GEOMETALLURGY OF COBALT: Global aspects & a Finnish case study

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COBALT FACTS & FIGURES

60% of the Co production goes to rechargeable batteries → **Essential for a technologically advanced low carbon society**

70% of the Co mine production comes from the DRC → **Ethical concerns**

80% of the Co sulphate market controlled by China → **Supply risk**

99% Co mined as a by product of Cu or Ni → **Production driven by the main commodity market**

How geometallurgy can help?

Will cobalt demand exceed supply?

<table>
<thead>
<tr>
<th>Year</th>
<th>Co Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>160,000 tonnes</td>
</tr>
<tr>
<td>2025</td>
<td>196,000 tonnes</td>
</tr>
</tbody>
</table>

so even if EV battery recycling, mining and substitution are developed as assumed in the forecasts, the future supply-demand gap will unlikely be avoided.

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Know terrestrial cobalt resources

- Sediment-hosted Cu-Co deposits: 51%
- Ni-Co Laterites: 33%
- Other (VMS, IOCG, etc.): 7%
- Magmatic Ni-Cu-Co sulphides: 9%
- Others: 9%

https://doi.org/10.1016/j.mineng.2020.106656
# Cobalt Minerals

## Common Cobalt-Bearing Minerals with Main Properties

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Group</th>
<th>Formula</th>
<th>Weight percent</th>
<th>Hardness</th>
<th>Avg. S.G.</th>
<th>Avg. Magnetic Susceptibility (10^-6)</th>
<th>Acid solubility</th>
<th>Example Deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Co minerals</strong></td>
<td></td>
<td></td>
<td>Co</td>
<td>Ni</td>
<td>Cu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skutterudite</td>
<td>Arsenide</td>
<td>(Co,Ni)As3+x</td>
<td>17.95</td>
<td>5.96</td>
<td>-</td>
<td>5.5-6</td>
<td>6.5</td>
<td>151.8</td>
</tr>
<tr>
<td>Smallite</td>
<td>Arsenide</td>
<td>CoAs3+x, x=[0,5,1]</td>
<td>28.2</td>
<td>-</td>
<td>-</td>
<td>5.5-6</td>
<td>6.5</td>
<td>38.0</td>
</tr>
<tr>
<td>Safflorite</td>
<td>Arsenide</td>
<td>(Co,Fe)As2</td>
<td>21.25</td>
<td>-</td>
<td>-</td>
<td>4-5</td>
<td>7.1</td>
<td>73.8</td>
</tr>
<tr>
<td>Cobaltite</td>
<td>Sulpharsenide</td>
<td>CoAsS</td>
<td>35.52</td>
<td>-</td>
<td>-</td>
<td>5.5</td>
<td>6.33</td>
<td>49.7</td>
</tr>
<tr>
<td>Allocasite</td>
<td>Sulpharsenide</td>
<td>(Co,Fe)AsS</td>
<td>26.76</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>6.17</td>
<td></td>
</tr>
<tr>
<td>Glaucodot</td>
<td>Sulpharsenide</td>
<td>(Co,Fe)AsS</td>
<td>26.76</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>5.95</td>
<td>854.6</td>
</tr>
<tr>
<td>Carrolite</td>
<td>Sulphide</td>
<td>Cu(Co,Ni)2S</td>
<td>28.56</td>
<td>9.48</td>
<td>20.53</td>
<td>4.5-5.5</td>
<td>4.65</td>
<td>108.6</td>
</tr>
<tr>
<td>Linnaeite</td>
<td>Sulphide</td>
<td>Co2+Co3+3S</td>
<td>57.95</td>
<td>-</td>
<td>-</td>
<td>4.5-5.5</td>
<td>4.8</td>
<td>532.0</td>
</tr>
<tr>
<td>Siegenite</td>
<td>Sulphide</td>
<td>(Ni,Co)2S2</td>
<td>14.51</td>
<td>43.36</td>
<td>-</td>
<td>5-5.5</td>
<td>4.65</td>
<td>179.2</td>
</tr>
<tr>
<td>Cattierite</td>
<td>Sulphide</td>
<td>CoS2</td>
<td>47.89</td>
<td>-</td>
<td>-</td>
<td>4.5</td>
<td>4.8-5</td>
<td>1012.4</td>
</tr>
<tr>
<td>Willyamite</td>
<td>Sulphide</td>
<td>(Co,Ni)SbS</td>
<td>20.78</td>
<td>6.90</td>
<td>-</td>
<td>5.5</td>
<td>6.76</td>
<td></td>
</tr>
<tr>
<td>Co-pentlandite</td>
<td>Sulphide</td>
<td>(Co,Ni,Fe)3S8</td>
<td>67.40</td>
<td>-</td>
<td>-</td>
<td>4.5</td>
<td>5.22</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary Co minerals</strong></td>
<td></td>
<td></td>
<td>Co2+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erythrite</td>
<td>Arsenate</td>
<td>Co2+AsO4·2H2O</td>
<td>29.53</td>
<td>-</td>
<td>-</td>
<td>1.5-2</td>
<td>1660.2</td>
<td>S</td>
</tr>
<tr>
<td>Roselite</td>
<td>Arsenate</td>
<td>Ca2+(Co,Mg)(AsO4)2·2(H2O)</td>
<td>9.95</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
<td>3.69</td>
<td></td>
</tr>
<tr>
<td><strong>Heterogenous Oxide</strong></td>
<td></td>
<td></td>
<td>CoO(OH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>64.10</td>
<td>-</td>
<td>-</td>
<td>3-5</td>
<td>4.3</td>
<td>255.6</td>
</tr>
<tr>
<td>Asbolane</td>
<td>Oxide</td>
<td>(Ni,Co)2+.Mn4+(O,OH)·nH2O</td>
<td>3.30</td>
<td>9.85</td>
<td>-</td>
<td>6</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Co-Lithiophorite</td>
<td>Oxide</td>
<td>(Al,LI,NI,Co)(Mn,Fe,Mg)O2(OH)2·nH2O</td>
<td>&lt;5.99</td>
<td>xx</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kolwezite</td>
<td>Carbonate</td>
<td>(Cu,Co)2(CO3)(OH)2</td>
<td>17.84</td>
<td>-</td>
<td>39.05</td>
<td>4</td>
<td>3.97</td>
<td></td>
</tr>
<tr>
<td>Sphaerocobaltite</td>
<td>Carbonate</td>
<td>CoCO3</td>
<td>49.55</td>
<td>-</td>
<td>-</td>
<td>3-4</td>
<td>4.1</td>
<td></td>
</tr>
</tbody>
</table>

