones. The key is to make it easy for investors.

The state government has also implemented policies to streamline approvals, reduce red tape and provide clear timelines for project development.

The independent Coordinator-General has wide-ranging powers to drive projects forward and support common-user infrastructure. For example, if a resource project is declared to be a prescribed project, it activates the Coordinator-General's powers under the State Development and Public Works Organisation Act 1971. These powers ensure the planning and approval of projects is coordinated across government, and for priority projects, a coordinated whole of government assessment team will further streamline complex approvals and remove barriers quicker.

This strong case management approach, together with targeted investment facilitation and a dedicated investment readiness program will equip these companies to present investment-ready opportunities and attract capital into Queensland. These policies provide increased certainty for investors and positions Queensland as a preferred destination for investment in mining, processing, refining, manufacturing and export of resources.

In addition, Queensland takes a proactive approach to accelerating projects. Some examples of this are the Queensland government's commitment of $250 million to the Queensland Critical Minerals

Fund through the Queensland Investment Corporation (QIC), the state's sovereign wealth fund provider, to support critical minerals projects. This funding package is designed to catalyse private sector investment and ensure Queensland remains competitive in the global market. Other examples are the upgrades to the Mount Isa Rail Line, construction of CopperString, investment in enabling infrastructure and capability like the Queensland Resources Common User Facility in Townsville and the Flexi-Lab at Mackay's Resources Centre of Excellence.

These actions strengthen Queensland's reputation as a stable, investment-ready jurisdiction and a reliable partner in supply chains. Accelerating the investment decision and getting the optimal attention from investors in a cluttered market also requires high quality collateral from miners that is tailored for the audience – no two investors are alike! This collateral needs to extend beyond a technical project summary to include a development roadmap so investors can visualise a clear pathway forward through permits and approvals, and a clear articulation of the funding requirements so investors can see how they can participate in the project.

Capital flows to confidence. Projects that demonstrate their value to investment partners are more likely to attract funding and progress to final investment decision. A compelling investment story can be just as important as the quality of the resource itself. For this reason, it is essential to identify the key capabilities within your project team, including who is responsible for shaping and communicating the investment proposition and who will lead the project through development and delivery. While these roles are equally important, they often require different skills and may be carried out by different people.

Targeted engagement remains essential. Events such as IMARC, Noosa Mining conference and AusIMM's Critical Minerals Conference provide opportunities for proponents to test their story, meet aligned investors and build strategic relationships. The most successful engagement is deliberate, investor-specific and supported by collateral that speaks directly to the investor's mandate.

CONCLUSION

Critical minerals investment is no longer secured by resource potential alone. In a more contested and selective global market, projects must build confidence by demonstrating a credible development pathway, clear funding requirements, strong environmental and social credentials, and targeted engagement with the right investors and offtakers. Queensland's opportunity lies in helping proponents convert geological strength into bankable propositions that reduce uncertainty, attract strategic capital and accelerate progress towards Final Investment Decision.

ACKNOWLEDGEMENTS

The author acknowledges the contributions of Critical Minerals Queensland and Queensland Government partner agencies involved in the support of mining project investment attraction initiatives.

Achieving bankability in critical mineral projects – integrating market, offtake and financing considerations

G R Goenka[1]

1. Principal, Pacific Continental Resources, Kolkata, West Bengal 700071, India.
   Email: govind.goenka@outlook.com

ABSTRACT

Critical Mineral projects are often technically credible yet remain difficult to finance. Conventional bankability assessments emphasise resource confidence, metallurgy, engineering studies and financial metrics. These remain essential, but they do not fully address the commercial and strategic uncertainties that now shape investment decisions. This paper argues that modern bankability is created through the integration of technical readiness, commercial readiness, market alignment, offtake strategy, strategic financing and environmental, social and governance preparedness. Early customer engagement can validate product specifications and demand; appropriately structured offtake can improve revenue visibility; and strategic investors can contribute capital, market access and downstream alignment. The paper also considers India's emerging role as a major industrial consumer and potential long-term partner in global Critical Mineral supply chains. An integrated framework is proposed to help developers identify and close bankability gaps throughout the project-development cycle. The central proposition is that bankability is not a single feasibility-stage milestone, but a progressive process of reducing technical, commercial and strategic uncertainty.

INTRODUCTION

The global shift towards electrification, renewable energy, energy storage and advanced manufacturing has increased the strategic importance of lithium, graphite, rare earth elements, nickel, cobalt and copper. This demand outlook has encouraged a large pipeline of exploration and development projects. Yet many projects with credible resources and positive technical studies still struggle to secure construction capital.

The underlying difficulty is that a technically feasible project is not automatically a financeable project. Traditional assessment focuses on resource and reserve confidence, metallurgical performance, mine and process design, capital and operating costs, and economic indicators such as net present value and internal rate of return. These measures demonstrate whether a project can work under stated assumptions. Investors and lenders must additionally determine whether the product can be sold at the required quality and volume, whether future revenue is sufficiently visible, whether the logistics chain is executable, and whether the project is aligned with durable industrial demand.

Critical Mineral markets intensify these questions. Product specifications may be customer-specific; pricing can be opaque or volatile; qualification periods can be lengthy; and geopolitical considerations increasingly influence investment and procurement. As a result, market access, customer validation, offtake structure and strategic partnerships are becoming central to investment readiness rather than matters to be addressed only after completion of a feasibility study.

This paper examines that shift and proposes an integrated approach to bankability. It first explains how bankability has expanded beyond conventional technical and financial analysis. It then considers the role of customer engagement, offtake and strategic financing, including the opportunity presented by India's growing industrial demand. Finally, it presents a practical framework through which project developers can coordinate technical, commercial, financial and ESG workstreams from an early stage.

Contribution of this paper

This paper extends the conventional concept of project bankability beyond technical and financial feasibility by proposing the Integrated Bankability Framework (IBF) for Critical Mineral projects. The framework integrates technical readiness, commercial readiness, market validation, offtake strategy, financial preparedness and ESG considerations into a unified approach for improving investment

readiness. It provides a practical decision-support framework for project developers, investors, lenders and strategic partners.

THE EVOLVING CONCEPT OF BANKABILITY

Conventional mining finance is built on a logical sequence: define the resource, demonstrate metallurgical recovery, select an engineering solution, estimate capital and operating costs, and test the resulting cash flows. Pre-feasibility and definitive feasibility studies consolidate this evidence and remain indispensable. However, Critical Mineral projects often face a second category of risk that technical studies alone cannot resolve: uncertainty over product acceptance, market entry and revenue durability.

This distinction is important. Geological and engineering work can establish that a saleable product should be produced, but commercial evidence is needed to establish who will buy it, under what specification, in what quantity and on what terms. A project may therefore possess a robust resource and attractive modelled economics while remaining exposed to customer-qualification risk, an untested marketing strategy or an underdeveloped logistics chain. Such gaps can materially affect financing decisions.

Modern bankability consequently combines three forms of readiness. Technical readiness concerns the resource, metallurgy, engineering, infrastructure and execution plan. Commercial readiness concerns product quality, customer validation, logistics, contracting and the credibility of the route to market. Strategic alignment concerns the project's relevance to resilient supply chains, downstream industrial priorities and the objectives of potential investors or government-backed partners. Financial readiness sits across all three: the capital structure must reflect the risks that remain and the parties best positioned to absorb them.

The practical implication is that commercial work should not be postponed until the technical program is nearly complete. Early engagement with prospective customers can influence test work programmers, product design, impurity thresholds, packaging and transport arrangements. This feedback can prevent technically successful but commercially misaligned development choices. It also creates evidence that the project team understands the market in which the proposed operation must compete.

Bankability should therefore be treated as an accumulating body of evidence rather than a binary status. Each development stage should reduce a different set of uncertainties: drilling reduces geological uncertainty; metallurgical work reduces process uncertainty; customer qualification reduces product risk; offtake improves revenue visibility; and strategic investment can strengthen both funding capacity and market access. The combined effect is more persuasive than any element considered in isolation. This evolution is illustrated in Figure 1.

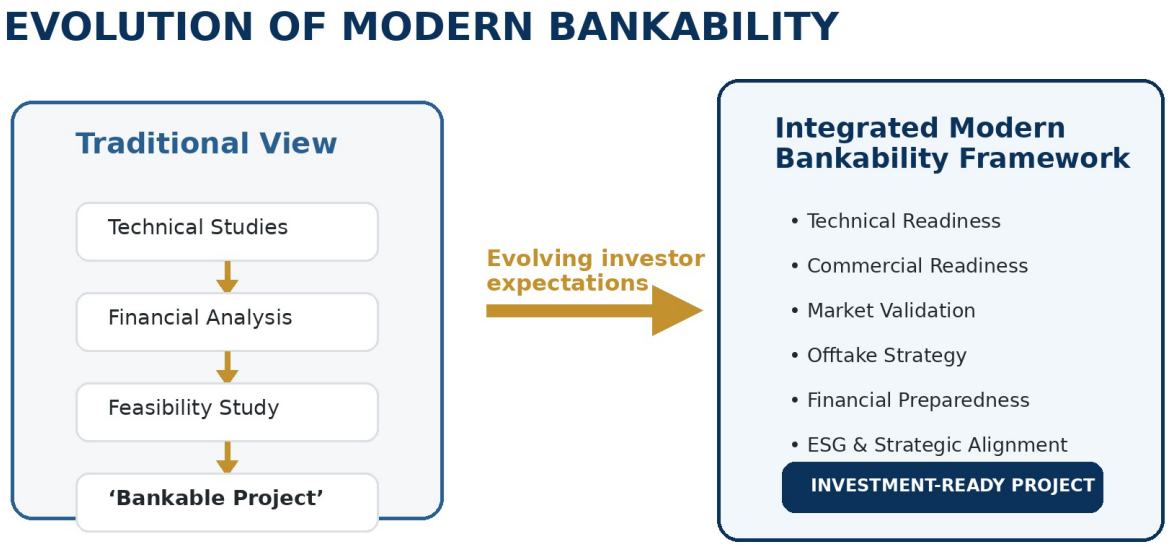


FIG 1 – Evolution of modern bankability from a predominantly technical-financial assessment to an integrated assessment of technical, commercial and strategic readiness.

STRATEGIC FINANCING, OFFTAKE AND MARKET ALIGNMENT

The financing landscape for Critical Minerals now includes a wider group of participants than conventional equity investors and commercial lenders. Downstream manufacturers, battery and technology companies, trading organisations, sovereign entities and government-supported institutions increasingly invest to secure long-term access to raw materials. Their objectives may include supply security, product traceability, geographic diversification, technology access or the development of an integrated value chain.

For developers, this creates financing options that are not available through a purely commodity-market approach. A strategic investor may accept a different risk-return profile where the project provides an important supply-chain benefit. It may also contribute technical expertise, customer access, qualification support or a credible route to market. Such participation is most valuable when aligned with the project's development requirements rather than introduced only as a late-stage funding solution.

Offtake agreements can support this alignment, but their bankability value depends on structure and counterparty quality. A credible agreement can demonstrate market acceptance, provide information on future sales volumes and strengthen lender confidence. It can also assist with product qualification and operating planning. Conversely, an agreement containing uncertain pricing, weak performance obligations or excessive restrictions may add little financing value and may limit future flexibility. Offtake should therefore be designed as part of the financing strategy, with careful attention to price mechanisms, tenor, volume, quality, credit support and termination rights.

A staged pathway is often more effective than attempting to secure a definitive long-term contract before the project has generated sufficient technical evidence. Initial market mapping can identify priority customers and specification requirements. Samples and test work can then support technical validation, followed by non-binding cooperation, qualification programmes, conditional offtake and, where appropriate, strategic equity or debt participation. Each step should correspond to the project's maturity and should reduce a specific financing uncertainty.

India is increasingly relevant within this pathway. Its national Critical Minerals programme explicitly addresses long-term supply, overseas asset acquisition and value-chain development. Indian public-sector enterprises and private industrial groups can therefore be potential customers, minority investors, technology partners and long-term offtakers. For overseas project developers, engagement with India may diversify both capital and demand while supporting bilateral supply-chain resilience. Effective engagement nevertheless requires a clearly defined product proposition, realistic project milestones and an investment structure suited to the mandate of the prospective Indian partner.

INTEGRATED BANKABILITY FRAMEWORK (IBF) FOR CRITICAL MINERAL PROJECTS

Building on the progressive reduction of uncertainty illustrated in Figure 2, the Integrated Bankability Framework (IBF) provides a structured approach for coordinating the technical, commercial, financial and strategic activities required to achieve investment readiness.

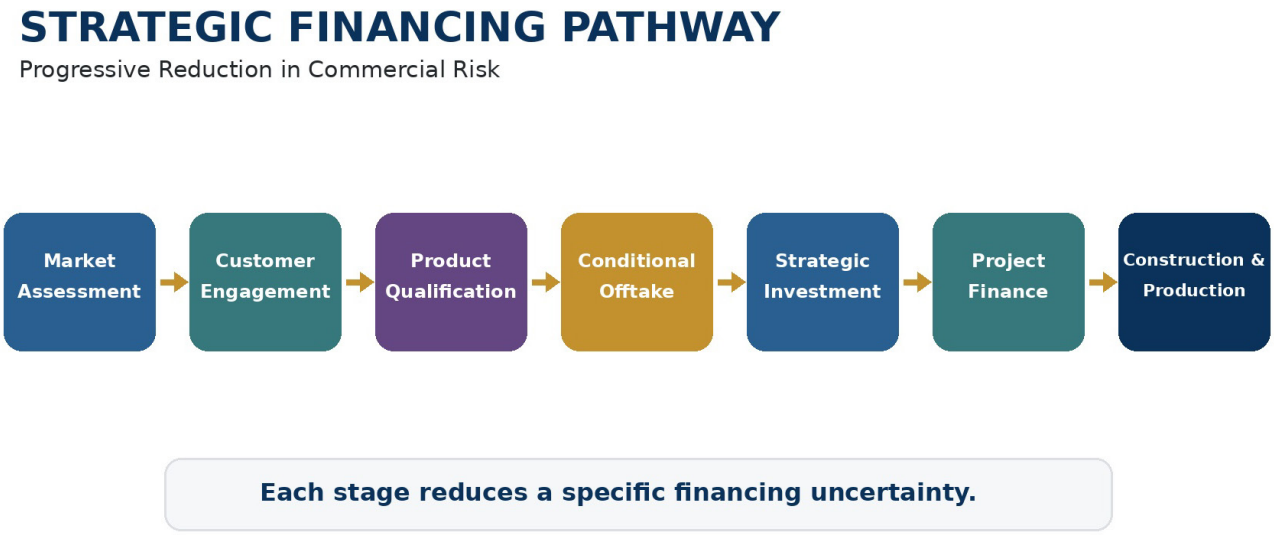


FIG 2 – A staged strategic-financing pathway in which customer engagement, product validation, offtake and investment progressively reduce commercial uncertainty.

Technical readiness remains the foundation. The resource model, mining method, metallurgical flow sheet, infrastructure plan and execution strategy must be sufficiently robust for the relevant investment stage. However, technical choices should be informed by market evidence. Product quality, recoveries and operating parameters have greater financing relevance when linked to identifiable customer requirements and realistic sales assumptions.

Commercial readiness converts a technically defined product into a credible market proposition. It includes customer segmentation, sample testing, qualification, competitor analysis, logistics, marketing capability and contracting strategy. The key question is not merely whether demand exists in aggregate, but whether the project has a defensible route to the customers most likely to purchase its specific product.

Offtake and strategic partnerships provide a bridge between commercial evidence and capital. Properly structured agreements can strengthen revenue confidence, while strategic investors can contribute capital, technology, and market access or policy alignment. The project should retain sufficient flexibility to manage price cycles and future customers; therefore, the value of certainty must be balanced against concentration, pricing and contractual risk.

Financial preparedness requires a capital strategy matched to the project's maturity and residual risks. Early stages may rely on sponsor equity, grants or strategic seed capital. Later stages may combine strategic equity, prepayments, export-credit support, government-backed facilities and conventional project debt. Financing should be sequenced so that each tranche funds the evidence required for the next decision point.

ESG and jurisdictional readiness cut across every dimension. Permitting, community acceptance, environmental performance, governance, traceability and regulatory stability can determine whether technical and commercial value is financeable. These matters should be integrated into project design and stakeholder engagement rather than addressed as a compliance exercise after major development decisions have been made.

The framework can be applied through a stage-gate review. At each gate, the developer should identify the technical, commercial, strategic, financial and ESG evidence required for the next commitment of capital. Gaps should be assigned to specific work programmes, counterparties and decision dates. This approach creates a transparent investment-readiness plan and allows management to direct limited resources towards the risks most likely to delay financing. The resulting structure is illustrated in Figure 3. The five dimensions and their contribution to bankability are summarised in Table 1.

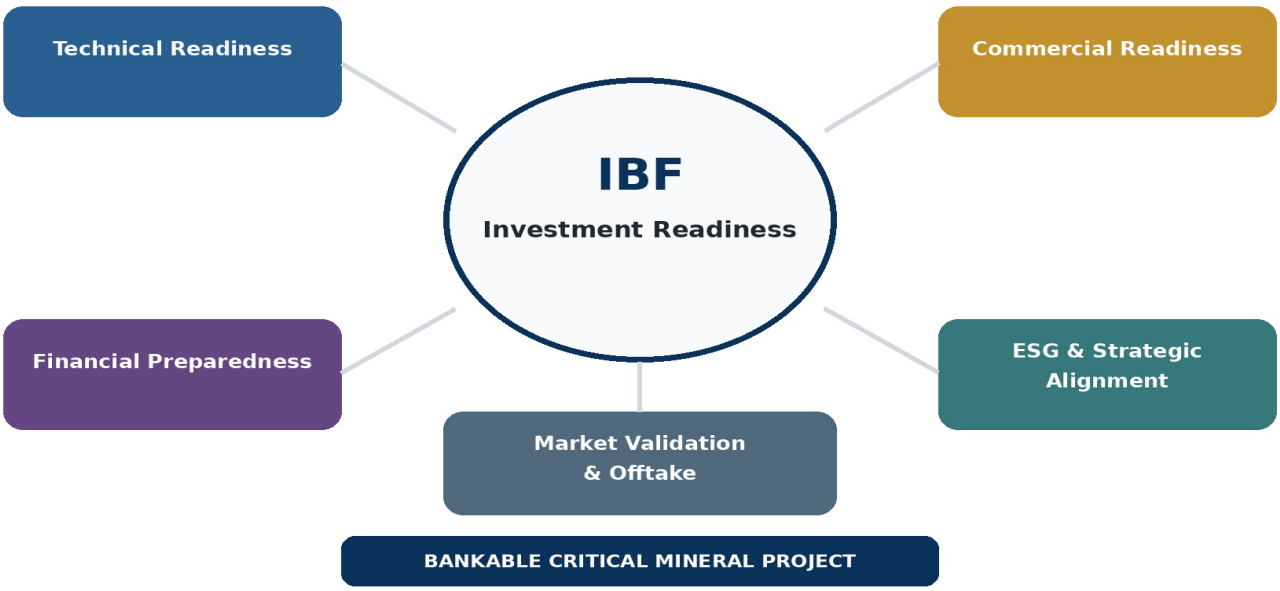


FIG 3 – Integrated Bankability Framework (IBF) illustrating the five mutually reinforcing dimensions required to achieve investment-ready Critical Mineral projects.

