Transforming mine waste into secondary resources: The search for critical metals

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What are ‘Critical Metals?’

Periodic table showing those of high criticality and the status of Australia’s resources in terms of those with current production and/or resources and/or undergoing exploration.

- Gases or artificially produced
- Resources (demonstrated and inferred) and exploration
- Production, resources and exploration
- Exploration
- High criticality

[Periodic table showing critical metals and their status in Australia's resources]

Why are they (suddenly) important?

- The transition to a low-carbon economy is well underway with increasing pressure to accelerate this
- Leading mining companies are recognising the importance of reducing their carbon emissions by:
  1. Using renewable energy
  2. Electrification of mines
  3. Focus on Scope 3 emissions

“The clean energy transition is going to be mineral intensive, providing an enormous opportunity for mining companies. There are significant opportunities for lithium, cobalt, copper, aluminum, nickel and many other minerals.”

Top producers of critical metals

<table>
<thead>
<tr>
<th>Critical Mineral</th>
<th>Production</th>
<th>Price</th>
<th>Market Value</th>
<th>Largest Produc</th>
<th>Country</th>
<th>Tonnes</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>REE</td>
<td>130000</td>
<td>186.782</td>
<td>24281.7</td>
<td>China</td>
<td>105000</td>
<td>80.8%</td>
<td></td>
</tr>
<tr>
<td>Phosphate Rock</td>
<td>2630000</td>
<td>75</td>
<td>19725.0</td>
<td>China</td>
<td>1400000</td>
<td>53.2%</td>
<td></td>
</tr>
<tr>
<td>Chromite ore</td>
<td>31000000</td>
<td>320</td>
<td>9920.0</td>
<td>South Africa</td>
<td>1500000</td>
<td>48.4%</td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>11000</td>
<td>54454</td>
<td>5989.9</td>
<td>Congo/DRC</td>
<td>64000</td>
<td>58.2%</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>290000</td>
<td>20282</td>
<td>5881.9</td>
<td>China</td>
<td>100000</td>
<td>34.5%</td>
<td></td>
</tr>
<tr>
<td>Platinum *</td>
<td>165.8</td>
<td>30869.167</td>
<td>5735.5</td>
<td>South Africa</td>
<td>135.7</td>
<td>73.0%</td>
<td></td>
</tr>
<tr>
<td>Palladium *</td>
<td>205.2</td>
<td>27652.733</td>
<td>5674.3</td>
<td>Russia</td>
<td>82.5</td>
<td>40.2%</td>
<td></td>
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<tr>
<td>Molybdenum</td>
<td>290000</td>
<td>18000</td>
<td>5220.0</td>
<td>China</td>
<td>130000</td>
<td>44.8%</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>95000</td>
<td>24500</td>
<td>2935.3</td>
<td>China</td>
<td>70000</td>
<td>83.2%</td>
<td></td>
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<tr>
<td>Graphite</td>
<td>1200000</td>
<td>1400</td>
<td>1680.0</td>
<td>China</td>
<td>780000</td>
<td>65.0%</td>
<td></td>
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<tr>
<td>Vanadium</td>
<td>80000</td>
<td>11464</td>
<td>1637.2</td>
<td>China</td>
<td>43000</td>
<td>53.8%</td>
<td></td>
</tr>
<tr>
<td>Antimony</td>
<td>150000</td>
<td>8840</td>
<td>1326.1</td>
<td>China</td>
<td>110000</td>
<td>73.3%</td>
<td></td>
</tr>
<tr>
<td>Niobium</td>
<td>64000</td>
<td>18000</td>
<td>1152.0</td>
<td>Brazil</td>
<td>57000</td>
<td>89.1%</td>
<td></td>
</tr>
<tr>
<td>Rhodium *</td>
<td>23.3</td>
<td>337120.558</td>
<td>786.7</td>
<td>South Africa</td>
<td>10.2</td>
<td>82.4%</td>
<td></td>
</tr>
<tr>
<td>Lithium</td>
<td>42000</td>
<td>13900</td>
<td>587.7</td>
<td>Australia</td>
<td>18700</td>
<td>43.5%</td>
<td></td>
</tr>
<tr>
<td>Indium</td>
<td>720</td>
<td>360000</td>
<td>259.2</td>
<td>China</td>
<td>310</td>
<td>43.1%</td>
<td></td>
</tr>
<tr>
<td>Tantalum</td>
<td>1300</td>
<td>19300</td>
<td>250.9</td>
<td>Rwanda</td>
<td>390</td>
<td>30.0%</td>
<td></td>
</tr>
<tr>
<td>Iridium *</td>
<td>8.2</td>
<td>2916387</td>
<td>239.1</td>
<td>South Africa</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>Germanium</td>
<td>134</td>
<td>1358000</td>
<td>182.0</td>
<td>China</td>
<td>88</td>
<td>65.7%</td>
<td></td>
</tr>
<tr>
<td>Bismuth</td>
<td>14000</td>
<td>10582</td>
<td>148.1</td>
<td>China</td>
<td>110000</td>
<td>78.6%</td>
<td></td>
</tr>
<tr>
<td>Beryllium</td>
<td>230</td>
<td>630000</td>
<td>144.9</td>
<td>USA</td>
<td>170</td>
<td>73.9%</td>
<td></td>
</tr>
<tr>
<td>Gallium</td>
<td>495</td>
<td>56500</td>
<td>117.8</td>
<td>China</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>Rhenium</td>
<td>52.0</td>
<td>155000</td>
<td>80.6</td>
<td>Chile</td>
<td>270</td>
<td>51.9%</td>
<td></td>
</tr>
<tr>
<td>Selenium</td>
<td>3300</td>
<td>23810</td>
<td>78.6</td>
<td>China</td>
<td>930</td>
<td>28.2%</td>
<td></td>
</tr>
<tr>
<td>Ruthenium *</td>
<td>37.5</td>
<td>1961415</td>
<td>73.6</td>
<td>South Africa</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>23000</td>
<td>1700</td>
<td>39.1</td>
<td>China</td>
<td>82000</td>
<td>35.7%</td>
<td></td>
</tr>
<tr>
<td>Tellurium</td>
<td>420</td>
<td>30000</td>
<td>15.1</td>
<td>China</td>
<td>280</td>
<td>80.7%</td>
<td></td>
</tr>
<tr>
<td>Strontium</td>
<td>202000</td>
<td>75</td>
<td>14.7</td>
<td>Spain</td>
<td>90000</td>
<td>44.6%</td>
<td></td>
</tr>
<tr>
<td>Hafnium</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>Scandium</td>
<td>nd</td>
<td>350000</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
</tbody>
</table>
## Critical Metals in Australia