+ in substitution in other minerals: sulphides (pyrrhotite, pyrite, arsenopyrite), oxides (goethite, limonite), clays (nontronite), carbonates (dolomite), etc.
COBALT PROCESSING
MAIN PROCESSING ROUTES BY DEPOSIT TYPE

• Stratiform sediment-hosted Cu-Co deposits:
  – Leach-SX-EW (oxides)
  – Flotation-Leach-SX-EW (mixed/sulphides)
  – Heap-leach

• Ni-laterites:
  – Caron ammonia leach process
  – High Pressure Acid Leaching (HPAL)
  – Rotary Kiln Electric Furnaces (RKEF)

• Magmatic Ni sulphides:
  – Flotation

CURRENT COBALT RECOVERY PRACTICE
COBALT PRODUCTION DATA

Production data from major cobalt producing mines in 2018 (annual or quarterly reports)

Co by-product recovery is intrinsically linked to deposits mineralogy (e.g., common vs separate Ni-Cu-Co sulphides) or ore types (e.g., oxides vs sulphides) and processing technology used.
RAJAPALOT AU-CO PROJECT
PROJECT PRESENTATION

• **Location:** The Rajapalot Au-Co project is located in the northern part of the Paleoproterozoic Peräpohja belt,

• **Resources:** 2020 Inferred Mineral Resource (IMR) estimated at 9.0 Mt @ 2.1 g/t Au & 570 ppm Co (Ni43-101),