TABLE 1

Summary of the Integrated Bankability Framework (IBF).

IBF dimension	Primary objective	Representative evidence	Contribution to bankability
Technical Readiness	Demonstrate that the project is technically feasible and executable	Resource estimates, metallurgical test work, mine design, engineering studies, infrastructure planning	Reduces geological and technical uncertainty
Commercial Readiness	Demonstrate that the product can be successfully marketed and delivered	Customer engagement, product qualification, logistics strategy, market analysis, contracting strategy	Reduces market acceptance and execution risk
Market Validation and Offtake	Improve confidence in future revenues and product demand	Customer qualification, conditional or binding off take agreements, pricing framework, sales strategy	Reduces revenue uncertainty and strengthens lender confidence
Financial Preparedness	Develop a financing strategy appropriate to project maturity	Capital structure, financial model, staged financing plan, strategic investors, project finance	Improves investment readiness and financing capability
ESG and Strategic Alignment	Ensure long-term sustainability and strategic relevance	Environmental approvals, social licence, governance, traceability, jurisdictional stability	Enhances investor confidence and long-term project resilience

PRACTICAL IMPLICATIONS AND CONCLUSIONS

For project developers, the framework suggests four practical priorities. First, commercial engagement should begin early enough to influence technical design, but only after the project can present a credible and well-defined product proposition. Second, customer and investor discussions

should be organised around explicit development milestones: sample availability, qualification, feasibility completion, permitting, construction readiness and production ramp-up. Third, offtake should be evaluated for its contribution to financing rather than its headline volume alone. Fourth, the capital strategy should recognise that different investors can absorb different risks and contribute different forms of value.

The framework is also relevant to investors and industrial consumers. A structured assessment of technical, commercial, strategic, financial and ESG readiness can reveal whether a project's principal weakness is the resource, the execution plan, the route to market, the proposed transaction or the jurisdiction. This distinction supports more targeted due diligence and enables investors to determine whether identified gaps can be resolved through capital, technical assistance, contracting or partnership.

For countries and institutions seeking resilient supply chains, the framework provides a basis for engaging projects before they become fully financed. Strategic participation can be most influential during the period when product specifications, processing options, logistics and market structures are still being established. India, in particular, can use its scale as an industrial market to develop long-term relationships that combine minority investment, technology collaboration, product qualification and secure supply.

The central conclusion is that modern bankability is broader than technical feasibility and modelled financial returns. It is the progressive reduction of uncertainty across an interconnected set of technical, commercial, strategic, financial and ESG dimensions. A feasibility study remains essential, but it becomes more persuasive when supported by evidence of customer acceptance, an executable route to market, credible revenue arrangements, appropriately structured capital and responsible project development.

Projects that integrate these elements from an early stage are better positioned to attract suitable partners, secure financing and progress to production. The proposed framework therefore reframes bankability as a continuous management discipline. Its value lies not in adding another layer of assessment, but in aligning the work already required so that each of; technical, commercial and strategic decision contributes directly to investment readiness.

Redrawing the investment map – government intervention and the evolution of critical minerals transactions for ASX companies

C Schofield[1]

1. Partner, AJ and Co Lawyers, Brisbane Qld 4000. Email: cschofield@ajandco.com.au

ABSTRACT

Government intervention is rapidly reshaping investment and transaction structures across Australia's critical minerals sector.

For ASX small and mid-capitalisation companies in particular, new policy settings in Australia and key allied jurisdictions are altering how projects are funded, risk is allocated, and value is captured across extraction and processing activities.

This paper examines how these interventions are changing the nature of investment transactions and project finance in the critical minerals sector.

Drawing on extensive experience advising on complex transactions in the mining and industrial sectors, the author will explore the structural challenges that have historically constrained investment in critical mineral projects, including funding gaps between exploration, development and processing, heightened technical and jurisdictional risk, long permitting time frames, and limited access to traditional project finance. These challenges have contributed to underinvestment in critical minerals at a time when global demand and strategic importance are accelerating.

The paper then analyses the impact of recent policy initiatives by the Australian Government and allied governments, including the United States, aimed at rapidly scaling critical mineral supply chains. These initiatives include targeted grant programs, accelerated regulatory and permitting pathways, concessional debt and equity support, strategic offtake frameworks, tax incentives such as the new 10 per cent critical minerals production tax credits, and the emergence of sovereign participation in selected projects.

Against this backdrop, the paper identifies key transactional shifts now evident in the sector, including:

- the growing use of joint ventures to bridge mining and downstream processing
- evolving capital stacks where government funding de-risks senior debt
- greater availability of non-dilutive funding alternatives to equity raisings
- financing structures tied closely to offtake and strategic reserve arrangements
- the increasing integration of policy considerations into core transaction terms (such as domestic supply chain security, First Nations participation, community benefits and decarbonisation commitments).

The paper concludes by considering what these developments mean for ASX-listed companies, investors and financiers navigating the next phase of growth in Australia's critical minerals economy.

Technology risk addressal in valuing assets containing novel commodity processing technologies

S Talan[1] and D Omosun[2]

1. Senior Consultant, Hatch Pty Ltd, Melbourne Vic 3000. Email: sidharth.talan@hatch.com
2. Principal, Hatch Pty Ltd, Brisbane Qld 4000. Email: doyin.omosun@hatch.com

ABSTRACT

The global push for critical minerals has accelerated the development of projects reliant on novel or first-of-kind processing technologies. While geological potential may be well understood, uncertainty around metallurgical performance, scale-up reliability, and operating stability introduces significant technology risk into asset valuation. Investors increasingly evaluate such projects through a structured set of risk-mitigation signals that extend beyond conventional resource metrics.

This paper proposes a three-pillar framework through which investors assess and price technology risk in emerging critical mineral assets. First, long-term pricing and market intelligence provide confidence that structural demand and sustained margins can support the additional uncertainty associated with new processing routes. Second, engineering validation and technical de-risking conducted by project owners including pilot testing, demonstration plants, and resolution of key process bottlenecks, serve as tangible indicators that scale-up challenges are understood and manageable. Third, owner capital participation and strategic alignment signal commitment and accountability, reducing perceived execution risk for external investors.

By examining these pillars across recent critical minerals projects, the paper highlights how capital markets translate technical uncertainty into valuation outcomes and identifies emerging patterns in how technology risk is assessed in the sector's next generation of projects.

Transparent market design for lithium – order books, price normalisation and quality adjusted auctions

L Tay[1], R Fenn[2], A Trench[3] and A Samuel[4]

1. Researcher, Digital Finance Cooperative Research Centre, Sydney NSW 2000. Email: lichoo.tay@dfcrc.com
2. Chief Executive Officer, Rise-X, Perth WA 6000. Email: rowan.fenn@rise-x.io
3. Professor, University of Western Australia, Crawley WA 6004. Email: allan.trench@uwa.edu.au
4. Chief Operating Officer, Rise-X, Perth WA 6000. Email: alan.samuel@rise-x.io

EXTENDED ABSTRACT

Despite the importance of lithium for electrification and energy security, lithium markets remain fragmented and opaque, with price discovery in spot markets largely dependent on price reporting agency (PRA) assessments (Wojewska *et al,* 2024). This study focuses on spodumene concentrate, Australia's primary lithium export, where limited transparency, episodic liquidity in bilateral trading and product heterogeneity contribute to delayed or potentially non-representative price signals which undermine market efficiency. These challenges are particularly relevant for Western Australia's large spodumene concentrate production, which is sold into export markets with diverse product specifications and contract structures.

In consultation with Australian spodumene producers who have expressed support for improving market transparency and price formation, we propose a new market design that integrates a fully transparent electronic 'quasi' limit order book (quasi-LOB) with a systematic price normalisation framework and a quality-adjusted auction mechanism. To our knowledge, this precise combination has not been previously implemented in any market. Ongoing engagement with downstream buy side participants continues to inform and refine the proposed design.

Heterogenous spodumene concentrate products which vary in lithium concentration, impurity content and delivery terms are transformed and normalised into standardised units which enables the aggregation and comparability of bids and offers within a unified order book. As in a conventional limit order book, firm bids and offers are displayed and ranked using their standardised prices. However, execution is not automatic. A parcel may be suitable for one buyer but not another because buyer-parcel compatibility depends on specific impurity tolerances, blend requirements and other commercial considerations. Participants can therefore interact with and select individual orders rather than being forced to transact solely according to price-time priority. The structure is 'quasi' because it organises and reveals trading interest without assumption that parcels are completely fungible with each other, or that the highest bid or lower offer are always feasible for every seller or buyer.

In general, a market structure that enhances transparency reduces both information asymmetries and market inefficiencies (Foucalt, Pagano and Röell, 2023). The initial proposal uses a fully transparent book in which firm, actionable orders and participant identities are visible. In a market with a small number of participants, parcel specifications and shipment locations may already make counterparties economically identifiable. Full visibility therefore provides substantial informational benefits with limited downside from the lack of concealment. As participation broadens and intermediary trading develops, the platform can consider progressively introducing greater anonymity.

To address potentially thin liquidity, the market design incorporates a Quality-Adjusted Uniform Price Auction (QA-UPA) within the quasi-LOB. This hybrid structure combines continuous trading on the quasi-LOB with periodic auctions that aim to concentrate liquidity and produce robust clearing prices. In scheduled auctions designed to clear the quasi-LOB, buyers bid on standardised units offered by suppliers while specifying technical requirements (eg impurity thresholds or minimum lithium grade). Unlike a pay-as-bid or discriminatory-price auction, the clearing algorithm determines a single normalised market clearing price while ensuring allocations are consistent with buyer constraints. Uniform pricing therefore applies to the normalised unit, not necessarily to the raw invoice price of every parcel. Transaction prices are converted back from the normalised clearing price to reflect the

actual quality and delivery characteristics of each allocated parcel. Unfilled bids and unsold parcels can return to the quasi-LOB, preserving continuity between the auction and continuous-trading stage.

This hybrid structure is intended to improve price discovery through two complementary channels. The quasi-LOB produces continuous pre-trade information on firm, executable interest. The auction periodically concentrates liquidity and produces a clearing price that aggregates information from multiple buyers and sellers at a common point in time. Together these mechanisms can generate a more reliable and transparent price signal than one derived from a small number of bilateral spot trades. They also strengthen existing PRA assessments by increasing the number of observable bids, offers and transactions, thereby reducing the degree of subjective judgement that is required when market observations are sparse.

The paper also presents a simple economic model that compares the proposed market with opaque bilateral trading. The bilateral trading market is subject to search frictions, as such, surplus-maximising trades may fail to occur because counterparties do not find each other at the appropriate time. The model shows that the proposed market can increase the number feasible, surplus-maximising trades and improve overall market outcomes when existing trading is affected by limited information and sporadic liquidity.

Our study develops the economic rationale, implementation considerations and price discovery implications in the proposed market design. In doing so, it provides a practical framework and roadmap for improving transparency, standardisation and liquidity in global lithium markets. Our findings may also be applicable to other critical-mineral markets where trading is mainly bilateral, and spot liquidity is limited.

REFERENCES

Foucault, T, Pagano, M and Röell, A, 2023. *Market Liquidity: Theory, Evidence, and Policy* (Oxford University Press).

Wojewska, A N, Staritz, C, Tröster, B and Leisenheimer, L, 2024. The criticality of lithium and the finance-sustainability nexus: Supply-demand perceptions, state policies, production networks, and financial actors, *The Extractive Industries and Society*, 17:101393.

Strategy, geopolitics and national capability

Strengthening Indo-Pacific critical mineral supply chains – opportunities for regional collaboration in the battery ecosystem

A Gill[1] and D Omosun[2]

1. Engagement Manager – Advisory, Hatch, Brisbane Qld 4000. Email: amandeep.gill@hatch.com
2. Principal – Advisory, Hatch, Brisbane Qld 4000. Email: doyin.omosun@hatch.com

ABSTRACT

Global demand for critical minerals is accelerating as electrification, battery energy storage systems, and electric vehicles reshape energy and mobility systems. Despite this rapid growth, the global battery value chain remains highly geographically concentrated, with China dominating multiple stages of mineral processing, battery materials production, and cell manufacturing. This concentration exposes the global energy transition to supply chain vulnerabilities and geopolitical risks, particularly for emerging critical mineral economies across the Indo Pacific.

The Indo Pacific, particularly South-east Asia and Australia, holds a uniquely complementary set of resource, industrial, and policy capabilities within the battery ecosystem. Australia is a leading producer of lithium and other critical minerals, underpinned by robust environmental, social, and governance (ESG) standards. South-east Asian economies, notably Indonesia, possess globally significant nickel resources and have rapidly expanded domestic processing and midstream battery material capacity. However, much of the region remains concentrated in upstream production, with limited capture of value in midstream and downstream segments.

This paper presents an analysis of strategic collaboration opportunities to strengthen regional critical mineral and battery supply chains within the Indo Pacific, with Australia and Indonesia examined as a focal partnership. It explores pathways for joint development of processing and refining capabilities, regional research and innovation cooperation, and greater alignment of ESG, traceability, and certification frameworks required to access global markets. The analysis also considers how policy coordination and private sector partnerships can support regional integration across the battery value chain.

The findings suggest that deeper regional collaboration could enable Indo Pacific economies to capture greater economic value, enhance supply chain resilience, and position the region as a competitive, sustainable alternative within the global battery ecosystem. These insights are relevant for governments, investors, and industry stakeholders seeking to accelerate secure and responsible critical mineral supply chains in support of the global energy transition.

Comparable results, credible trade – accreditation, standards and national capability in critical minerals

D Hobday[1]

1. AAusIMM, Sector Manager, Materials, Assets and Products, NATA, Camberwell Vic 3124. Email: diane.hobday@nata.com.au

EXTENDED ABSTRACT

Critical minerals supply chains rely on technical data. That data supports resource evaluation, process control, product specification, regulatory decisions, investment and trade. Where results cannot be readily compared across laboratories, jurisdictions and markets, decisions based on those results become harder to defend.

The World Bank describes standards as part of the invisible infrastructure of modern economies and as the hidden foundations of prosperity. Standards support trust, interoperability, market access and trade. The report opens with a quotation attributed to Werner von Siemens: 'Whoever owns the standards, owns the market' (World Bank, 2025).

The methods used to characterise critical minerals are therefore not administrative detail. They form part of the technical infrastructure that determines whether results are accepted across a supply chain and the ease with which Australian materials can be traded on terms the market understands.

STANDARDS, METHODS AND COMPARABILITY

Internationally agreed methods provide a common and readily recognised basis for specification and comparison. They establish shared terminology, procedures and performance requirements, reducing the need for each participant in a supply chain to determine independently whether a method is suitable.

Laboratory-developed methods may be necessary where no applicable standard method exists, where established methods do not suit a particular material or purpose, or where laboratories are developing new capability. A validated in-house method can be entirely fit for its intended use.

However, accreditation of a laboratory-developed method does not, by itself, establish comparability with results produced by other methods. Where different methods are used across laboratories and markets, additional evidence may be needed to demonstrate comparability.

Nor does use of a published standard, by itself, establish that the method has been selected or applied correctly. Accreditation provides independent confidence of competence to undertake the specified testing. Standard methods and accreditation perform different functions, but work together to support confidence in results.

THE CURRENT POSITION IN CRITICAL MINERALS

Standards coverage across critical minerals is uneven. Some commodities are supported by established International Organization for Standardization (ISO) technical committees, published standards and active work programs. Others have limited standards coverage or no clear pathway to internationally agreed test methods.

Rare earths and lithium have a growing number of active standards, while others do not have an obvious committee responsible for the relevant testing and analysis work (R Toledo Bell, personal communication, 2026).

The presence of national or industry methods can provide an important starting point. Methods developed in one country may also offer technically sound material from which an international method can be developed. However, adoption of a national method outside its originating market cannot be assumed. An international consensus process is still required if the objective is a method recognised across jurisdictions and supply chains.

ISO AND INTERNATIONAL STANDARDS DEVELOPMENT

ISO provides an established international route through which methods relevant to critical minerals can be developed and maintained. Its processes bring national standards bodies together to reach agreement on common requirements.

ISO's processes provide legitimacy and international acceptance, but they also require suitable proposals, expert participation and sustained national engagement.

International standards development is therefore part of national capability. Australia has technical expertise in mining, minerals processing, testing, metrology and conformity assessment. The expertise needs to be mobilised.

ACCREDITATION AND QUALITY INFRASTRUCTURE

Standards do not operate in isolation. The broader quality infrastructure includes standardisation, metrology, conformity assessment and accreditation. Together, these functions support confidence that requirements are meaningful, measurements are traceable and conformity assessment bodies are technically competent.

Accreditation provides independent attestation of the competence of testing laboratories and other conformity assessment bodies. It does not replace method development, validation, regulation or commercial judgement. It provides assurance that a laboratory has the resources and technical capability to perform the activities included in its accredited scope.

This is particularly relevant where test results are used beyond the laboratory's immediate customer. Results may inform commercial contracts, regulatory decisions, investment, product acceptance or the movement of materials between countries. In these circumstances, internationally agreed methods provide a common technical reference, while accredited testing provides confidence in data.

NATIONAL PRIORITY-SETTING

The Critical Minerals Strategy 2023–2030 sets out Australia's national policy framework for developing resilient and sustainable critical minerals supply chains (Department of Industry, Science and Resources, 2023). The Australian Critical Minerals Research and Development Hub has a role in identifying priorities, gaps and technical obstacles across critical minerals supply chains. It brings together the Commonwealth Scientific and Industrial Research Organisation, Geoscience Australia and the Australian Nuclear Science and Technology Organisation, and aligns research and development with national strategic priorities (Australian Critical Minerals Research and Development Hub, 2026).

That work provides context for considering standards and accreditation. Priorities should reflect Australia's role in international supply chains, demand for comparable data, gaps in standards coverage, method maturity, relevant expertise, and the practical capacity to implement and accredit the resulting methods. Standards development and accreditation should be considered explicitly within national capability planning, particularly where the absence of internationally agreed, accreditable methods limits comparability, confidence or trade.

CONCLUSION

National capability in critical minerals extends beyond geology, extraction, processing and manufacturing. It includes the technical infrastructure needed to describe materials, measure their properties and provide results that can be accepted across markets.

Internationally agreed methods provide a common basis for comparison. Accreditation provides independent confidence in the competence of laboratories applying those methods. Neither resolves every technical or commercial issue, but together they provide a stronger basis for credible data and trusted trade.

Australia is already identifying national priorities for critical minerals research and development. Standards development and accredited testing capability belong within that work. If standards help

shape markets, Australia should identify where it needs to contribute to their development and ensure that competent, accredited testing is available to support their use.

This poster brings these elements together as a basis for discussion. It does not propose a new standards program or a predetermined list of priorities. It proposes that standards coverage, accredited capability and the need for comparable results should form part of the evidence used when national critical minerals priorities are set.