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Considered Critical by</th>
<th>Major Applications</th>
<th>Global Production</th>
<th>Australian Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimony</td>
<td>EU, UK, USA</td>
<td>flame retardants, lead acid batteries, plastics catalyst</td>
<td>150 000 t</td>
<td>Single mine at Costerfield (VIC), ~3000 tpa; other mines on care &amp; maintenance; large resources known</td>
</tr>
<tr>
<td>Cobalt</td>
<td>EU, UK, USA</td>
<td>specialty alloys, batteries, catalysts, tyre adhesives, pigments</td>
<td>110 000 t</td>
<td>Significant mine at Murrin Murrin (WA), ~3000 tpa, plus minor production from nickel sulfide mines (WA); large resources known</td>
</tr>
<tr>
<td>Gallium</td>
<td>EU, UK, USA</td>
<td>renewable energy, electronics</td>
<td>495 t</td>
<td>No production; major resources expected in bauxite and zinc deposits</td>
</tr>
<tr>
<td>Germanium</td>
<td>EU, UK, USA</td>
<td>infrared devices, fibre optics</td>
<td>134 t</td>
<td>No production; major resources expected in zinc deposits</td>
</tr>
<tr>
<td>Indium</td>
<td>EU, UK, USA</td>
<td>renewable energy, electronics, specialty alloys, touch screens</td>
<td>680 t</td>
<td>No production at zinc refineries, no value paid for indium in exported concentrates; large resources known</td>
</tr>
<tr>
<td>Lithium</td>
<td>UK, USA</td>
<td>renewable energy, electronics, batteries</td>
<td>43 000 t</td>
<td>Major mines at Greenbushes, Pilgangoora, Mount Cattlin, and Mount Marion (WA); Australian production 21 000 t; large resources known</td>
</tr>
<tr>
<td>Niobium</td>
<td>EU, UK, USA</td>
<td>specialty alloys</td>
<td>64 000 t</td>
<td>No production; major resources known</td>
</tr>
<tr>
<td>PGEs</td>
<td>EU, UK, USA</td>
<td>automotive catalysts, chemical catalysts, jewellery, specialty alloys</td>
<td>~410 t</td>
<td>Minor production from nickel sulfides (WA); modest resources known</td>
</tr>
<tr>
<td>Rare earth oxides (REOs)</td>
<td>EU, UK, USA</td>
<td>renewable energy, electric vehicles, military technologies, electronics, specialty alloys, batteries</td>
<td>130 000 t</td>
<td>Single mine at Mount Weld (WA), 2200 tpa; monazite from mineral sands mines not extracted or exported; large resource known at the Olympic Dam deposit but this resource is not recoverable using current technology at present prices; significant REE-only deposits at early stage of production (e.g. Browns Range) or in feasibility studies (e.g. Nolans Bore, Toongi)</td>
</tr>
<tr>
<td>Rhenium</td>
<td>UK, USA</td>
<td>specialty alloys, chemical catalysts</td>
<td>52 t</td>
<td>No production; major resource known at Merlin (QLD)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>EU, UK, USA</td>
<td>specialty alloys</td>
<td>95 000 t</td>
<td>Minor production 245 t; major resources known</td>
</tr>
</tbody>
</table>
Environmental risks in mining