REFERENCES

Australian Critical Minerals Research and Development Hub, 2026. About the Hub. Available from: <https://research.csiro.au/critical-minerals-hub/about-us/about-the-hub/>

Department of Industry, Science and Resources, 2023. Critical Minerals Strategy 2023–2030. Available from: <https://www.industry.gov.au/publications/critical-minerals-strategy-2023–2030>

World Bank, 2025. World Development Report 2025: Standards for Development. https://hdl.handle.net/10986/43949

How government can support the acceleration of critical mineral project delivery, supported by policy, regulation and initiatives

P Holden[1], A Neil[2] and B Johns[3]

1. Lead, Critical Minerals Queensland, Townsville Qld 4800.
   Email: paul.holden@nrmmrrd.qld.gov.au
2. Director, Program Delivery, Critical Minerals Queensland, Brisbane Qld 4000.
   Email: anne.neil@nrmmrrd.qld.gov.au
3. Director, Zones and Projects, Critical Minerals Queensland, Townsville Qld 4800.
   Email: ben.johns@nrmmrrd.qld.gov.au

ABSTRACT

In today's interconnected and competitive global economy, resource-rich jurisdictions are unable to compete on geological endowment alone, but demonstrate project and capital efficiency, to appeal to investors. Queensland is stepping up its global competitiveness through a coordinated, government-led case management model, working in tandem with other levers available to government to support critical mineral project advancement.

The Queensland government plays a pivotal market enabler role in critical minerals project development emphasising active facilitation alongside statutory assessment functions to accelerate projects. This paper demonstrates the Critical Minerals Queensland approach and the value in case management to accelerating critical mineral projects.

Central to this approach is establishment of Critical Minerals Zones (CMZs) and targeted investment in enabling infrastructure, particularly rail and power, to boost mineral transport capacity while reducing barriers to production. Additionally, funding for common-user processing facilities allows proponents to pilot and scale up projects, de-risking investments and bolstering investor confidence.

Beyond physical infrastructure, the Queensland Government invests in baseline ecological, social, and groundwater studies, making datasets available to proponents, avoiding duplication of effort and reducing regulatory approval timeframes.

These initiatives are reinforced by operational policy settings, including government led initiatives supporting exploration, feasibility, and early-stage development activities, lowering barriers to entry and accelerating project progression.

Collectively, this integrated place-based model fosters investor confidence, accelerated project timelines, enhanced industry competitiveness, and greater long-term economic resilience. The paper offers a practical roadmap for strategic government intervention to secure Queensland's place in global critical minerals supply.

Australia's opportunity to add value to critical minerals through downstream pyrometallurgical processing

E Jak[1], D Shishin[2], P C Hayes[3], M Shevchenko[4] and J Chen[5]

1. Professor, PhD, PYROSEARCH, School of Chemical Engineering, The University of Queensland, St Lucia Qld 4072. Email: e.jak@uq.edu.au
2. Senior Research Fellow, PhD, PYROSEARCH, School of Chemical Engineering, The University of Queensland, St Lucia Qld 4072. Email: d.shishin@uq.edu.au
3. Professor Emeritus, PhD, PYROSEARCH, School of Chemical Engineering, The University of Queensland, St Lucia Qld 4072. Email: p.hayes@uq.edu.au
4. Senior Research Fellow, PhD, PYROSEARCH, School of Chemical Engineering, The University of Queensland, St Lucia Qld 4072. Email: m.shevchenko@uq.edu.au
5. Senior Research Fellow, PhD, PYROSEARCH, School of Chemical Engineering, The University of Queensland, St Lucia Qld 4072. Email: j.chen5@uq.edu.au

ABSTRACT

As global jurisdictions such as the USA and Europe move aggressively toward 'metal-centric' resource security, Australia faces a critical juncture in its industrial evolution. We ask the question, as a country are we making the best use of our mineral resources? Are we to continue exporting low value concentrates or should we be adopting a more integrated broader strategic approach to industry development? Rather than relying on individual companies to make the quantum leap of taking the invention of new technologies from the mine gate to the international market, we should be building capacity that supports this difficult and complex step. Increase the possibilities of success by further developing the value chain and more fully utilising our metallurgical capabilities and expertise.

To facilitate the downstream pyrometallurgical processing of complex primary and secondary feedstocks, a research program on the development of the comprehensive 20-component multiphase thermodynamic database (Cu-Pb-Zn-Fe-Ca-Al-Mg-Si-S-O-As-Sn-Sb-Bi-Ag-Au-Ni-Co-Cr-Na) is undertaken at Pyrosearch, The University of Queensland, supported by consortia or major international metallurgical companies. This tool predicts the partitioning of chemical elements across complex gas-slag-matte-speiss-metal-salt-solids systems. It optimises the operating conditions of individual high-temperature units by integrating mass and energy balances with physicochemical property calculations. The models are refined using a continuous stream of data generated through targeted, systematic, and laboratory-controlled experimentation. By providing precise predictive capabilities, the project enhances industry confidence in the domestic integration of complex primary and recycled materials.

Aligned with the Australia National Interest Framework, this research facilitates the downstream processing of complex concentrates, mine tailings, and electronic waste. By transitioning from empirical methods to innovative, high-fidelity modelling, Australia can boost the competitiveness of its mineral-to-metal value chain, ensuring a sustainable and secure supply of critical metals independent of current geopolitical constraints.

From strategy to scale – why critical minerals innovation stalls between pilot and bankability

D Kitsos[1]

1. Managing Director, Rata Group, Singapore. Email: donna@ratagroup.co

INTRODUCTION

With critical minerals firmly on policy, investment and industrial agendas, attention is turning from strategy to delivery. Technologies are being advanced through field trials, pilots and demonstrations, supported by corporate, strategic and public capital. Yet technical validation is not evidence that a technology will scale, attract customers or become financeable. It establishes performance under defined conditions. Bankability requires more.

Drawing on experience investing in early-stage technologies across the mining and minerals value chain, from exploration and extraction through processing, refining, recovery and recycling, this paper examines what must be proven beyond technical validation for a technology to scale.

The route differs materially by technology. Exploration platforms, sensing and equipment technologies, processing routes and first-of-a-kind refining projects require different validation pathways, commercial models and forms of capital. There is no single critical-minerals scale-up model. What is consistent is the need to solve a material problem and create sufficient value to justify the cost, disruption and risk of adoption.

TECHNICAL AND COMMERCIAL PROOF

For technologies interacting directly with ore or process streams, a successful pilot does not establish that performance will remain consistent across changing mineralogy, feed characteristics or operating conditions. Nor does it demonstrate that the economics remain attractive once integration, maintenance, energy, water, reagents, logistics and full-scale capital requirements are included. In mining, variability is part of the operating reality. A credible scale-up case needs representative operating data and an understanding of where performance degrades, not simply a headline recovery rate, throughput figure or successful demonstration.

Commercial validation needs to develop alongside technical validation. Customer qualification and routes to revenue should be addressed while validation is underway. Paid trials, staged deployments, equipment sales, licensing, service revenues and strategic partnerships can provide more meaningful evidence of adoption than non-binding interest. They also answer a more important question: whether someone is prepared to pay for the value created.

For projects producing a saleable mineral or material, offtake can strengthen the financing case, but not all offtake is bankable. Its value depends on the counterparty, pricing structure, product specification, qualification requirements, committed volume, duration and conditions. Letters of intent and memoranda of understanding may demonstrate interest without transferring meaningful risk. In thin or concentrated critical-mineral markets, the route to customer can be as important to financing as the quality of the resource or technology (Diasselliss *et al*, 2026).

SCALING, FINANCING AND MARKET RESILIENCE

Scale needs to be considered before validation is complete. Who supplies the feedstock? Who owns the first commercial asset? Who carries performance and integration risk? Who funds construction and working capital? For some technologies, asset ownership may be unavoidable. For others, licensing, equipment sales, tolling, joint ventures, OEM integration or operator partnerships may offer a more financeable route to market. The right model places each risk with the party best positioned to understand, manage and finance it.

The financing model must evolve as risks change. Venture capital can support technical development and early commercial validation, but it is rarely designed to finance large processing assets, lengthy commissioning or substantial working-capital requirements. Later stages may require strategic equity, customer-backed capital, grants, equipment or asset finance, concessional capital,

export-credit support or project debt. Debt providers require credible counterparties, predictable cash flows, defined construction and performance risk and resilience under downside scenarios. Waiting until a company is considered ‘ready for project finance’ to address these questions is often too late.

For asset-based projects, bankability extends beyond technology and financing. Permitting, infrastructure, jurisdictional risk, power and water, logistics, workforce capability and community acceptance can become critical-path constraints. A technology may be proven and commercially attractive but still be unable to progress if the surrounding project environment cannot support deployment.

Market resilience is another important test. The International Energy Agency reported that overall critical-minerals investment fell 9 per cent in 2025, but the headline masked different commodity cycles: lithium companies reduced investment by around 40 per cent while copper-focused companies increased spending by 8 per cent (International Energy Agency, 2026). This divergence is a reminder that there is no single critical-minerals market and that long-term strategic demand does not insulate projects from price cycles or shifts in capital allocation.

A credible investment case must hold up beyond the base case. Commissioning can slip, capital costs can rise, customer qualification can take longer than expected and commodity prices can move materially during ramp-up. The key is to understand which assumptions the economics are most sensitive to, how much funding headroom is required and who carries the downside. Projects that only work under favourable pricing, uninterrupted schedules or continuous access to equity remain exposed regardless of technical performance.

PARTNERSHIPS AND POLICY

Partnerships become meaningful when they remove a specific barrier to deployment or place risk with a party capable of managing it. Operators can provide representative operating environments and integration expertise. Customers can define qualification requirements and demand. Engineering and OEM partners can strengthen delivery credibility. Strategic investors can combine capital with commercial alignment. Governments can address genuine market failures through targeted risk-sharing mechanisms (Brunelli, Jain and Moerenhout, 2026).

Policy support can improve project economics and help address structural disadvantages in critical-mineral supply chains. It may be needed to overcome concentrated incumbent supply, uncertain demand or first-of-a-kind risk. It should not, however, be mistaken for evidence of technical or commercial competitiveness. Where continuing policy support is required, that dependency should be explicit within the investment case and tested alongside commodity volatility, delayed demand, higher costs and periods of constrained capital.

CONCLUSIONS

Bankability should therefore be understood not as a milestone reached after a successful pilot, but as a sequence of technical, operational, commercial and financial proofs built from the outset. The question is not simply whether a technology works. It is whether it solves a problem that matters, for a customer willing to pay, under realistic operating and market conditions, with the right commercial model, risk allocation and financing structure to carry it through scale.

REFERENCES

Brunelli, K, Jain, G and Moerenhout, T, 2026. Making Critical Minerals Bankable: Policy Tools to Unlock Investment [online]. Geneva, World Economic Forum. Available from: <https://www.weforum.org/publications/making-critical-minerals-bankable-policy-tools-to-unlock-investment/> [Accessed: 27 July 2026].

Diasselliss, J, Das, S, Johnson, C, Scodova, B, Hardin, K and Purohit, A, 2026. 2026 Mining and Metals Industry Outlook [online]. Deloitte Research Center for Energy & Industrials, Deloitte Development LLC. Available from: <https://www.deloitte.com/us/en/insights/industry/mining-metals/mining-and-metals-industry-outlook.html> [Accessed: 27 July 2026].

International Energy Agency, 2026. Global Critical Minerals Outlook 2026 [online]. Paris, International Energy Agency. Available from: <https://www.iea.org/reports/global-critical-minerals-outlook-2026> [Accessed: 27 July 2026].

Critical minerals and strategic alignment – Australia at an inflection point

N Mackay[1] and J Townsend[2]

1. Managing Director, Critical Minerals Association Australia, Brisbane Qld 4000, Australia. Email: namali@cmaaustralia.org
2. Founder, Critical Minerals Association UK, London, United Kingdom. Email: jeff@criticalmineral.org

ABSTRACT

The global critical minerals sector is being rapidly reshaped by coordinated government intervention, industrial policy, and intensifying geopolitical competition. Allied economies are no longer passive market participants – they are actively deploying capital, underwriting risk, and structuring demand to secure supply chains and reduce exposure to concentrated markets. For Australia, this presents a clear but time-sensitive opportunity. The Australian Government's Critical Minerals Strategic Reserve initiative signals a shift toward demand-side support, seeking to connect domestic projects with allied offtake and financing. In parallel, the United States has expanded mechanisms that can support Australian projects, while European governments are increasingly mobilising public capital with mandates that extend to upstream supply. Japan and South Korea continue to deepen long-standing investment and offtake relationships across the sector. These developments are unfolding against a more challenging domestic reality. China's export controls on critical minerals and materials continue to shape market dynamics. At the same time, recent price volatility – particularly in nickel and lithium – has placed pressure on Australian operations, with projects delayed, curtailed, or placed into care and maintenance. Competing supplier nations are moving quickly, often benefiting from lower energy costs, more integrated industrial ecosystems, and stronger alignment between policy and industry. Drawing on detailed and consistent feedback from allied governments, investors, and downstream partners, this paper examines whether Australia's current approach is aligned with the realities of this evolving landscape. The feedback is clear: while Australia is seen as a critical part of future supply chains, there are growing concerns around pace, cost competitiveness, and the alignment between policy ambition and commercial outcomes. At this inflection point, the question is not whether Australia participates in the global realignment, but whether it is focused on the right priorities to capture value. Without sharper prioritisation, faster execution, and a clearer focus on competitiveness, there is a real risk that capital, capability, and strategic advantage will flow elsewhere.

Critical minerals for energy and supply network risks in the Indo-Pacific

B C McLellan[1]

1. Professor, Kyoto University, Kyoto 606-8501, Japan. Email: b-mclellan@energy.kyoto-u.ac.jp

ABSTRACT

Critical minerals for energy transitions have been one of the key drivers behind criticality discussions in recent decades, notably with the potential and real impacts of monopolisation of supply chains in China. Geopolitical uncertainty with trade policies from the USA has added to concern over supply chain risks. In the Indo-Pacific, which has a large, growing population and rapidly expanding regional economies, bilateral trade agreements and domestic policy directions have potential to secure supply on some fronts, while undermining longer-term viability of other strategic facilities. The example of downstreaming policies in Indonesia, which has significantly impacted upstream viability of nickel production in countries such as Australia, and with similar policies for copper potentially impacting the viability of recycling facilities in countries such as Japan, demonstrate the need for systemic consideration. This study considers the current Indo-Pacific policy and industrial ecosystem for energy-critical minerals, and the systemic geopolitical implications of trade and domestic policy standpoints. Opportunities and risks for future critical mineral security will be discussed.

Demystifying the midstream bottleneck – an analytical framework for critical minerals policies

D M Ramizo[1], H Cabalu[2], M Harris[3] and J Inchauspe[4]

1. PhD Candidate, Curtin University, Perth WA 6102.
   Email: dorothea.ramizo@postgrad.curtin.edu.au
2. Professor, Curtin University, Perth WA 6102. Email: h.cabalu@curtin.edu.au
3. Professor, Curtin University, Perth WA 6102. Email: mark.harris@curtin.edu.au
4. Senior Lecturer, Curtin University, Perth WA 6102. Email: julian.inchauspe@curtin.edu.au

ABSTRACT

Critical minerals are key inputs to clean energy technologies and play a fundamental role in the low-carbon transition. China's dominance in the midstream processing of the critical minerals value chain creates strategic leverage through export restrictions and supply chain control. This drives the proliferation of critical minerals policies to build a supply chain that excludes China (ex-China), yet their success remains uneven and uncertain. This paper develops a conceptual framework grounded in the economics and metallurgy of critical minerals processing to explain why China's dominance persists. It identifies the transmission channels through which these policies affect the economic and financial viability of critical minerals processing projects. The framework shows that capability in mineral processing is accumulated through learning-by-doing, which requires the availability of feedstock, finance, a specialised workforce, secure demand, and stable prices to support a specific feedstock-to-qualified output route. The study finds that China deliberately built a policy ecosystem over several decades to meet these requirements and develop the processing capabilities it now possesses. The study also identifies the structural positions of Japan, the United States, and Australia along the critical minerals value chain, their respective binding constraints, and evaluates whether their critical minerals policies address these constraints. For these countries, the policy recommendation is to align state interventions on finance, demand at scale, shared testing and certification, and buyer qualification along priority feedstock-to-qualified output routes.

A regional blueprint for Australia's critical minerals future – the Mackay and Greater Whitsunday model

J Thompson[1]

1. Diversification Lead, Greater Whitsunday Alliance, Mackay Qld 4740. Email: jodie@gw3.com.au

ABSTRACT

Australia's transition to a secure, sustainable critical minerals industry relies not only on national policy settings but on the capacity of regions to activate their industrial ecosystems.

The *Mackay and Greater Whitsunday Roadmap to Establishing a Critical Minerals Processing and Services Hub* (Greater Whitsunday Alliance, 2026) demonstrates how a mature mining equipment, technology and services (METS) hub can reposition itself as a globally relevant processing and services centre, supporting national ambitions while driving regional diversification.

Situated at the heart of the Bowen Basin, the Greater Whitsunday region offers unmatched advantages: the southern hemisphere's highest density of METS firms, emerging pilot scale processing capability through the Critical Minerals Flexi-Lab, and a rapidly developing skills and innovation precinct at the Resources Centre of Excellence and Isaac Resources Excellence Precinct (IREP). Together, these assets form a foundation for downstream processing, mine waste reprocessing, and postmining land-use innovation.

The roadmap outlines a cohesive, partnership centred model grounded in four themes essential to regional development:

1. **Skills pipelines and workforce transition**, leveraging transferable METS expertise and new training pathways to build capability for critical minerals processing.
2. **Regulatory and approvals readiness**, with streamlined local planning settings to attract junior miners, innovators and investment.
3. **Postmining land use as an economic driver**, including recovery of critical minerals from tailings and rehabilitation-led development opportunities.
4. **Institutional collaboration**, through the proposed Australian Centre for Critical Minerals Intelligence (ACCMI), linking regional infrastructure with national R&D and global supply chain partners.

This presentation will showcase how the roadmap operationalises these elements through targeted, low risk, high impact actions designed for rapid implementation. It offers a replicable blueprint for regional Australia: one that accelerates sovereign capability, unlocks circular economy opportunities, and ensures communities benefit from the next wave of resource-sector transformation.

REFERENCES

Greater Whitsunday Alliance, 2024. Greater Whitsunday METS Sector Revenue Diversification Strategy (internal report), Greater Whitsunday Alliance. Available from: <https://greaterwhitsundayalliance.com.au/wp-content/uploads/2024/10/GW3MetsDiversificationStrategy_DigitalFinal04.09.24.pdf>

Greater Whitsunday Alliance, 2025. Reimagine Rehab Prospectus (internal report), Greater Whitsunday Alliance. Available from: <https://greaterwhitsundayalliance.com.au/wp-content/uploads/Prospectus-Reimagine-Rehab-Updated-27-October-25.pdf>

Greater Whitsunday Alliance, 2026. Mackay and the Greater Whitsundays: A Roadmap – Establishing a Critical Minerals Processing and Services Hub (internal report), Greater Whitsunday Alliance. Available from: <https://static1.squarespace.com/static/65b1e45e053a9d1c5f3b904c/t/6a5c87a9a27ab31cf4999643/1784448937944/GW3+Critical+Minerals+Processing+and+Services+Hub+-+Final+Report+190726.pdf>

Resources Centre of Excellence, 2025. Flexi-Lab Capability Prospectus: Part of the Future Industries Hub (internal report), Resources Centre of Excellence. Available from: <https://www.rcoe.com.au/future-industries-hub>

Digging into Australia's 'sweet spot' on critical minerals

D Usher[1], P Baker[1] and S Taylor[2]

1. Critical Minerals Lead, GHD Pty Ltd, Melbourne Vic 3000.
2. Critical Minerals Lead, GHD Pty Ltd, Melbourne Vic 3000. Email: sam.taylor@ghd.com

ABSTRACT

Australia has the potential to become a world leader in critical minerals, yet it remains at a disadvantage in refining the minerals it produces. To compete globally, Australia must play to its strengths and clearly define its evolving 'sweet spot' in the critical minerals value chain—a position shaped by the maturity, scale, and readiness of national infrastructure. As logistics, energy systems, and processing capabilities improve, Australia's ability to form compelling, investment-ready business cases grows, strengthening its global competitiveness.

Infrastructure across transport, energy, water, and digital systems, directly determines where Australia can add the most value. More mature infrastructure shortens development cycles for mining and processing projects, reduces time-to-market, and makes investment more attractive.

The objective is not only economic growth but also building sovereign capability and deepening long-term global partnerships. With volatile supply chains and growing demand for low-carbon, sustainable materials, Australia's ability to process and secure critical minerals is essential. Achieving this requires decisive government leadership and common-user infrastructure that lowers barriers to entry, provides fair access to processing, and boosts sector-wide viability. Australia has done this before—most notably in the early 2000s when it helped establish a globally competitive LNG export industry. With the right mix of investment, policy support, and enabling infrastructure, it can do the same for critical minerals, delivering new regional jobs, stronger supply chain security, and long-term national prosperity.

Key points for consideration:

- **Industry Coordination Around Processing:** For emerging mineral industries, the need to collaborate on shared processing and technical challenges to meaningfully activate their industry.
- **Infrastructure and Workforce Gaps:** Remote-area infrastructure and skilled-worker shortages limit progress, access to re-agents, investment in logistics, utilities, and green energy is essential.
- **Government Leadership:** Policy certainty, funding, and common-user infrastructure are needed to unlock private capital.
- **Understanding End User Requirements:** There is still an underdeveloped understanding from proponents of what form of critical minerals end customers want, by when, in what volumes and with what assurances.

Critical minerals in an age of strategic fragmentation – from resource endowment to industrial delivery

V Vivoda[1]

1. Honorary Fellow, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4067. Email: v.vivoda@uq.edu.au

ABSTRACT

Critical mineral supply chains are no longer shaped by market fundamentals alone. They are being reorganised by strategic rivalry, export controls, industrial subsidies, defence procurement rules and renewed resource nationalism. Although mineral deposits remain geographically uneven, the most consequential concentrations increasingly lie in midstream capabilities: refining, separation, metallisation, precursor production, component manufacture and customer qualification. This produces a central paradox: governments can mandate diversification quickly, but alternative supply chains must be financed, permitted, built, commissioned and qualified on much slower industrial timescales.

This presentation examines how the widening gap between geopolitical urgency and industrial delivery is reshaping mineral economics. Donald Trump's return to the White House has intensified uncertainty through a more transactional approach to alliances, trade, tariffs and domestic production. At the same time, China's use of export controls and its entrenched processing advantages demonstrate how relatively small volumes of specialised material can exert disproportionate leverage over large downstream industries. The resulting policy response – stockpiles, price support, offtake agreements, public equity, procurement restrictions and friend-shoring – may improve resilience, but can also fragment markets, duplicate capacity and transfer risk to governments and producers.

Australia illustrates both the opportunity and the constraint. Its resource base and strategic partnerships position it as a preferred supplier, yet extraction alone does not create supply-chain sovereignty. Capturing greater value requires commercially durable processing, enabling infrastructure, technical skills, patient capital and reliable access to downstream customers. The presentation argues that success should be judged not by project announcements or tonnes in the ground, but by strategic deliverability: the capacity to move material through an economically viable, technically qualified and politically sustainable chain. It concludes with practical implications for industry and government as they navigate price volatility, policy instability and an increasingly fractured global market.

From exploration to refining – is Australia innovating where value is created?

R Wulff[1], R Moore[2] and N Amitay[3]

1. Principal, Griffith Hack, Sydney NSW 2060. Email: robert.wulff@griffithhack.com.au
2. Associate, Griffith Hack, Perth WA 6000. Email: radhika.moore@griffithhack.com.au
3. IP Intelligence Manager, Griffith Hack, Melbourne Vic 3000.
   Email: noam.amitay@griffithhack.com

ABSTRACT

As Australia looks to secure its supply of critical minerals in an ever-changing geopolitical environment, ensuring that Australia is innovating in all parts of the critical minerals supply chain is essential. Historically, investment into critical minerals technologies in Australia has had a heavy upstream focus. However, to be able to properly exploit its resources, Australia needs to develop onshore mid- and down-stream processing capabilities. To understand how well Australia is placed in the mid- and down-stream sectors, we need to understand who is investing into developing technologies related to each part of the supply chain in Australia.

In this presentation, we focus on the level of investment in **nickel, cobalt and lithium** technologies, using patent data as a proxy for the state of development of technology mainly related to mid- and down-stream processing of these critical minerals in Australia. In particular, we look to identify the strength of innovation in each of these areas in Australia. This helps us to identify gaps in our supply chain and the areas that require further investment for Australia to ensure a reliable supply chain into the future.

We used the patent data to explore and identify who the major investors are in the critical minerals sector and where the major investors are based. We looked into the big players internationally. We also investigated who the major players are in Australia. The data reveals that the major international players are filing into Australia in **nickel, cobalt and lithium** technologies, indicating that certain players are looking to monopolise all parts of our supply chain. The data also revealed that there is really only one Australian player (the CSIRO) that is innovating in mid- and down-stream technologies for nickel, cobalt and lithium.

Sustainability

Revalorising historical tin mine wastes – a sustainable source of In, Sn, Sb, W and Bi

S J Chingwaru[1], O Mejías[2], R Blannin[3], N Fox[4] and A Parbhakar-Fox[5]

1. Postdoctoral Researcher, W H Bryan Mining Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4068. Email: s.chingwaru@uq.edu.au
2. Research Fellow, W H Bryan Mining Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4068. Email: o.mejiasgonzalez@uq.edu.au
3. Research Fellow, W H Bryan Mining Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4068. Email: r.blannin@uq.edu.au
4. Senior Research Fellow, W H Bryan Mining Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4068. Email: nathan.fox@uq.edu.au
5. Honorary Professor, W H Bryan Mining Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4068. Email: a.parbhakarfox@uq.edu.au

ABSTRACT

Demand for critical elements such as In, Sn, Sb, W, and Bi is increasing due to their importance in advanced technologies, renewable energy systems, and strategic industries. However, global supply remains uncertain because many of these metals are produced as by-products, are geographically concentrated, and have declining discovery rates. Reprocessing historical mine waste offers a sustainable alternative by recovering valuable metals without additional mining, while reducing environmental liabilities associated with legacy tailings.

This study evaluates mine waste from eight legacy sites within the Herberton Sn–W–Sb–Bi mineral field, Australia, as a secondary resource for In, Sn, Sb, W, and Bi. A multi-scale characterisation workflow integrating bulk geochemistry, automated mineralogy, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), and gravity recovery modelling was applied to determine element concentrations, mineral hosts, deportment, and recovery potential.

Results reveal significant enrichment of critical elements, with maximum concentrations of In (1155 ppm), Bi (3640 ppm), Sb (53 600 ppm), Sn (81 600 ppm), and W (11 650 ppm). Element deportment varies systematically between samples, reflecting differences in mineralogical composition and weathering history. Lower-grade materials host critical elements primarily within secondary Fe–Sn–Pb–Sb phases, whereas higher-grade materials contain these elements within primary sulfides (chalcopyrite, pyrite, tetrahedrite, sphalerite, and bismuthinite) and Sn–W oxides. Gravity separation modelling predicts potential recoveries of 22–85 per cent In, 53–99 per cent Sn, 26–91 per cent Sb, 13–91 per cent W, and 26–51 per cent Bi. Variations in recovery are primarily associated with mineral liberation, silicate locking, fine grain size distribution, and secondary mineral associations, highlighting the importance of mineralogical controls in selecting appropriate processing pathways.

These findings demonstrate the significant potential of historical mine waste in the Herberton mineral field as a secondary source of critical elements. However, variability in mineralogy and liberation characteristics presents challenges for process scalability and economic implementation. Integrating mineralogical characterisation with geometallurgical modelling provides a framework for optimising flow sheet selection, assessing processing limitations, and supporting sustainable circular mineral development.

Baseline environmental studies for the development of oil shale-hosted vanadium projects

M Edraki[1], L Rochford[2] and C Cote[3]

1. Professor, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4067. Email: m.edraki@uq.edu
2. Senior Research Fellow, Sustainable Minerals Institute, The University of Queensland, St Lucia Qld 4067. Email: louisa.rochford@uq.edu.au
3. Principal Water and Environmental Specialist, Egis, Brisbane Qld 4000. Email: claire.cote@egis-group.com

ABSTRACT

The Julia Creek-Richmond region is designated as a Critical Minerals Zone under the Queensland Critical Minerals Strategy, with several vanadium projects at varying stages of development. This paper draws on publicly available project documentation, regional baseline data, and the scientific literature to examine environmental considerations associated with mining development in the region and the production of vanadium pentoxide (V_2O_5), and potentially high-purity alumina and rare earth elements. In particular, the paper discusses co-disposal strategies for mine waste and processing residues and identifies risk mitigation measures and key knowledge gaps.

Vanadium in the Toolebuc Formation is hosted in organic-rich oil shales and is strongly redistributed during weathering, transferring from organic matter to clay minerals and iron oxyhydroxides. Vanadium mobility is highly sensitive to redox and pH conditions; oxidising, neutral to alkaline environments favour mobile and toxic V(V) (vanadate), while reducing conditions limit mobility. Consequently, strategies focused solely on suppressing acid generation do not necessarily control vanadium and associated trace element release.

Sulfide-rich mudstones in the Wallumbilla Formation and lower transition units oxidise rapidly and pose a critical acid generation risk if not promptly encapsulated. Neutral to saline drainage remains a long-term concern, with trace elements, including vanadium, showing moderate to high mobility.

Neutralised processing residues differ from natural lithologies, being sulfate-rich, moderately saline, and lacking low-permeability characteristics, making long-term performance dependent on careful placement and control of water and oxygen ingress. The current study identified regional knowledge gaps, highlighting opportunities for coordinated research and the application of emerging methods to support the sustainable extraction of vanadium from oil shale within the local environmental context.

INTRODUCTION

Vanadium is used in both traditional heavy industry and emerging clean energy technologies. Its applications include steel and alloy production, vanadium redox flow batteries, which are increasingly used for large-scale renewable energy storage, aerospace, and as chemical catalysts. Queensland contains some of the world's largest known vanadium resources, particularly within the Toolebuc Formation oil shales of the Eromanga Basin around Julia Creek region, which also contains molybdenum, and other trace critical elements. This creates opportunities for integrated resource recovery and improved project economics and could position Queensland as a major supplier of vanadium for both the steel industry and the emerging global energy-storage sector. One of the most advanced projects seeks to develop a greenfield, open cut mine to extract and process vanadium pentoxide (V_2O_5) and High Purity Alumina (HPA), along with minor quantities of other Rare Earth Elements (REE). This paper utilises publicly available information to evaluate potential environmental risks associated with the project and to identify opportunities for risk mitigation. In addition, it offers recommendations that may assist the planning and assessment of similar vanadium developments within the region.

Oil shale

Oil shale is a fine-grained sedimentary rock that contains a high proportion of mineral matter and kerogen, with minor bitumen, and can produce liquid hydrocarbons through thermal degradation (retorting). Kerogen consists of complex, high-molecular-weight organic compounds rich in aliphatic hydrocarbons and typically low in aromatic structures (Hu *et al,* 2022).

The Toolebuc Formation, an organic-rich shale unit of Early Cretaceous age, has long attracted interest as a potential unconventional hydrocarbon resource. It is a heterogeneous unit consisting of limestone, calcareous shale, oil shale, coquinite, sandstone, siltstone and mudstone (Senior, Saxby and Ferguson, 1975; Senior, Saxby and Smart, 1978; Smart, Senior and Saxby, 1980). Mineralogically, the shale is composed mainly of calcite, kerogen, quartz, kaolinite, smectite and pyrite, with minor mixed-layer clays and gypsum and trace sulfide minerals such as sphalerite, chalcopyrite and galena. In oxidised zones, kerogen and pyrite are largely altered, forming amorphous oxidised organic residues and iron oxides such as goethite and hematite (Riley and Saxby, 1982). The formation is also enriched in a range of trace elements including molybdenum (Mo) and Rare Erath Elements (REE). Vanadium enrichment is interpreted to have resulted from biological accumulation from sea water under anaerobic marine conditions during deposition. Vanadium occurs in several mineralogical hosts including organic matter, clay minerals, pyrite and silicates. Around 60 per cent of the vanadium in fresh shale from the Julia Creek area is associated with mixed-layer clays, with the remainder occurring in silicates, pyrite and organic matter (Patterson, 1994). A review by Ng and Forbes (2025) found that from a mineral processing perspective, the bulk of the vanadium is hosted in clays, particularly montmorillonite and illite. Vanadium is adsorbed onto clay surfaces, substituting into octahedral Al sites (V^{3+} or V^{4+}), and structurally or surface-bound within phyllosilicates.

Vanadium geochemistry

Vanadium occurs in four oxidation states (+II, +III, +IV and +V), but only +III, +IV (vanadyl) and +V (vanadate) are environmentally significant. V(II) is unstable in aqueous systems and does not occur within the stability field of water. Vanadium speciation is strongly controlled by redox and pH conditions: vanadate (V^{5+}) predominates under oxic and moderately alkaline conditions, whereas vanadyl (V^{4+}) is favoured in reducing, low-pH environments, particularly where dissolved organic matter is abundant. Under very low redox conditions, V(III) becomes stable and is commonly associated with reduced sediments and black shales.

In soils and sediments, vanadium occurs as both structurally bound and surface-bound species. Structurally bound vanadium is typically octahedrally coordinated V^{4+}, while surface-bound vanadium mainly occurs as vanadate adsorbed onto iron and aluminium (hydr)oxides, forming strong bidentate complexes. Organically complexed vanadyl may also be important in acidic organic soils.

Vanadium mobility is highly sensitive to redox changes, with events such as flooding causing substantial but site-specific variations in dissolved concentrations. Although vanadium is an essential micronutrient for some organisms, environmental risks arise because vanadate (VO_4^{3-}) closely resembles phosphate (PO_4^{3-}), enabling interference with key biochemical processes in aquatic organisms. Reflecting its toxicity, the Australian and New Zealand freshwater guideline value is only 6 µg/L (ANZG, 2018), while typical freshwater concentrations are often below 1 µg/L.

Transport of vanadium from terrestrial to aquatic environments occurs largely via suspended particulate matter because dissolved vanadium is highly particle-reactive and strongly sorbs to iron oxyhydroxides and organic matter such as humic substances (Gustafsson, 2019).

GEOLOGY, MINING AND MINERAL PROCESSING

The project area is located in the Eromanga Basin region and involves formations that are part of the basin's geological system, but it is actually situated on a structural high (Euroka Ridge) that separates the Eromanga Basin and the Carpentaria Basin, so it is not entirely within the main basin depocentre.

The Toolebuc Formation, which hosts the orebody, comprises a sequence of marine limestones and calcareous oil shales of Cretaceous (Upper Albian) age and is widespread throughout much of the

Northern Eromanga Basin. The formation locally includes fossil rich limestone with minimal diagenesis and is dominated by heterogeneous calcareous and bituminous siltstone, black sandstone, and shale that host the minerals of interest. It is underlain by the argillaceous sediments of the Wallumbilla Formation.

The vertical mining sequence is described as:

- Quaternary Alluvium: comprising topsoil (thickness 0.5 m) and subsoil.
- Wondoola Beds (WLD): consists of soil, clay, sand and gravel.
- Mudstone Horizon: The Allaru Mudstone (ALM) consists of blue-grey mudstone composed of clay-sized particles with some siltstone beds. This unit is considered overburden waste material and will be used as backfill.
- Limestone: The Toolebuc Formation horizon (TLBA) contains low vanadium grades. Some of this limestone will be required for processing and neutralising acidic materials and the remaining will be considered waste and handled accordingly.
- Mineral Resource: The weathered Wilat's Crossing Oil Shale (TLBB) and Arrolla Shale (TLBD) are considered mineral resources and will undergo processing.
- Floor: The transition geology unit (TLBE) between the Toolebuc Formation and the underlying Wallumbilla Formation, is considered poor quality for vanadium but will be mined for REE. The basement Wallumbilla Formation is a blue-grey mudstone unit.

The case study will be developed as a shallow open pit operation using conventional truck and shovel strip mining, with no blasting required due to the weathered and unconsolidated nature of the materials. Mining will progress over an estimated 26-year life, with pit depths of approximately 15–30 m and will be accompanied by progressive in-pit backfilling to minimise the final disturbance footprint.

The project plan emphasises integrated waste and rehabilitation management, including early soil stripping, strategic placement of acid consuming materials, and encapsulation of any potentially acid forming units. At closure, the mine will not contain a permanent open void, with the backfilled pit expected to form a stable, non-polluting landform suitable for long-term rehabilitation and agreed post mining land use.

The following is the current understanding of the treatment of run-of-mine (ROM) ore to produce V_2O_5 and high purity alumina (HPA) products:

1. Crushing: This will reduce the size of the ore to below 5 mm and also includes a scrubber to pre-condition the ore and disperse the clays from the calcite and other gangue. The waste from this step is coarse ore rejects which is mostly acid-consuming and will be backfilled into the pit void.
2. Flotation: In a reverse flotation circuit calcite is floated off leaving the valuable vanadium-bearing minerals in the tailings. The tailings will be dewatered before leaching.
3. Sulfuric acid Leach: Vanadium is extracted from the ore by H_2SO_4 in stirred tanks. This leach also extracts aluminium and iron as sulfates.
4. Solvent Extraction: Involves addition of organic solvent to the leachate followed by the addition of ammonia to remove vanadium (stripped in multiple stages) from organic, to produce a clean vanadium-loaded strip solution.
5. Ammonium Metavanadate (AMV) precipitation: pH is adjusted and ammonium sulfate is added to the liquor to precipitate NH_4VO_3.
6. Calcination to V_2O_5: The filtered AMV is dried and calcined at high temperature to produce V_2O_5, with released ammonia captured and recycled. The calcined V_2O_5 is then packaged for transport.

The waste from steps 3–6 is leached vanadium residue which is highly acidic and will be neutralised by Ca-rich concentrate (from step 2) and will be mixed and co-disposed with other mine waste and allowed to dry before backfilling into the pit void.

7. High Purity Alumina (HPA): This involves extraction of aluminium into a sulfate solution as a side stream of solvent extraction. Lava Blue will develop a suitable stream to feed their patented HPA process.

   The disposal options for the waste from Al extraction are still under consideration.

8. Rare Earth Elements will be extracted through a water-based beneficiation, followed by leaching with H_2SO_4, and then neutralisation and precipitation.