- **License to operate** remains in the No. 1 slot with 44% of business risks survey respondents putting it at the top of the list.

Several national challenges… one solution?

AUSTRALIA’S CRITICAL MINERALS STRATEGY 2019

Critical metal exploration of mine waste at abandoned and operational sites
Tasmania: ~215 mine waste sites

Redrawn from MRT (2001)
Tasmania: Exploration target map

Redrawn from MRT (2001)

Zn Zinc [Ar] 3d\(^{10}\)4s\(^{2}\) Transition Metals

Co Cobalt [Ar] 3d\(^{7}\)4s\(^{2}\) Transition Metals

In Indium [Kr] 4d\(^{10}\)5s\(^{2}\)5p\(^{2}\) Post-Transition Metal

Au Gold [Xe] 4f\(^{14}\)5d\(^{10}\)6s\(^{1}\) Transition Metals

Sn Tin [Kr] 4d\(^{10}\)5s\(^{2}\)5p\(^{2}\) Post-Transition Metal

Cu Copper [Ar] 3d\(^{9}\)4s\(^{1}\) Transition Metals

NAP (kg H\(_{2}\)SO\(_{4}\))

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Geochem. Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFR</td>
<td>I</td>
</tr>
<tr>
<td>PAFR</td>
<td>II</td>
</tr>
<tr>
<td>NAFR</td>
<td>III</td>
</tr>
</tbody>
</table>

0 - 100 kilometers
Case study: Savage River mine, Tasmania

Images from Google Earth

Northern Pond

Zone D

Zone C

Zone B

Zone A

North Pit

South Lens

Centre Pit

Savage River

OTD

MCTD

4 km

600 m
Geometallurgical characterisation approach

Bulk samples (20 kg; n = 4) → Sample preparation → Milled and rotary split → Chemical and mineralogical analysis → Flotation test work → Bioleaching experiments → Fe-Co-Ni separation tests

Results confirmed suitability of Co extraction via. biohydrometallurgical experimentation

Potential business case for remining?

38 Mt tailings

7% pyrite

2.66 Mt pyrite

0.1% Co

2,660 t cobalt

LME Co = US $38,000/t

90% recovery

Value = US ~ $90 million

NB. Excludes CAPEX and OPEX
2019: New program commissioned by Grange Resources/TAS EPA to extend sampling (co-funded by UQ’s COB program)

Optimise flotation by finer grind (<33 µm) and introducing polysaccharides

Refine bioleaching by increasing O$_2$ into the tanks

Other case studies in Tasmania

Mathinna Gold

Co, Cu, Au, Sn, W

Zn, Pb, Au, Ag

Sn, W

Co, Cu

Zn, Sn, W
Queensland: Mines and mine waste
Critical minerals mines and deposits

Stream 1: Refocussing and extending current efforts

“Cobalt and other critical metals in tailings (and other mine waste) of major mineral deposits in north Queensland”