The rejected coarse material from RRE ore will likely be co-disposed with acid-consuming V coarse rejects and backfilled into pit void.

The co-disposed combined residue stream in the mined pit will be covered with waste rock material including Toolebuc Limestone, Allaru Mudstone, Quaternary Alluvium and original subsoil and topsoil profile.

Figure 1 provides a conceptual model of the open pit during the operational phase of mining and after mine closure and rehabilitation, outlining key hydrological transport pathways.

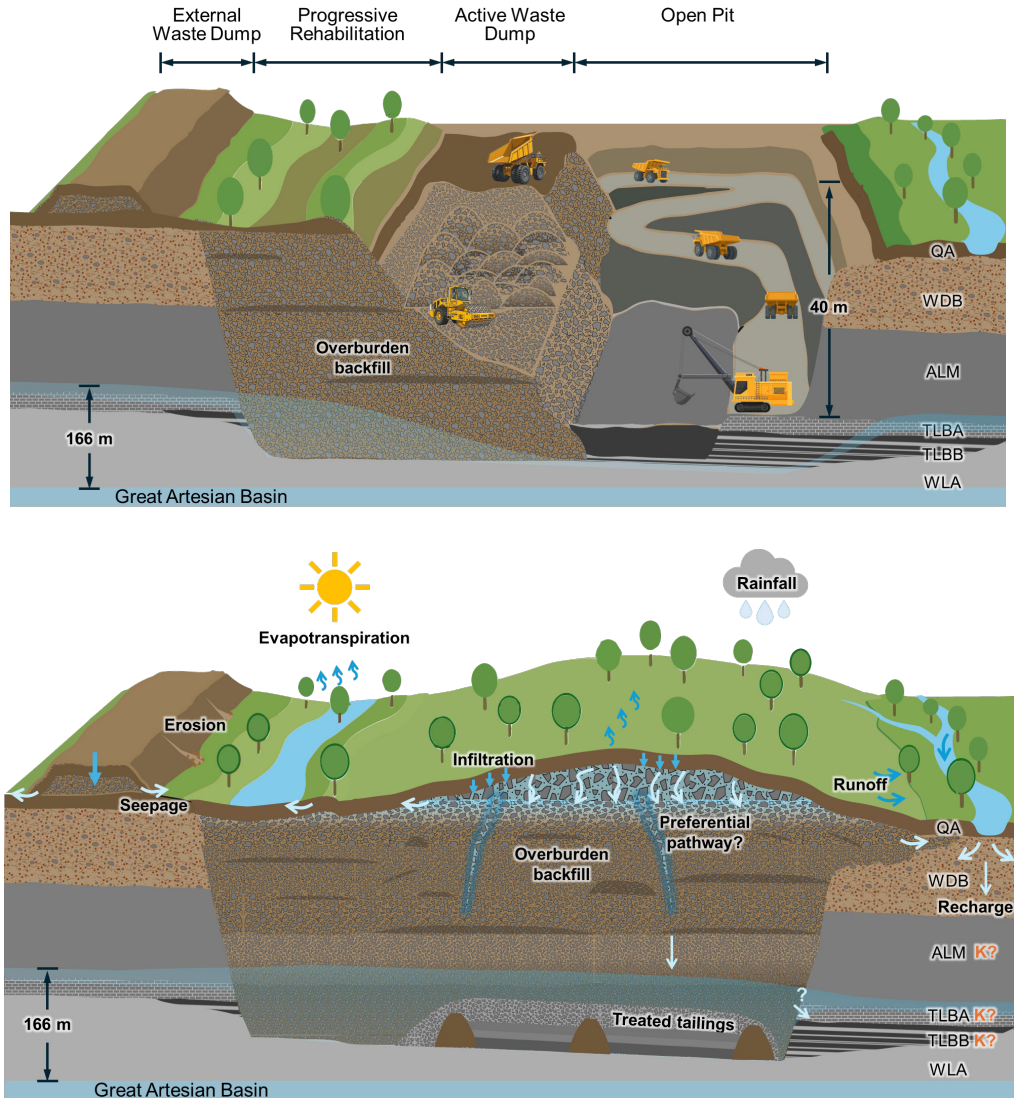


FIG 1 – A conceptual model of the open pit during the operational phase of mining (top) and after mine closure and rehabilitation (bottom).

CLIMATE AND WATER RESOURCES

The project area experiences a semi-arid climate, characterised by hot, humid summers and dry, warm winters. Rainfall is highly seasonal and irregular, with the majority occurring during the summer wet season (October–March), typically as heavy thunderstorms or rain depressions from decaying cyclones. Rare rainfall events can occur in any given year. It cannot be assumed that the possibility of experiencing a rare rainfall event can be excluded because the life of the mine is short. Rare rainfall events must be considered when designing the mine and its associated infrastructure. In addition, based on research conducted at the University of Queensland, the region in which the project is located will be a 'hot spot' of climate change. It is projected to experience the largest increases in rainfall erosivity, maximum daily precipitation, drought frequency, and duration of dry periods (Bulovic, McIntyre and Trancoso, 2024). This poses risks to:

- stormwater management: increased erosive power of rainfall means that traditional erosion and sediment control measures might not be as effective.
- mine water system: increases in maximum daily precipitation can impact on the selection of design criteria for the structures that store mine-affected water.
- water supply: if the mine relies on surface water for its water supply, increase in drought frequency and duration of dry periods can influence the reliability of water supply.

Surface water

The project is located near the Saxby River, an ephemeral watercourse that remains dry for much of the dry season but can experience substantial flows during the wet season. In theory, it would be possible to extract water from the river in periods of high flows to provide water supply to the mine, but it would require complex infrastructure to extract and transport large volumes during short periods and to store the water at the mine.

There are substantial gaps for several physico-chemical parameters relevant to the Saxby River and surrounding catchments. The limited availability of guideline values means that many indicators commonly used to assess potential impacts of mine-affected water, such as major ions and several metal species, do not currently have locally appropriate thresholds for slightly to moderately disturbed ecosystems. Among the parameters assessed, turbidity is the most notable exceedance when compared with available guideline values. Field data show that turbidity levels at Julia Creek and within the wider Flinders River system frequently rise well above the guideline value during periods of high flow. Elevated turbidity is likely to reflect natural hydrological dynamics rather than anthropogenic disturbance.

It will be necessary to derive site-specific guideline values (SSGVs) following the framework set out in ANZG (2018) and the Queensland Water Quality Guidelines. Establishing SSGVs is particularly important in this region given the natural mineralisation of soils, the episodic hydrology of the Saxby River, and the need to ensure that release conditions reflect operational constraints, natural background variability and ecological protection objectives.

Groundwater

The principal hydrogeological units in the Project area are:

- The Toolebuc Formation, in which the upper fossiliferous limestone unit (St Elmo Coquina) forms the primary water-bearing zone. The permeability of the underlying shale and mudstone units is largely controlled by the presence, extent, and connectivity of fractures.
- The Gilbert River Formation, a productive porous sandstone aquifer within the Great Artesian Basin (GAB), which is confined beneath the Wallumbilla Formation and exhibits artesian conditions in the vicinity of the Project.
- Minor local unconfined aquifers, which may occur within Quaternary alluvium associated with the Saxby River and within the Tertiary Wondoola Beds where sandy facies are present.

Faults intersecting the orebody may act as preferential pathways for the off-site migration of contaminants following groundwater recovery within the pit. This potential should be considered in

the design of the groundwater monitoring program and assessed as part of the Environmental Impact Statement (EIS).

If discontinuities, fault zones, or other higher-permeability pathways are present within the Wallumbilla Formation, upward leakage from the Gilbert River Formation (GAB) into the Toolebuc Formation may occur.

Regional aquitards in the Project area include the Allaru Mudstone, which overlies the Toolebuc Formation, and the Wallumbilla Formation, which separates the Toolebuc Formation and Gilbert River Formation. Both comprise predominantly low permeability mudstone and siltstone.

Recharge to the Gilbert River Formation occurs approximately 100 km east of the project, where the aquifers are exposed at the surface or where the Cenozoic cover is relatively thin.

Several active spring complexes occur within 50 km of the Project. These springs are sourced from GAB aquifers. For example, the Sesbania Spring Complex is recognised as having high ecological value, comprising a permanently active groundwater-dependent ecosystem that supports specialist plant and animal species largely restricted to spring wetland habitats within the region.

Other groundwater-dependent ecosystems (GDEs), in which species composition and ecological functions depend on the availability of groundwater, include:

- The Saxby River and its tributaries, together with the aquatic ecosystems they support, which may be hydraulically connected to shallow groundwater within the underlying alluvium or Wondoola Beds.
- Terrestrial GDEs mapped within the proposed mining area and along the Saxby River riparian corridor. These ecosystems are underlain by alluvium or the Wondoola Beds and may rely on groundwater to varying degrees.

All registered water-supply bores within 20 km of the Project access groundwater from GAB aquifers. No bores extract groundwater from the alluvium, Wondoola Beds, or Toolebuc Formation, reflecting the generally low yields of these units. The bores are used primarily for water supply, most likely for stock and domestic purposes, although three are also used for groundwater monitoring. All of the bores are artesian.

Mine water management

A detailed water balance is not yet available. Understanding the mine water balance enables understanding of water-related risks, as well as identification of potential performance indicators. The water balance tallies the input of water into the mine from the water supply source, rainfall and run-off, and groundwater; and tallies the output of water through evaporation, entrainment in waste streams and tailings, releases to the receiving environment and any other losses incurred by the mine, such as haul road dust suppression.

There are requirements to ensure that managing non-mine-affected run-off does not lead to soil loss and export of sediments to the receiving environment. To this end, mines must design and implement an erosion and sediment control plan (ESCP). Sediment dams form part of the ESCP and are meant to only capture non-mine-affected water. Run-off from disturbed landforms is deemed mine-affected water unless water quality data are available to prove that it does not contain elevated concentrations in any contaminants. There is a knowledge gap regarding the quality of the various sources of mine-affected water, and they will need to be addressed through testing of the waste materials that constitute the waste rock dumps.

POTENTIAL GEOCHEMICAL HAZARDS

The orebody (TLBB to TLBE) contains acid neutralising capacity (ANC) that is initially high but decreases with depth, whereas the ANC in the Mudstone floor black shale (WLA) is low. It is assumed that the entire TLBB to TLBE formation will be processed and returned to the pit as NAF residue. During this process, the WLA formation will be exposed. If the WLA formation locally contains sulfide minerals, it will react and become acid forming (AF) within days to weeks of exposure. Based on this information, while most materials at the site are non-acid forming or

acid-consuming due to low pyrite content and/or abundant acid neutralising capacity, localised sulfide-rich units, particularly the mudstone floor, can rapidly generate acid and sulfate upon exposure.

Aqua regia digest dissolves most sulfides, carbonates, oxides, and some silicates and reflects total (or near-total) element abundance in the solid phase. The aqua-regia elemental concentration results for all samples can be divided into four ranges of concentrations:

1. Major (>1 wt per cent or >10 000 mg/kg): aluminium, calcium, iron, sulfur.
2. Minor (1000–10 000 mg/kg): magnesium, phosphorous, potassium, sodium.
3. Sub minor (100–1000 mg/kg): barium, copper, manganese, molybdenum, nickel, strontium, titanium, vanadium, zinc.
4. Trace (<100 mg/kg): antimony, arsenic, beryllium, bismuth, cadmium, caesium, cerium, chromium, cobalt, gallium, germanium, hafnium, indium, lanthanum, lead, lithium, mercury, rhenium, rubidium, scandium, selenium, silver, tellurium, thallium, thorium, tin, uranium, yttrium, zirconium.

Elements likely to become mobile in groundwater

Leachate (or water extract) represents mobile or readily soluble fraction. The unfiltered water extracts provide a good estimate of the readily water-mobilisable pool of ions, metals, and metalloids. A comparison of the filtered versus unfiltered water-extract results can help us understand which elements are most-likely in soluble form and transported in groundwater. The unfiltered results represent the total material mobilised into the aqueous phase during the extraction, including both dissolved and very fine particulate phases, including nanoparticles, clay colloids, Fe/Al oxyhydroxide particles, and organic-metal complexes. This is a good representation of surface water after first-flush during high intensity rainfall. However, it is worth noting that the filtered samples are not representative of true dissolved form of water constituents. The filter size commonly used for dissolved metals in water is 0.45 µm (micrometres). This is the standard operational definition used in most environmental and geochemical studies. However, this filter size may still pass colloids and nanoparticles. The truly dissolved species are much smaller and ideally water samples should be filtered below 0.003 µm. Also important to note is that mobility of elements under oxidising laboratory conditions would be different from variable redox environment of groundwater in a backfilled pit.

The elements most likely to become soluble in groundwater can be grouped as follows:

- Highly soluble/mobile (B, Li, Mo, Sr, Se, U).
- Moderately soluble depending on conditions (Ni, V, Co, Cu, Mn).
- Low solubility, particle-bound (Al, Ti, Cr, Pb, REEs, Zr, Y).

Redox conditions and vanadium mobility

The vanadium species V(IV) or ‘vanadyl’ occurs in moderately reducing environments and prevails at solution pH below 4, whereas V(V) is referred to as ‘vanadate’ and occurs in oxidising conditions as the oxyanion vanadate (H_2VO_{4-}), which dominates above pH 4 (Larsson, Gustafsson and Berggren, 2013). Vanadate is the bioactive and toxic form absorbed in the body, and toxicological assessments consider V(V) the species of concern.

The vanadium mobility is likely controlled by a combination of oxidation state ($V^{4+} \rightarrow V^{5+}$ increases mobility), adsorption onto Fe oxyhydroxides, and pH-dependent surface complexation. Figure 2 shows the stability field for vanadium species and the range of pH values for the main lithologies and the treated residue. Most water extract samples are circumneutral to alkaline (pH 6.51 to 10.1). Vanadium would most likely occur as vanadate under oxidising alkaline conditions, meaning high mobility in oxidised waste rock, potential attenuation by Fe oxides, increased transport in carbonate-buffered waters.

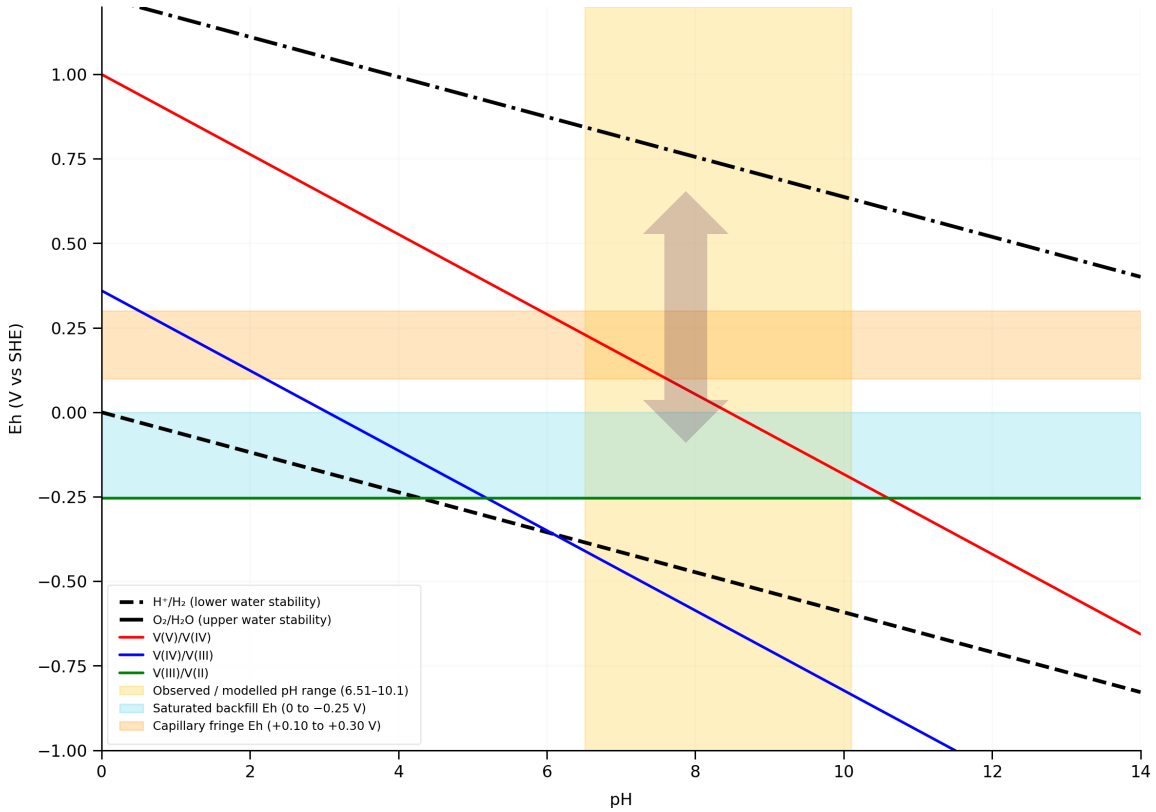


FIG 2 – A generic Eh-PH (plotted with Copilot) diagram for vanadium with site-specific redox and pH bands. dashed black lines are the stability limits of water and the air O_2/H_2O line. The coloured domains show where each oxidation state of V is thermodynamically favoured.

If some waters are suboxic or reducing in the field, their actual Eh could lie below the O_2/H_2O line, shifting points into V(IV) or V(III) regions, especially at neutral to alkaline pH.

Once the water table re establishes in the backfill, from oxic to anoxic, conditions are expected to change.

The backfilled pit's saturated zone will shift stability away from V(V) toward V(IV) (and locally V(III)), reducing vanadate mobility relative to oxic conditions. However, the capillary fringe may be transiently oxic. As discuses below differential compaction may create zones with less or more oxygen in the backfilled pit.

In surface water, a key pathway for vanadium transport from the terrestrial to the aquatic environment is via suspended particulate matter because dissolved vanadium is highly particle-reactive and sorbs strongly to both inorganic mineral phases (eg iron oxyhydroxides) and organic matter (eg humic substances) (Gustafsson, 2019).

Including measurements of dissolved oxygen, oxidation-reduction potential (ORP), and redox-indicator species such as ferrous iron and nitrate in the monitoring program would refine sample positioning and interpretation and support improved risk assessment.

WASTE MANAGEMENT AND FINAL LANDFORM

The mine pit will be progressively backfilled with overburden and processing residues over the projected 26-year mine life. An initial ex-pit waste dump will be constructed early in operations until sufficient pit void becomes available for backfilling. Both the ex-pit dump and backfilled areas will be capped with 1.5 m of subsoil and 0.5 m of topsoil to restore the pre-mining soil profile. All external slopes will be formed at a maximum gradient of 1:10 to reduce erosion risk.

Processed residue will be produced on-site and will be returned to the base of the open pit. The residue will be a combined stream of ore processes to recover vanadium, residue processed to recover high purity alumina (HPA) and ore processed to recover rare earth elements (REE). The

combined residue stream is planned to be co-disposed into the mined pit and covered with Toolebuc Limestone, Allaru Mudstone, Quaternary Alluvium and the original subsoil and topsoil profile.

The backfill may contain local layers with different permeabilities. Bulldozer placement may create heterogeneous compaction with highly compacted traffic lanes, less compacted loose pockets, variable density between lifts, and differential settlement zones. Therefore, variable compaction and differential settlement in the overburden backfill could lead to perched water tables.

In addition, preferential flow and seepage pathways commonly develop in-pit backfill with heterogeneous materials. Preferential flow occurs when water moves rapidly through specific pathways instead of uniformly through the entire material. These pathways typically develop along fractures or cracks, coarse layers or lenses, material interfaces, poorly compacted zones, desiccation cracks.

Heterogeneous backfill materials have different grain sizes and permeabilities, which naturally produce hydraulic contrasts.

Backfill placed by dozers rather than engineered compaction tends to produce uneven densities, localised loose zones, coarse rock clusters, compacted traffic layers. This may create a patchy hydraulic structure.

Over time, the backfill will settle because fine materials consolidate, coarse fragments remain stable, and void spaces collapse unevenly. This process can create vertical fractures, preferential void networks, and open flow channels.

CONCLUSIONS AND RECOMMENDATIONS

Most mined and processed materials are non-acid forming or acid consuming due to abundant carbonate minerals, but geochemical risk is highly localised and material specific, rather than uniform across the site. The dominant acid generating risk is associated with the mudstone floor (Wallumbilla Formation, WLA) and, to a lesser extent, lower transition units (TLBE) that contain elevated sulfide sulfur. These materials can oxidise rapidly and generate acidic, sulfate rich drainage within weeks of exposure. While many overlying units (limestone roof, Allaru Mudstone, weathered orebody) contain substantial acid neutralising capacity, exposure and poor placement of WLA material represent a critical risk, particularly during pit floor exposure prior to backfilling.

Even where acidity is neutralised, neutral to saline drainage remains a risk pathway. Many lithologies and residues release high concentrations of sulfate, sodium, calcium and magnesium, producing saline waters capable of transporting contaminants at circumneutral to alkaline pH. High electrical conductivity values in water extracts indicate that salt mobilisation, rather than acidity alone, is a dominant long-term water quality concern, especially under arid to semi-arid climatic conditions where evaporation concentrates dissolved ions.

Several trace elements of concern, including vanadium, molybdenum, selenium, uranium, boron and lithium, are present at elevated solid phase concentrations and show moderate to high mobility in water extracts, particularly under neutral to alkaline conditions. These elements form stable oxyanion or conservative dissolved species that are not effectively controlled by pH neutralisation alone. Vanadium is of particular concern due to its low freshwater guideline value and its tendency to occur as mobile vanadate under oxic, alkaline conditions.

Processing residues, especially treated vanadium and HPA residues, are chemically distinct from natural lithologies. While neutralisation increases pH and reduces acid risk, residues are sulfate rich, moderately saline, and enriched in certain trace elements, creating a potential source of long-term leaching once saturated in the backfilled pit. Residues also lack sufficient clay content to reliably act as a low permeability barrier, increasing reliance on placement control and encapsulation performance.

Table 1 (following the References) summarise the risk analysis results and recommendations arising from this study. The study identified knowledge gaps, some of which are project specific and should be addressed by the proponent through targeted testing and design refinement, while others are regional in nature and warrant coordinated, large scale studies to avoid duplication across multiple proposed projects in the Julia Creek vanadium province. In addition, several recommended

investigations involve emerging methods that would benefit from direct involvement of research institutions alongside conventional consultancy studies. At regional scale, coordinated studies are recommended to develop shared baseline data sets, regional hydrogeological models, and regionally derived water quality and ecological guideline values, avoiding duplication of effort across proponents and enabling more robust cumulative impact assessments.

Several of the recommended investigations, particularly those involving advanced redox monitoring, long-term coupled geochemical–hydrological experiments, and process informed residue characterisation, remain at the boundary between consultancy practice and research. These would benefit from active involvement of universities and research organisations, working alongside industry and regulators to advance applied knowledge while directly informing project design, regulatory assessment and closure planning across the broader Julia Creek vanadium province.

REFERENCES

Australian and New Zealand Guidelines (ANZG), 2018. Guidelines for fresh and marine water quality, Australian and New Zealand Governments and Australian state and territory governments, Canberra.

Bulovic, N, McIntyre, N and Trancoso, R, 2024. Climate change risks to mine closure, *Journal of Cleaner Production*, 465:142697. https://doi.org/10.1016/j.jclepro.2024.142697

Gustafsson, J P, 2019. Vanadium geochemistry in the biogeosphere: speciation, solid-solution interactions, and ecotoxicity, *Applied Geochemistry*, 102:1–25. https://doi.org/10.1016/j.apgeochem.2018.12.027

Hu, S, Wang, Q, Li, Y and Zhang, J, 2022. Kerogen structure and hydrocarbon potential of marine oil shales, *Energy and Fuels*, 36(2):965–978.

Larsson, E, Gustafsson, J P and Berggren, D, 2013. Vanadium bioavailability and toxicity in soils, *Environmental Toxicology and Chemistry*, 32(10):2266–2273.

Ng, W S and Forbes, E, 2025. Flotation separation of vanadium-bearing clays, kerogen, and calcite in the Julia Creek oil shales, *Minerals Engineering*, 233:109630. https://doi.org/10.1016/j.mineng.2025.109630

Patterson, D J, 1994. Vanadium mineralogy of the Toolebuc Formation, *Australian Journal of Earth Sciences*, 41:123–136.

Riley, K W and Saxby, J D, 1982. Weathering of oil shale and redistribution of trace metals, *Chemical Geology*, 36:189–205.

Senior, B R, Saxby, J D and Ferguson, J, 1975. Geology of the Toolebuc Formation, Bureau of Mineral Resources, Canberra.

Senior, B R, Saxby, J D and Smart, J, 1978. Depositional environment of the Toolebuc Formation, *AAPG Bulletin*, 62:1201–1218.

Smart, J, Senior, B R and Saxby, J D, 1980. Stratigraphy of the Julia Creek oil shale, *BMR Journal of Australian Geology and Geophysics*, 5:45–58.

TABLE 1

Risk analysis results and recommendations arising from this study.

Open pit domain					
Risk description	**Cause(s) of risk**	**Potential impacts**	**Predicted controls**	**Uncertainty**	**Recommendations**
Release of contaminants from partially backfilled **overburden materials** into pit water during operation through run-off and infiltration.	Desorption of elements from clay-rich units (eg Mn, F, V). Dissolution of carbonates releasing associated elements (eg Sr, V, U). Oxidation and dissolution of sulfides, leading to the release of acidity, sulfate and chalcophile elements in the Toolebuc Formation and the mudstone floor unit. Dissolution of secondary minerals/salts.	Contamination of surface water in the pit and local groundwater. The likelihood of local contaminant release from spoils during operation is moderate, but the severity of impact will depend on coordination and efficiency of mining and in-pit waste and water management efforts.	A sump will collect the infiltration and run-off from partially backfilled materials, contaminated water is pumped back to surface and treated. WLA Floor is not allowed to oxidise.	Hydrogeology of the partially backfilled materials, the effects of differential settlement, spatial variations in the degree of saturation, diffuse versus preferential flow, variety of particle size, clay content and durability of rocks. Timing of cover placed over WLA Floor. Efficiency of compaction of overburden materials used as cover over residue cells.	A sequential extraction test to analyse chemical forms and mode of occurrence of contaminants in main lithologies and residues. Scale up kinetic column leaching test to take into account factors such as particle size, hydraulic conductivity, realistic water-rock ratios, and spatial heterogeneity of backfill materials.
Release of contaminants from **process residues** placed on the floor of the partially backfilled open pit.	Both types of residues (vanadium and HPA) contain moderate to highly mobile elements (eg V, U, Se, As) which can be leached out by interaction with percolating water.	Contamination of surface water in the pit and local groundwater. The likelihood of local contaminant release from residues during operation is high, but the severity of impact will depend on timely coordination and efficiency of mining and in-pit spoil/reside and water management.	A sump will collect the infiltration and run-off from partially backfilled materials, contaminated water is pumped back to surface and treated. Dewatering and blending with calcite and lime. Efficient in-pit drying and compaction process. The residue materials effectively perform as low permeability layers.	A limited number of samples which do not represent the ore variability and process efficiency over time. No REE residue available yet. Efficiency of the dewatering and blending with calcite and lime. Efficiency of the in-pit drying and compaction process. *In situ* performance of the residue materials as low permeability layers.	Geochemical characterisation of residues, including testing the effectiveness of the neutralisation process and sequential extraction. Column leaching incorporating hydraulic parameters (eg at different compaction and desiccation rates) and as part of a cover with overburden on top.

Open pit domain					
Risk description	**Cause(s) of risk**	**Potential impacts**	**Predicted controls**	**Uncertainty**	**Recommendations**
Release of contaminants from backfilled **overburden materials and residues** into pore water after mine closure.	After mine closure, the circumneutral to mildly alkaline pH conditions in backfilled spoils may enhance the mobility of certain elements. Residues also lack sufficient clay content to reliably act as a low permeability barrier, increasing reliance on placement control and encapsulation performance. The cover may not perform as designed leading to solute transport and elevated water table inside the pit.	As groundwater rebounds in the former pit, it may contact waste materials, causing contamination and possible off-site migration. The likelihood of local contaminant release from spoils after closure is high, but the severity and extent of its impact will depend on the performance of soil cover system, and the placement and performance of the treated residue over the mudstone floor, as well as the quality surrounding natural groundwater.	Natural attenuation due to saturation and reducing environments, treated residue acts as an effective cover and acid consuming, and backfilled materials with highly effective acid neutralising capacity, the soil cover system performs as designed.	Degree of saturation at various locations inside the backfilled pit, local exposure to oxygen, performance of the cover in reducing infiltration and oxygen ingression. The current geochemical models. Not enough local groundwater monitoring data.	Current pit water quality geochemical models are based mainly on extract and kinetic leaching tests, which capture contaminant release processes but not the hydrological reality of a backfilled pit. Larger column tests tailored to the site conditions will help validate those models, by generating key parameters required for solute transport models. Residue and spoil to be tested together Performance of encapsulation and the cover system to be tested.

Out of pit landscapes					
Risk description	**Cause(s) of risk**	**Potential impacts**	**Predicted controls**	**Uncertainty**	**Recommendations**
Release of contaminants from out of pit landscapes into surface water.	Reactive materials in overburden dumps, cleared areas, and areas under early rehabilitation.	Contaminants can be transported as suspended particulate form, or in solution polluting stream sediments and stream water. Vanadium, for example, is particle-reactive. There is a high risk of non-compliant mine-affected water releases if not appropriately managed.	This water must be contained in mine-water storage structures, and any overflow must occur only in accordance with release conditions.	The performance of cover system over the out-of-pit waste rock pile.	Testing is required to determine the quality of run-off from disturbed areas. Required studies include geochemical characterisation, leachability testing and run-off simulation experiments. Undertake water-balance modelling incorporating likely mine-affected run-off. Redesign structures classified as ‘sediment dams’ into mine-water dams where necessary. Ensure all storages align with required release criteria.
Increased erosive power of rainfall leads to reduction of effectiveness of controls.	Climate-change projections indicate increased rainfall erosivity.	Reduction in the effectiveness of traditional erosion and sediment control measures (eg sediment basins, diversion drains, slope stabilisation), leading to minor to moderate risk depending on extent of non-compliance with erosion and sediment control conditions.	Update and strengthen erosion and sediment control plan (ESCP) design criteria to reflect future rainfall erosivity.	Uncertainty arises from climate-change projections, although the downscaled modelling used in the study that is referred to (Bulovic, McIntyre and Trancoso, 2024) has high confidence and indicates this is a credible risk. This risk may become more significant over the coming 20–40 years.	Incorporate climate change projections into water balance models.
Release conditions are not adapted to local conditions.	Release conditions based on default guideline values might be overly conservative.	Over-design of the mine water system (with associated high capital cost), inability to release excess water during wet seasons, and accumulation of mine water, ultimately interrupting operations.	Review and resize mine-water storages based on updated release criteria.	There is insufficient water quality data for developing appropriate thresholds.	Develop site-specific guideline values (SSGVs) for several parameters. Develop release conditions aligned with hydrology of ephemeral systems and local baseline water chemistry.

Mineral processing domain					
Risk description	**Cause(s) of risk**	**Potential impacts**	**Predicted controls**	**Uncertainty**	**Recommendations**
Release of contaminants from solid and liquid waste.	Acid solutions and (any solid phase) containing residual toxic elements.	Risk of polluting local soil, surface water and shallow groundwater, land and water.	Treatment and Containment.	Fate of chloride waste from HPA, acid from REE extractions and acid from vanadium extraction. Efficiency pf dewatering and blending process.	Appropriate plans for liquid waste management, proper design of waste storages.

Project water supply					
Risk description	**Cause(s) of risk**	**Potential impacts**	**Predicted controls**	**Uncertainty**	**Recommendations**
To source water from existing bores and pump it to the Project site via a pipeline will not meet the Project water requirements.	The presence of multiple high-yield uncontrolled bores within 20 km of the Project site poses a risk to regional water supply through potential drawdown, competition for groundwater resources, and unmanaged abstraction.	Insufficient water supply, capping multiple bores, complex negotiations with landholders or purchasing properties with uncontrolled bores.	Alternative options, such as a borefield or water harvesting from the Saxby River.	Potential environmental risks.	Identify an alternative water supply solution and assess the potential environmental impacts.
The Saxby River provides an unreliable water supply for the Project.	Ephemeral nature, highly variable short-duration flows, infrastructure constraints for capturing wet-season events, and reduced reliability under projected climate-driven increases in drought and dry-season duration.	This represents an operational risk, with potential impacts including operational interruptions, financial losses, and production delays, ranging in severity from moderate to major depending on the duration of the disruption.	Secure water from another source, which is what the project's proponent is investigating.	No major knowledge gaps exist: flow variability is well understood, and surface water is unreliable as a primary supply source.	A regional approach to water supply should be developed.

Using metal-organic frameworks to move acid mine drainage from liability to resource

E Jennings[1], M Edraki[2], J Hou[3] and J Powell[4]

1. Postdoctoral Research Fellow, W H Bryan Mining and Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, Brisbane Qld 4067. Email: elin.jennings@uq.edu.au
2. Professorial Research Fellow, Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, Brisbane Qld 4067. Email: m.edraki@uq.edu.au
3. Associate Professor, Nanomaterials Centre, School of Chemical Engineering, The University of Queensland; ARC Centre of Excellence for Green Electrochemical Transformation of Carbon Dioxide, Brisbane Qld 4067. Email: jingwei.hou@uq.edu.au
4. Postdoctoral Research Fellow, Nanomaterials Centre, School of Chemical Engineering, The University of Queensland, Brisbane Qld 4067. Email: j.powell1@uq.edu.au

ABSTRACT

Mine wastes are a long-term environmental liability, often associated with substantial remediation costs. As declining ore grades drive increased material throughput, the generation of waste streams such as acid mine drainage (AMD) continues to rise, contributing to persistent risks related to environmental contamination, and long-term treatment. These challenges are accompanied by significant operational and closure costs, which are often underestimated in conventional economic assessments.

There is growing interest in re-framing mine waste within a circular economy perspective, particularly where waste streams contain recoverable critical and strategic metals. In this context, AMD represents a chemically complex but potentially valuable feedstock due to its elevated iron content and dissolved species.

This work investigates the utilisation of AMD as a precursor for the synthesis of metal-organic frameworks (MOFs), a class of porous materials with applications in carbon capture, water treatment, and critical metal recovery. The study focuses on synthesising iron-based MOFs (eg MIL-100) from both synthetic and site-derived AMD.

The influence of AMD variability, including iron concentration and speciation, acidity, and co-occurring contaminants on MOF formation, crystallinity, and functional performance, is investigated. The incorporation of impurities into the framework structure is evaluated, and the formation of competing phrases, including alternative MOF and AMD-related secondary phases (such as iron oxides), which may reduce and alter MOF-phase properties.

Preliminary characterisation using simulated AMD indicates successful formation of iron-based MOF-phases, with BET surface areas (N_2, 77k) exceeding 80 per cent from MOFs synthesised with laboratory-grade reagents, suggesting high sorption rates can be obtained using complex materials such as mine waste. Furthermore, the synthesis is tolerant to the presence of a variety of heterometals, indicating the potential for upcycling from a wide range of AMD sites. Therefore, this work demonstrates a pathway for converting AMD from a remediation burden into a reuse benefit, supporting the development of closed-loop systems for water treatment and resource recovery, in the mining industry.

Collaborative assessment of legacy materials – potential to improve environmental outcomes and unlock copper and cobalt value at Mt Oxide

M Longbottom[1] and L Nicholls[2]

1. Head of ESG and Innovation, True North Copper, Brisbane Qld 4000.
   Email: mark.longbottom@truenorthcopper.com.au
2. Geologist – Australia Site Evaluation, Regeneration Enterprises, Brisbane Qld 4000.
   Email: lnicholls@regeneration.enterprises

ABSTRACT

Legacy mine sites across Australia commonly contain substantial volumes of historical waste materials that represent long-term environmental liabilities, rehabilitation obligations and ongoing management costs. These materials, including waste rock, low-grade ore stockpiles and historical heap leach residues, have traditionally been regarded as liabilities despite potentially containing recoverable concentrations of critical minerals. At a time of increasing demand for copper and cobalt to support electrification and the energy transition, re-evaluating these legacy materials offers the potential to convert legacy mine liabilities into productive assets that may support the restart of historic mining districts while improving environmental outcomes.

The Mt Oxide Project in north-west Queensland contains a range of historical mine materials remaining from mining operations undertaken between 1967 and 1971. Since acquiring the project in 2023, True North Copper has implemented a district-scale exploration strategy that has expanded beyond the historical mine footprint, culminating in the Aquila copper discovery approximately 5 km north of Mt Oxide in 2025. Alongside this exploration success, True North Copper partnered with Regeneration Enterprises to undertake a comprehensive technical assessment of the legacy mine materials, evaluating their geological characteristics, metallurgical response and potential contribution to future project development.

A multidisciplinary characterisation program was completed across the Mt Oxide legacy waste inventory to evaluate the geological, geochemical and metallurgical characteristics of the historical mine materials. The investigation included a 16-hole sonic drilling program (201.7 m), geological and geometallurgical logging, multi-element geochemical analysis, quantitative mineralogical characterisation, sequential copper leach testing and metallurgical evaluation. The work demonstrated that copper is predominantly hosted within secondary, acid-soluble copper minerals, with 71–83 per cent of copper readily leachable under conventional hydrometallurgical conditions. Geometallurgical domaining successfully predicted metallurgical performance, identifying material capable of achieving 83–86 per cent copper recovery through atmospheric acid leaching, while evaluation of an emerging halide leach technology achieved copper extractions of up to 95 per cent under ambient conditions. These findings significantly reduced technical uncertainty and established a robust foundation for future techno-economic assessment of legacy material reprocessing.

Delivered through the Queensland Government Collaborative Exploration Initiative, with support from the Queensland Government's Abandoned Mines Program, the project demonstrates how collaboration between industry, government and the social enterprise sector can unlock new opportunities from legacy mine waste. The presentation discusses the technical findings, key lessons learned and the potential role of legacy material reprocessing in reducing environmental liabilities while supporting the future redevelopment of historic mining districts.