- What is the genetic relationship between ore deposit type and critical metal content in mine waste?
- How have critical metals been cycled in different mine waste environments?
- What mineral processing technologies are suitable for recovering critical metals?
Stream 1: Project scope

Focus on initial characterisation of critical metal abundances and their modes of occurrence in tailings (and other mine wastes) in north Queensland. This will be achieved through:

1. **Compilation of the relevant available information from public and confidential sources**
2. **Targeted sampling of up to 10 sites**
3. **Multi-element geochemistry**
4. **Targeted mineralogical and geochemical characterisation of selected representative samples, to determine dominant modes of occurrence of relevant critical metals**

Target critical metals: **Co, Ga, Ge, In, REE & W**
Proposed workflow and timeline

Sampling campaign planning/ background data review

Sampling campaign (BRC & GSQ teams)

Sampling transportation to Brisbane and sample preparation

XRD

Chemical assay

RL, MLA and LA-ICPMS

Data Interpretation

Reporting - Description of critical metal tenor and deportment

RL: Reflected light
MLA: Mineral liberation analysis
XRD: X-ray diffractometry
LA-ICPMS: Laser ablation ICPMS

Nov ‘19
Jan or Feb ‘20
Apr ‘20
Jun ‘20
Case study: Baal Gammon - mine waste

Granite-related Sn-W lodes and polymetallic Cu-Pb-Zn-Ag skarns with alluvial Sn

Historical production: 150 kt Sn & 4 kt W

Indicated and inferred resource
2.8 Mt @ 1.0% Cu; 0.2% Sn; 40 g/t Ag and 40 g/t indium Monto Minerals (2014)

Metal-rich leachate discharged into adjacent Jamie Creek during seasonal floods

Environmental risk from historical waste with resource potential

2015: Study to determine deportment and quantification of trace metals
Case study: Baal Gammon - mine waste

Historical waste rock material

River cobbles from adjacent creek

Polysulfidic/massive sulfide

Well developed oxidised rinds

Whole rock geochemistry

Mineralogy (EMPA, FE-SEM, XRD)

Static testing (NAG, paste pH)

LA-ICPMS analysis

Polished slab – massive, polysulfidic boulder with Fe-oxide rind – Sample BG14A

Fox and Parbhakar-Fox (2016)
Case study: Baal Gammon- sulphide mineralogy

Chalcopyrite 33.5 %
Arsenopyrite 28.4 %
Pyrrhotite 21.4 %
Chlorite 9.3 %
Quartz 2.1 %
Fluorite 1.5 %
Goethite 1.2 %

Other phases identified by XRD (<1 wt.%)
- Pyrite – FeS$_2$
- Stannite – Cu$_2$FeSnS$_4$
- Roquesite – CuInS$_2$
- Sphalerite – (Zn,Fe)S

Leica automated microscopy – reflected light image; Quantified mineralogy – by Rietveld refinement (QXRPD)

Fox and Parbhakar-Fox (2016)
Case study: Baal Gammon- critical metals

Fox and Parbhakar-Fox (2016)
Case study: Baal Gammon - critical metals

![Graphs showing Se (ppm) vs. Sb (ppm) and Co (ppm) vs. Ni (ppm) with different minerals indicated.](image)

*Fox and Parbhakar-Fox (2016)*
Case study: Baal Gammon- new opportunities

2015 study: Examined waste boulders off mine lease only

2019/2020: High-level critical metal value of waste assessment

Additional geological data (e.g., HyLogger) to also be reviewed

Opportunity to break pollutant linkage chains through reprocessing
Approaches to mine waste management need to be revised to successfully and cost-efficiently break pollutant linkage chains.

Drive for establishing critical metal mining projects in Queensland provides a new opportunity to examine mine waste with significant geoenvironmental benefits (e.g., AMD and dust reduction).

An integrated mineralogy, geochemistry and mineral chemistry approach to be applied at up to 10 sites in the next 6 months specifically to identify: Co, In, W, Ga, Ge and REEs in mine waste.

Geometallurgical assessment of mine waste is a key part of the life-of-mine cycle for remediation and future extraction.
Thanks for your attention

Questions?

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