Selective copper recovery from acid mine drainage using ion-exchange technologies

J G Outram[1], S J Couperthwaite[2] and D T Alexander[3]

1. Lecturer, Queensland University of Technology, Brisbane Qld 4000. Email: j2.outram@qut.edu.au
2. Professor, Queensland University of Technology, Brisbane Qld 4000. Email: sara.couperthwaite@qut.edu.au
3. Chief Science Officer, Lava Blue, Brisbane Qld 4000. Email: dom.alexander@lavablue.com.au

ABSTRACT

Acid mine drainage (AMD) remains one of the most persistent environmental legacies of historic mining, requiring long-term water treatment to mitigate the release of dissolved metals into surrounding ecosystems. Conventional AMD treatment approaches typically focus on neutralisation and precipitation, producing large volumes of sludge while discarding potentially valuable metals contained in the drainage. The use case for ion exchange technologies to recover valuable metals from AMD has gained recent attention (Vecino *et al,* 2021).

This study collected scalable experimental data to inform a process mass balance and techno-economic assessment of the treatment flow sheet. Selective ion-exchange resin was used to capture and concentrate copper from AMD solution to produce a copper sulfate concentrate (14 800 ± 90 mg Cu/L). Preliminary analysis evaluated copper recovery performance, reagent consumption, and concentrate production.

The breakthrough profile observed removal of Cu, Zn, Ni, and Co for the initial 30 bed volumes, after which Zn and Ni broke through sharply to $C_e/C_0 = 1$ and Co gradually broke through to $C_e/C_0 = 1$. Copper was completely removed on the resin for up to ~360 BV, then started to breakthrough sharply at ~480 BV. During the recovery stage, Cu was eluted at a concentration greater than 2000 mg/L between 1.6–3.8 BV, where a concentrate sample was combined from treatment fractions corresponding to 1.9–3.4 BV. This concentrate reported 95.8 per cent Cu (on metals basis), where Al was the main contaminant (3.1 per cent), all other reported metals were <1 per cent.

This work presented preliminary insight into selective copper recovery and concentration as a sulfate electrolyte directly from AMD. Future work will use the data collected to conduct viability studies for site specific process conditions. This preliminary work highlighted the use case for ion exchange technologies to selectively recover valuable metals from AMD streams while simultaneously treating the water.

REFERENCES

Vecino, X, Reig, M, López, J, Valderrama, C and Cortina, J L, 2021. Valorisation options for Zn and Cu recovery from metal influenced acid mine waters through selective precipitation and ion-exchange processes: promotion of on-site/off-site management options, *Journal of Environmental Management*, 283:112004. https://doi.org/10.1016/j.jenvman.2021.112004

Recovery of critical metals from copper tailings – a Queensland case study

A Parbhakar-Fox[1] and R Magwaneng[2]

1. Principal Research Fellow, WH Bryan Mining Geology Research Centre, Sustainable Minerals Institute, University of Queensland, Indooroopilly Qld 4068. Email: a.parbhakarfox@uq.edu.au
2. Resource Engineer, Japan Organization for Metals and Energy Security (JOGMEC), Kosakakozan, Kosaka, Akita, 017-0202 Japan. Email: magwaneng-refilwe@jogmec.go.jp

ABSTRACT

Whilst interest in Co in mine waste has grown, there is lack of fundamental knowledge on Co minerals and their processing. Cobalt recovery efficiency is generally low due to its complex mineralogy, fine particle size and content in a given slurry feed. This paper focuses on: i) determining Co tailings tenor at a mine site in NW Qld, and ii) testing floatability of Co and Cu from two types of tailing feeds- fresh slurry tailings (ST) and stored old tailings (SOT). Specifically, xanthate collectors, activator and pH were used to test the efficacy for concentrating Co and Cu.

139 tailings samples were collected with an average of 570 ppm Co and 2021 ppm Cu. Quartz, plagioclase, calcite, chlorite, magnetite, and amphibole dominate, with average pyrite between 3.1 wt per cent (XRD) to 3.8 wt per cent (MLA). Oxide and sulfides are dominantly free liberated grains with low abundance of mineral locking. Mineral chemistry investigations confirmed maximum Co of 51 815 ppm in pyrite. Other elements notably high in pyrite include Cu (ie pyrite with chalcopyrite intergrowths with up to 277 167 ppm Cu measured), Ni (max: 16 785 ppm) and As (max: 28 092 ppm).

Flotation produced different results for ST and SOT feeds because of mineralogical variability with SOT feed containing more Co than ST. Potassium isopropyl xanthate (PIPX) exhibited favourable flotation for SOT feed while sodium ethyl xanthate was favourable to ST feed. The activator, $CuSO_4$, had a slight improvement for Co recovery, however a higher dosage, 200 g/t, was detrimental to concentrating the target minerals. The pH had the most significant effect for Co recovery using PIPX collector when floating SOT and ST feed. Lastly, copper recoveries were significantly low due to their finer particle size resulting in poor floatability.

Uncovering unconventional critical metal ore deposits in western Tasmania, Australia

A Parbhakar-Fox[1], L Jackson[2], M Tayebi-Khorami[3] and R Coleman[4]

1. Honorary Professor, Sustainable Minerals Institute, University of Queensland, Indooroopilly Qld 4068. Email: a.parbhakarfox@uq.edu.au
2. Adjunct Research Fellow, Sustainable Minerals Institute, University of Queensland, Indooroopilly Qld 4068. Email: l.jackson@uq.edu.au
3. Principal Metallurgist, Core Resources, Albion Qld 4010. Email: mtayebi-khorami@coreresources.com.au
4. Chief Executive Officer, Core Resources, Albion Qld 4010. Email: rcoleman@coreresources.com.au

ABSTRACT

Mineralogical and geochemical characterisation of sulfide minerals in historic tailings can assist in determining whether there are economic and environmental benefits of reprocessing using modern metallurgical practices. At a mine site in Western Tasmania, 38 Mt of pyritic tailings were deposited into an old tailings dam, which is currently being managed by the State Government.

Recent studies sought to determine if Co could be recovered using biohydrometallurgical techniques (Parbhakar-Fox, Glen and Raimondo, 2018). The study proved Co could be recovered, however, experiments were performed on shallow bulk samples. To determine the Co tenor throughout the dam, five sonic drill holes were sunk in 2021. Logged sediments were dominated by three facies: coarse gravels (CG), sulfide sands (SS) and sulfide clays (SC). In total, 238 tailings samples were collected (1 m composites) and subjected to chemical, mineralogical, geoenvironmental and metallurgical investigations.

The average concentration of Co (n=50) was 535 ppm with the highest concentrations identified in proximity to the fixed spigot point. The SS facies contained the highest Co concentrations with pyrite the dominant host. Cobalt and Ni showed strong positive correlation whilst Co showed positive (but less) correlation with Cu. Metallurgical test work indicated that by conventional flotation methods (PAX and a P_{80} of 84 µm), a sulfide concentrate could be made. Concentrates were subjected to three types of Co extraction tests, with the Albion Process™ the most effective to extract Co, Cu and Ni. The new tailings produced was significantly desulfurised with net acid producing potential dropping from 1110 kg H_2SO_4/t for the feed to 61 kg H_2SO_4/t.

These results have helped to provide a strategic understanding of the potential Co resource at depth to assist with long-term business case development. Ultimately this will help the site custodians to develop a long-term economic rehabilitation plan for this historic tailings dam.

REFERENCES

Parbhakar-Fox, A, Glen, J and Raimondo, B, 2018. A geometallurgical approach to tailings management: An example from the Savage River Fe-ore mine, Western Tasmania, *Minerals*, 8(10):454. https://doi.org/10.3390/min8100454

Integrating mine waste remediation with the material demands of the sustainable energy transition

L Roper[1], E Prangige[2] and S Couperthwaite[3]

1. PhD Student, Queensland University of Technology, Brisbane Qld 4000.
   Email: lauren.roper@hdr.qut.edu.au
2. Postdoctoral Research Fellow, Queensland University of Technology, Brisbane Qld 4000.
   Email: e.prangige@qut.edu.au
3. Professor, Queensland University of Technology, Brisbane Qld 4000.
   Email: sara.couperthwaite@qut.edu.au

ABSTRACT

The rapid expansion of renewable energy technologies is increasing demand for critical mineral inputs required for downstream manufacturing. Emerging photovoltaic technologies, including metal halide perovskite solar cells, rely on precursor materials whose supply chains remain dependent on primary mining and geographically concentrated refining capacity. These constraints create supply vulnerabilities while also intensifying environmental pressures associated with new extraction. Developing sovereign and circular supply lines for renewable technology materials is therefore an important challenge for the energy transition. With the abundance of critical minerals residing in Australian waste sources, there is ample opportunity to provide a blueprint for leveraging Australia's status in the development of solar technologies. This work investigates the valorisation of mine wastes and tailings as alternative feedstocks for photovoltaic precursor materials, creating new resource pathways while addressing legacy environmental liabilities.

The research developed a process for the selective recovery and purification of lead (Pb) from complex mine waste streams to produce high-purity lead iodide (PbI_2) for perovskite solar cells. The work targets a waste-to-value approach, whereby Pb can be extracted from low-grade ores, simultaneously reducing the toxicity of the waste for environmental benefit. Additionally, understanding the relationship between the feedstock mineralogy and the dissolution kinetics allowed for process optimisation and impurity control. Whilst Pb itself is not defined yet as a critical mineral in Australia, it remains vital for the energy transition and to contribute value to the supply chains for emerging photovoltaic materials. Although repurposing supports resource circularity, mitigating the environmental footprint requires specific measures for safe Pb handling, toxicity control, and responsible end-of-life management.

By using mineral acids as lixiviants and optimising reaction conditions, selective lead dissolution was achieved while suppressing the co-extraction of common tailings impurities (Fe, Cu, As and Zn). Preferential dissolution of Pb was achieved, with no detectable As and some co-leaching of Fe and Zn. The recovered Pb was stabilised as a chemically reactive species providing a consistent feedstock for the precipitation of lead iodide precursor that met the stoichiometric and morphological requirements for high-efficiency photovoltaic devices. The final PbI_2 product obtained was of >99 per cent purity, with the major impurities able to be removed to comprise of <1 per cent of the final precursor composition. Through further process optimisation and photovoltaic performance testing, a high-efficiency metal halide perovskite solar cell may be synthesised through this work.

This recovery from complex tailings matrices to meet the stringent specifications for precursor materials, such as high purity, size and morphology, presents an opportunity to further Australia's standing in renewable energy by strategic production of materials. By extracting Pb from legacy wastes and converting it into functional precursors, this approach demonstrates a pathway toward environmentally beneficial, sovereign supply chains for renewable technologies, linking mine waste remediation with the growing material demands of the energy transition.

Thermal pretreatment for selective recovery of rare earth elements from permanent magnet waste

R Tao[1], J Schicks[2], K Forsberg[3] and M Svärd[3]

1. Department of Chemical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden. Email: rent@kth.se
2. Faculty of Sciences, Université Catholique de Louvain (UCLouvain), Brussels, Belgium.
3. Department of Chemical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden.

ABSTRACT

The transition towards a low-carbon economy is driving an increasing demand for rare earth elements (REEs), particularly for NdFeB permanent magnets used in electric vehicles and wind turbines. Given the supply chain vulnerabilities associated with primary mining, recycling end-of-life magnets is a strategic priority for securing REEs (Zheng *et al,* 2025). However, the high iron content (60–70 wt per cent) in these magnets poses a significant challenge for conventional hydrometallurgical as well as more novel solvometallurgical routes, often leading to excessive acid consumption and iron separation issues (Tunsu *et al,* 2015). Thermal pretreatment, specifically oxidative roasting, is a promising strategy to facilitate the separation of REEs from iron during leaching. Iron oxide (Fe_2O_3) is more acid-resistant compared with REE oxides, contributing to the selective dissolution of REEs in mild acidic systems (Liu *et al,* 2020). However, simple roasting without additives can promote the formation of stable rare earth orthoferrites ($NdFeO_3$) (Orefice *et al,* 2020), which are insoluble in mild acids and which bind the REEs together with Fe in one solid phase. This necessitates the development of advanced roasting strategies and more selective, environmentally friendly leaching systems to achieve efficient separation.

We develop a selective recycling process integrating alkali-assisted roasting, water washing, and solvometallurgical leaching using a natural deep eutectic solvent (NADES). We systematically evaluate the phase transformation mechanisms across different pretreatment pathways. Direct NADES leaching of raw magnets shows unselective dissolution, with >85 per cent extraction of Nd, Dy, Fe, Co, and B. Roasting without additives confirms the difficulty in preventing $NdFeO_3$ formation, which hinders subsequent REE dissolution. Introducing sodium hydroxide (NaOH) as a roasting additive (NaOH/magnet mass ratio of 0.8, 660°C, 4 h) fundamentally alters the phase transformation, converting Fe into sodium ferrate ($NaFeO_2$) and REEs into oxides. A subsequent water washing step removes sodium and recovers boron, leaving a residue where iron exists as insoluble Fe_2O_3 and neodymium as soluble $Nd(OH)_3$. The losses of REEs, Fe, and Co during water washing are all below 1 per cent. Leaching this pretreated residue with a NADES system composed of choline chloride and levulinic acid (ChCl:LevA, 1:2 molar ratio, 20 wt per cent H_2O) achieves dissolutions of 99.47 per cent Nd, 96.04 per cent Dy, 4.02 per cent Fe, and 16.56 per cent Co, exhibiting high REE/Fe separation selectivity ($S_{Nd/Fe}$ 4448 and $S_{Dy/Fe}$ 578). This selectivity is driven by the tunable proton donor capability of levulinic acid and the difference in the intrinsic stability of Fe and REE compounds.

Overall, this integrated flow sheet provides a sustainable, highly selective route for REE and B recovery, significantly mitigating iron-induced processing bottlenecks. To further advance this technology toward industrial scalability, future research focuses on optimising B recovery from the alkaline wash liquor, demonstrating closed-loop recycling of NaOH and the NADES system, and assessing long-term solvent stability.

REFERENCES

Liu, C, Yan, Q, Zhang, X, Lei, L and Xiao, C, 2020. Efficient Recovery of End-of-Life NdFeB Permanent Magnets by Selective Leaching with Deep Eutectic Solvents, *Environmental Science and Technology,* 54:10370–10379.

Orefice, M, Van Den Bulck, A, Blanpain, B and Binnemans, K, 2020. Selective Roasting of Nd–Fe–B Permanent Magnets as a Pretreatment Step for Intensified Leaching with an Ionic Liquid, *Journal of Sustainable Metallurgy,* 6:91–102.

Tunsu, C, Petranikov, M, Gergoric, M, Ekberg, C and Retegan, T, 2015. Reclaiming rare earth elements from end-of-life products: A review of the perspectives for urban mining using hydrometallurgical unit operations, *Hydrometallurgy,* 156:239–258.

Zheng, H, Ding, Y, You, S, Ding, Y, Zhang, S and Zhang, J, 2025. A comprehensive review of neodymium-iron-boron (NdFeB) waste recycling: Processes, mechanisms, and prospects, *Journal of Environmental Management,* 391:126513.

Effect of low temperature alkaline treatment on the oxidation of end-of-life NdFeB magnets

R Velpoor[1], R Mukhlis[2], W Bruckard[3] and M A Rhamdhani[4]

1. PhD student, Swinburne University of Technology, Hawthorn Vic 3122. Email: rvelpoor@swin.edu.au
2. Adjunct Lecturer, Swinburne University of Technology, Hawthorn Vic 3122; CSIRO Mineral Resources, Clayton South Vic 3168. Email: rmukhlis@swin.edu.au, reiza.mukhlis@csiro.au
3. Principal Scientist, CSIRO Mineral Resources, Clayton South Vic 3168. Email: warren.bruckard@csiro.au
4. Professor, Swinburne University of Technology, Hawthorn Vic 3122. Email: arhamdhani@swin.edu.au

INTRODUCTION

Rare earth elements (REEs) are widely used in devices such as fluorescent lamps, light-emitting diodes, batteries, and permanent magnets (PMs). More than 25 per cent of REEs are used in Neodymium-Iron-Boron (NdFeB) and Samarium-Cobalt (SmCo) PM production. NdFeB PMs are known for their high energy density and coercivity, with high consumption in electronics (hard disk drives (HDDs)), electric vehicle (EV) motors, wind turbine generators (WTGs), and magnetic resonance imaging (MRI) devices. EV motors contain 1–2 kg magnets, whereas WTGs and MRIs comprise 1–2 t magnets, and small consumer electronics and HDDs contain 1–15 g of magnets, with a typical life span of 2–3 years in electronics, 5–7 years in EV motors, and 20–30 years in WTGs and MRIs. End-of-Life (EoL) NdFeB PMs mainly contain Nd (20–30 per cent) and Pr (0–7 per cent), in addition to a small amount (0–6 per cent) of expensive, heavy rare-earth elements (Gd/Dy/Tb) (Yang *et al,* 2017). Recovering Nd and other REEs from EoL NdFeB PMs could reduce dependence on primary resources, decrease waste generation in ore beneficiation and processing, and secure the supply chain.

REE recovery through pyro, hydro, pyro-hydro, and electrometallurgical processes has been studied. The pyrometallurgical process involves high temperatures with the use of fluxes to recover REE from slags or vacuum distilled phases or water-soluble salts. While hydro metallurgical processes involve complete dissolution followed by selective REE precipitation or Fe removal. Pre-treatment, such as oxidation or alkali-assisted roasting-oxidation, can enhance selective leaching of REEs. $NdFeO_3$ phase formation and its encapsulation by Fe_2O_3 during oxidation require high temperatures and prolonged leaching times to achieve higher REE recovery. Alkali-assisted roasting prior to oxidation decreases the oxidation temperature and enhances the REE recovery. The present study emphasises a low-temperature alkaline treatment involving a solid-liquid reaction to partially oxidise the NdFeB to their respective hydroxides, oxides and investigates the effects on phase evolution and morphological changes during thermal oxidation.

ALKALI TREATMENT-OXIDATION

The NdFeB magnet powder can contain mainly $Nd_2Fe_{14}B$ phase, can be dissociated into $Nd(OH)_3$ and Fe_3O_4 in aq. NaOH, while dissolving B. However, NaOH concentration, $\mathrm{P_{O_2}}$ along the with temperature, influence the equilibrium phases. The solution contains aqueous species of $\mathrm{BO_2^-}$, $\mathrm{Na^+}$, and $H_2\mathrm{BO_3^-}$, and the gas mostly consists of H_2, with H_2O. Temperature rise increases P_{H_2O}, facilitating high $\mathrm{P_{O_2}}$ and favouring Fe_3O_4 formation over Fe. Fe_2O_3, $NdFeO_3$, and $NdBO_3$ are the equilibrium phases at lower temperature (<1000°C) oxidation in air ($\mathrm{P_{O_2}} = 0.21\ atm$), with more $NdFeO_3$ and no $NdBO_3$ phases in alkali treated-oxidised.

However, the experimental investigation of alkali treatment (30 per cent (w/w) aq. NaOH, 60°C, 1h) reveal the phases $Nd(OH)_3$, FeO(OH), Fe_3O_4, and Fe in the XRD (Figure 1a). In the SE image (Figure 1b), solid rock and small, dispersed particles were observed, and the BSE images show that these bright particles are located farther outward. The BSE image of cross-sections (Figure 1c) further distinguishes reacted and unreacted regions. Unreacted region with bright contrast and no oxygen in the EDS (spectrum 1) and black-contrast FeO(OH), while grey-contrast particles

(spectrum 2) consisted of a mixture of oxides and hydroxides. The unreacted $Nd_2Fe_{14}B$ was identified by small peaks in the XRD and quantified at ~4 per cent. Because diffused OH^- readily reacted with highly reactive Nd in the $Nd_2Fe_{14}B$ matrix, $Nd(OH)_3$ formed, thus grew more outward, whereas Fe oxide and hydroxide still shared the reactive boundary interface with the unreacted region.

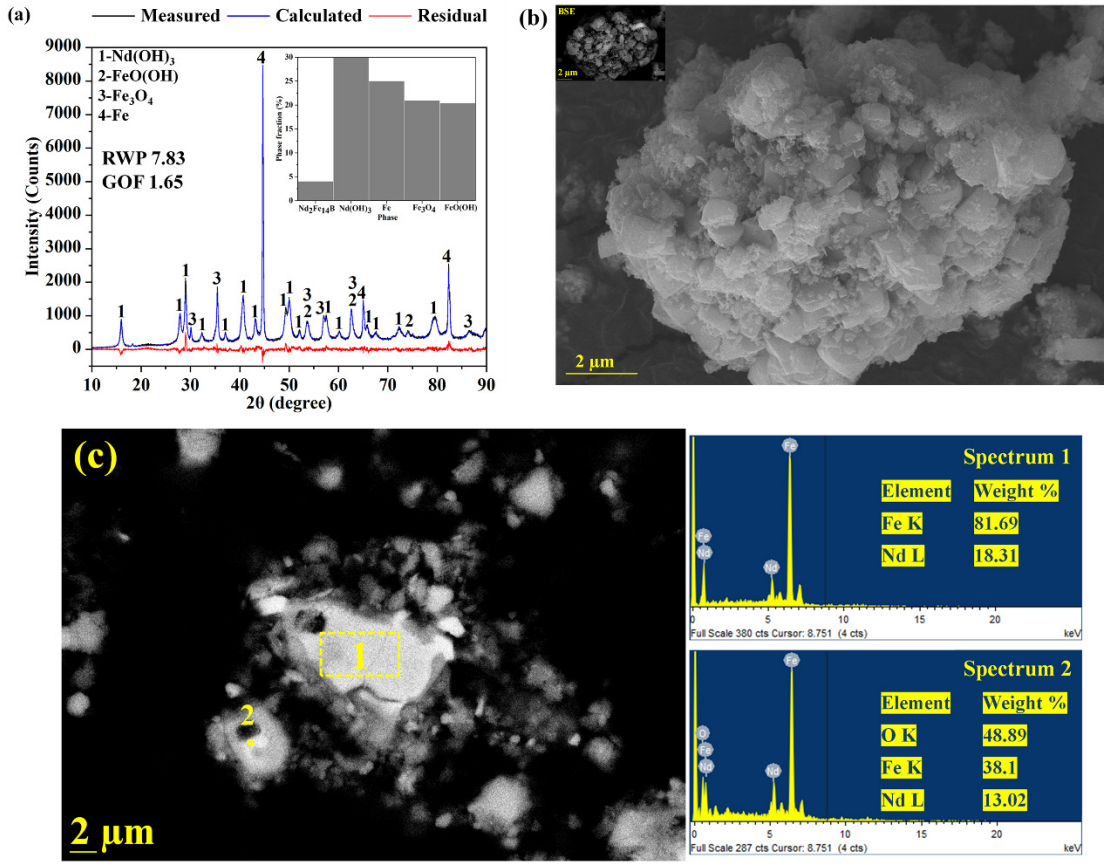


FIG 1 – (a) XRD pattern, Rietveld fitting, and phase fraction; (b) SE and BSE image; (c) cross-sectional BSE image of Alkali treated NdFeB magnet powder.

Weight gain in untreated NdFeB was almost saturated at 800°C, with continuous weight gain, whereas alkali-treated NdFeB saturated at 600°C, with weight loss between 200 and 300°C during thermal response in air (Figure 2a). XRD of alkali-treated oxidised NdFeB magnet powder (Figure 2b) identified oxide phases Fe_2O_3, Fe_3O_4, $NdFeO_3$, and Nd_2O_3. The absence of hydroxides can be attributed to dehydration to the respective oxides in air above 200°C. Fractions of Fe_2O_3 and $NdFeO_3$ increased with oxidation temperature, whereas those of Nd_2O_3 and Fe_3O_4 decreased. Figure 2c shows SE images of oxidised particles with spherical (Fe_2O_3), nanorod (Nd_2O_3), dispersed small, and solid-rock (Fe_3O_4) morphologies. The density of spherical morphologies increased with temperature, as did that of small particles. In contrast, oxidation of untreated NdFeB at 800°C resulted in $NdFeO_3$, $NdBO_3$, and Fe_2O_3 phases, which were assessed and quantified by XRD (Figure 2d), and a solid-rock morphology was observed in the SE images (Figure 2e), revealing no distinguishing phases. The equilibrium composition of $NdFeO_3$ is higher during oxidation in alkali-treated NdFeB than in untreated NdFeB. Conversely, $NdFeO_3$ formed less during complete oxidation of alkali-treated NdFeB at 600°C than in untreated NdFeB at 800°C. The $Nd(OH)_3$ phase grew outward during the alkali treatment, limiting $NdFeO_3$ formation, which is increased with temperature due to the reaction between Nd_2O_3 and Fe_2O_3.

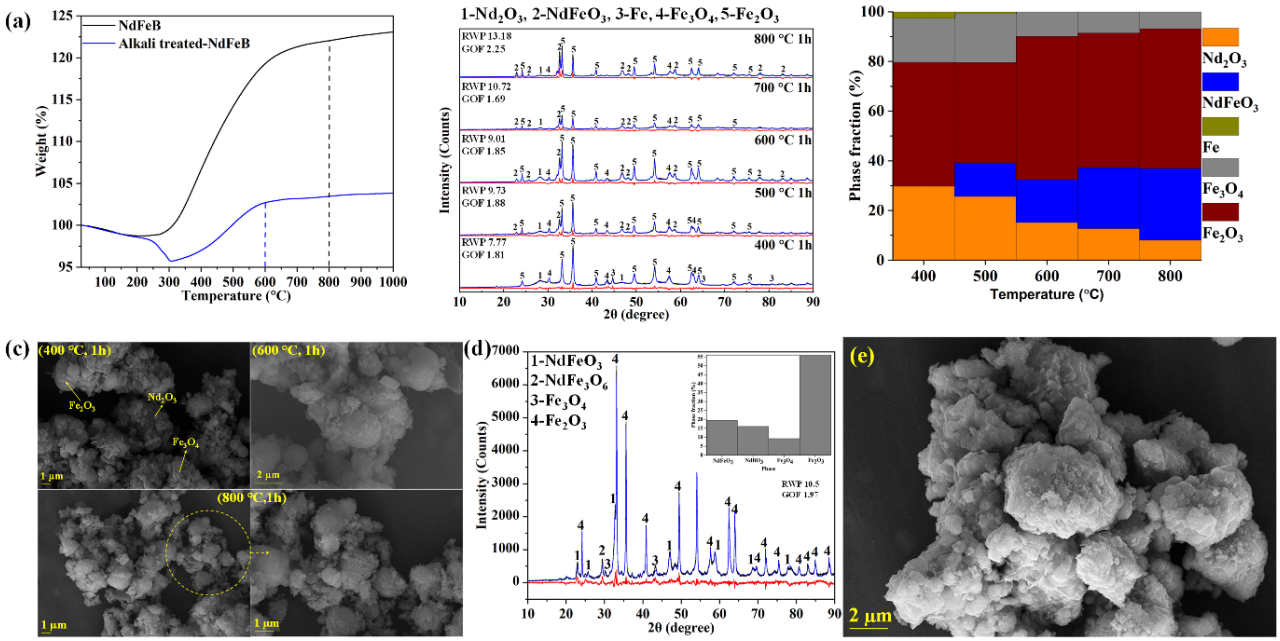


FIG 2 – (a) Thermogravimetric analysis; (b) XRD pattern, Rietveld fitting, and phase fraction; (c) SE images of Alkali Treated-Oxidised NdFeB magnet powder; (d) XRD pattern, Rietveld fitting, and phase fraction; (e) SE image of untreated oxidised NdFeB magnet powder.

CONCLUSION

Low-temperature alkali treatment effectively dissociates the Nd_2Fe_1B phase in an aqueous NaOH medium, converting it into a mixture of metallic Fe, their respective hydroxides and oxides Also, highly alkaline medium, thermodynamically favours the leaching of B into water-soluble species. Microstructural and morphological evaluations demonstrate that thermal oxidation of the alkali-treated powder results in distinct phase morphologies such of Fe_2O_3, Nd_2O_3, and Fe_3O_4—which grow independently. Moreover, alkali-treated NdFeB completely oxidised at 600°C with less $NdFeO_3$, compared with untreated NdFeB at 800°C. The study demonstrates that alkali pretreatment lowers the oxidation temperature and producing physically distinct, segregated oxide phases, thereby preventing complex phase encapsulation, which is more conducive to downstream REE leaching processes.

REFERENCES

Yang, Y, Walton, A, Sheridan, R, Güth, K, Gauß, R, Gutfleisch, O, Buchert, M, Steenari, B M, Van Gerven, T, Jones, P T and Binnemans, K, 2017. REE recovery from end-of-life NdFeB permanent magnet scrap: a critical review, *Journal of Sustainable Metallurgy*, 3(1):122–149.

Strengthening Australia's critical minerals competitiveness – LCA and supply chain data as strategic trade tools

P Whattoff[1], A Samuel[2] and J Twohig[3]

1. Director, Minviro, Perth WA 6000. Email: phoebe@minviro.com
2. COO, Rise-X, Perth WA 6000. Email: alan.samuel@rise-x.io
3. Head of Delivery, Rise-X, Perth WA 6000. Email: julian.twohig@rise-x.io

ABSTRACT

As global demand for critical minerals intensifies and major economies tighten requirements around supply chain transparency, Australian producers face a new commercial reality – the ability to quantify and communicate the environmental and supply chain credentials of their products is no longer a sustainability exercise, it is a market access requirement.

Minviro and Rise-X, supported by Powering Australia and Future Made in Australia funding, has developed a world-class digital platform purpose-built for the critical minerals sector that integrates life cycle assessment (LCA) methodology with supply chain traceability. The platform enables developers and producers to collect, quantify and communicate ESG data across multiple frameworks with their supply chains to target increasing the speed, efficiency and accuracy of data that is increasingly (strike-through) demanded by offtakers, investors, and regulators in key export markets including the European Union, United States, Japan and South Korea.

This paper presents the development and application of the platform across Australian critical mineral projects, demonstrating how robust LCA and traceability data can be leveraged to strengthen offtake negotiations, satisfy due diligence requirements, and improve project bankability. It also examines how nationally consistent, government-backed data infrastructure positions Australia as a trusted, transparent supplier in an increasingly scrutinised global market.

As supply chain security climbs the agenda of Australia's trading partners, the ability to provide verified, quantified product data represents a tangible competitive advantage. This paper argues that investment in LCA and traceability capability is not a compliance cost, it is a sovereign trade asset.

Assessing the sustainability of entrapped sulfate-reducing bacteria for acid mine drainage treatment – techno-economic analysis and life cycle assessment

X Yin[1], S Koay[2], N Gurieff[3] and A Oehmen[4]

1. PhD student, The University of Queensland, St Lucia Qld 4072. Email: x.yin@uq.edu.au
2. Bachelor student, The University of Queensland, St Lucia Qld 4072. Email: s.koay@student.uq.edu.au
3. Rio Tinto, Brisbane Qld 4000. Email: nick.gurieff@riotinto.com
4. Associate Professor, The University of Queensland, St Lucia Qld 4072. Email: a.oehmen@uq.edu.au

ABSTRACT

Mining activities generate acid mine drainage (AMD), characterised by high acidity and elevated concentrations of sulfate and dissolved metals. Sulfate-reducing bacteria (SRB) offer a sustainable alternative to conventional lime dosing by simultaneously neutralising acidity and recovering valuable metals. However, widespread implementation of biological AMD treatment is limited by biomass washout, process instability under continuous operation, and uncertainties regarding economic and environmental sustainability. This study evaluated microbial entrapment as a strategy to overcome these limitations by enabling stable, high-throughput operation of entrapped SRB (ESRB) systems and benchmarking their performance against conventional lime dosing.

Chemically crosslinked and freeze-thaw crosslinked ESRB systems were compared with a non-entrapped SRB reactor under progressively reduced hydraulic retention times (HRTs), followed by validation using real AMD at the selected HRT. Both ESRB systems maintained stable sulfate reduction, pH neutralisation, and metal recovery at a 12 h HRT, whereas the non-entrapped reactor failed because of biomass washout. During real AMD treatment, the chemically and freeze-thaw crosslinked ESRB systems achieved sulfate reduction rates of up to 5.15 and 3.29 g SO_4^{2-} L^{-1} d^{-1}, respectively, while maintaining near-complete removal and recovery of Cu, Co, and Zn. Techno-economic analysis (TEA) demonstrated that both ESRB systems achieved lower levelised treatment costs than conventional lime dosing, with electron donor consumption identified as the primary operating cost driver. Life cycle assessment (LCA) showed comparable global warming impacts between ESRB and lime treatment. When metal recovery was incorporated using an avoided-burden approach, toxicity-related impacts were substantially reduced, indicating that resource recovery can offset the environmental burdens associated with biological treatment.

These findings demonstrate that microbial entrapment enables stable continuous operation at reduced HRTs, improves biomass retention, and enhances process scalability. By integrating technical performance with techno-economic and environmental assessments, this study provides evidence that ESRB technology is a promising and sustainable alternative to conventional AMD treatment while creating opportunities for resource recovery.

Author index

Agbenyo, F 3
Aldrich, C 5
Alexander, D T 317
Alorro, R D 135
Amitay, N 293
Ang, K L 113
Baensch, A 145
Baker, P 289
Barnard, K R 7
Beh, C C 135
Belousova, E 169
Beniwal, D 145
Bhaskar, H 89
Bhatellia, T 141
Bheemireddy, R 131
Blannin, R 297
Bonnici, N K 153
Breaden, R 251
Breitfuss, M J 209
Brent, A 9
Brereton, C 41
Bruckard, W 125, 139, 327
Bullen, L 11
Bunney, K 25
Cabalu, H 285
Canbulat, I 129
Carneiro, A B 31
Case, M 211, 247
Chapman, N 27
Chen, J 277
Chhabra, K 29
Chingwaru, S J 297
Coleman, R 321
Cote, C 299
Couperthwaite, S 31, 317, 323
Currie, B 33
Daiyan, R 129
Dawe, R 61
Degeling, H 87
Dhnaram, C 169
Di Maio, F 131
Dicinoski, W 63
Didonna, R 187
Dlame, M 35
Dominish, E M 183
Dunham, M 147
Duran, I 111
Dyer, L 3
Eames, A 213
Edraki, M 299, 313
Eksteen, J J 81, 135
Evans, K 3
Farrelly, M 229
Fenn, R 265
Forsberg, K 325
Fortin, M-O 227
Fox, N 165, 297
Franks, G V 91
Freeman, D 9
Gabeva, D 37
Gazley, M 147
Gill, A 269
Giurco, D P 121
Glynn, L 41
Goenka, G R 255
Gomes, Y 111
Gordon, M 149
Grabsch, A 27
Graham, M 61
Greenwood, M 151
Grimsley, L 89
Gurief, N 333

Halatchev, A 37
Halatchev, R 37
Haque, N 125, 139
Harris, M 285
Hayes, P C 277
Hien-Dinh, T T 153
Hobday, D 271
Holden, P 275
Hou, J 313
Hunter, D M 63
Ilankoon, N D 81
Inchauspe, J 285
Issa, T B 113, 133
Jackson, L 321
Jago, C 165
Jak, E 95, 123, 277
Jegatheesan, V 125
Jennings, E 313
Johns, B 215, 223, 275
Kashi, E 83
Kendall-Langley, L 147
Khan, M H A 129
Kitsos, D 279
Kng, L 87
Koay, S 333
Komelkov, A 89
König, U 111
Kontonikas-Charos, A 169
Laukamp, C 167
Laver, R J 63
Lawton, J 225
Lester, L 229
Lilly, K 147
Lisitsin, V 169
Liu, D 9
Loh, J 25
Longbottom, M 315
Lu, Y 147
Luce, M 89
Luo, D 91
Ma, X 87
MacGill, I 129
Mackay, N 93, 281
Magwaneng, R 319
Makvandi, S 111
Manis, A 117
McLellan, B C 283
Mejías, O 87, 297
Mendonca Severiano, B 121, 183
Mercy, E 95
Millar, A D R 97
Moffat, K 227
Moffatt, J E 145
Molver, D 63
Moore, R 293
Moulson, J 41
Mugebe, P 171
Mukhlis, R 327
Narygina, O 111
Negrão, L 111
Neil, A 275
Newman, A 119
Ng, W S 91
Nicholls, L 315
Nikoloski, A N 113, 133
Noor, R 229
Northey, S A 121, 183
Nsiah, J 113
Oehmen, A 333
Omosun, D 263, 269
Oraby, E A 81
Outram, J G 317
Owen, S 3
Owen, S R 153
Parbhakar-Fox, A 87, 165, 185, 297, 319, 321
Pareek, V 141
Pernechele, M 111

Pianta, D 115
Porteous, H 87
Powell, J 313
Pramanik, B 125, 139
Prangige, E 323
Quentin de Gromard, R 147
Quinn, J 117
Rahangdale, S 29
Ramanaidou, E 187
Ramizo, D M 285
Randall, A 87
Rashidi, B 187
Razmjou, A 187
Readett, D J 63
Reaney, I M 127
Reja, Y 119
Rhamdhani, M A 327
Rochford, L 299
Rollin, L 245
Roper, L 323
Ryan, T G 121, 183
Safari, M 35
Salter, S 93
Samuel, A 265, 331
Sarmadi, A 187
Saydam, S 129
Saylor, M 211, 247
Schartner, E P 145
Schicks, J 325
Schofield, C 261
Shakirova, I 123
Shevchenko, M 95, 277
Shishin, D 123, 277
Shree, J 125
Siame, B 127
Singh, P 133
Singh, R 129
Smithies, H 147
Soldenhoff, K 117
Spooner, N A 145
Su, H 131
Svärd, M 325
Tade, M 3
Talan, S 263
Tannock, L 147
Tao, R 325
Tapu, A 169
Tay, L 265
Tayebi-Khorami, M 321
Taylor, S 289
Tedesse, B 3
Thompson, G 133
Thompson, J 287
Tong, A 87
Townsend, J 281
Tran, Q T 135
Trench, A 265
Twohig, J 331
Usher, D 289
Valencia Bejarano, M 117
Velpoor, R 327
Vershinina, K 245
Vivoda, V 291
Wen, X 95
Whattoff, P 331
Williamson, R 137
Wilske, C 145
Wilting, K 41
Wu, Y 131
Wulff, R 293
Yadav, S 139
Yin, X 333
Yolalmaz, A 131
Zafar, S 141