• **Deposit type:** Stratabound disseminated & hydrothermal mineralisation, sulphide-associated and structurally controlled → Metasedimentary rock-hosted Au-Co

• **Raja prospect** → Au-Co mineralisation in muscovite-biotite-chlorite quartz pyrrhotite-rich schist with albite, Fe-Mg amphiboles & tourmaline. **Co in cobaltite**

• **Palokas prospect** → Au-Co mineralisation within a retrograde alteration assemblage including chlorite, Fe-Mg amphiboles, tourmaline and pyrrhotite associated with quartz veining. **Cobalt host are less constrained (cobaltite or cobalt pentlandite).**
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BF BATCircle project (WP1) → Evaluate Finnish battery mineral deposits (especially Co) by developing a geometallurgical decision-making methodology.

Geometallurgical orientation study:

3 Ore types selected based on lithology, observed minerals & Co content:
- MPC-PAL1: Fe-Mg mineralisation style in Palokas,
- MRC-AY: Pyrrhotite-albite-rich host,
- MRC-MP: Muscovite-biotite (potassic) host.

95% Bulk Raja mineralisation

Questions:
- What are the main geometallurgical characteristics of each ore type?
- Is there a clear distinct process behavior between the ore types?
- Is there a mineralogical control on the process behavior of these ore types?
RAJAPALOT AU-CO PROJECT
BULK ORE MINERALOGY

Modal mineralogy by ore type (QEMSCAN)

Ore-type classification (QEMSCAN/XRD)

- Distinctive gangue mineralogy between the 3 ore types
- Ore type classification → Micas+Qtz/Plagioclase/Amphibole system
Co found in several minerals (by order of importance):

- **Cobaltite** (Cob) - CoAsS
- **Linnaeite** (Lin) - Co$^{2+}$Co$^{3+}$S$_4$
- **Ni-rich Linnaeite** (Ni-Lin) - (Co,Ni)$_3$S$_4$
- **Cobaltian Pyrite** (Py) - (Fe,Co)S$_2$
- **Cobaltian Pentlandite** (Pt) - (Co,Fe,Ni)$_9$S$_8$
- + traces in pyrrhotite (Po) and chalcopyrite (Cpy)
Cobalt found in several minerals (by order of importance):

- **Cobaltite** (Cob) - CoAsS
- **Linnaeite** (Lin) - Co²⁺Co³⁺₂S₄
- **Ni-rich Linnaeite** (Ni-Lin) - (Co,Ni)₃S₄
- **Cobaltian Pyrite** (Py) - (Fe,Co)S₂
- **Cobaltian Pentlandite** (Pt) - (Co,Fe,Ni)₉S₈
- + traces in pyrrhotite (Po) and chalcopyrite (Cpy)

- Cobalt content in cobaltite is relatively constant regardless of the ore type,
- Cobalt content in Linnaeite is highly variable depending on the ore-type
Distinctive cobalt deportment with linnaeite dominant (PAL1) and cobaltite-dominant (AY & MP) ore types,

Almost all the arsenic (> 95 wt%) is deported in cobaltite in AY and MP ore types,

Arsenic can be used as a proxy for cobaltite in these ore types, i.e., the Raja prospect.
RAJAPALOT AU-CO PROJECT

KEY MINERALS LIBERATION BY ORE TYPE

QEMSCAN Mineral map (Palokas)

Pyrrhotite & linnaeite only

~100 µm

Coarse granular Linnaeite

~100 µm

~Always locked

Varible liberation depending on the ore type

Always liberated
The 3 ore types show a distinct:

- Gangue minerals signature in the Micas+Qtz-Amphiboles-Plagioclase system,
- Cobalt deportment (cobaltite vs linnaeite),
- Cobaltite liberation degree,
- Process behaviour, in particular for cobalt, PAL1 vs (AY+MP),

Mineralogical control:

- There is a clear mineralogical control over cobalt recovery,
- This control is determiner by the amount of cobaltite (or the proportion of cobalt therein) in the ore,
- This can be readily integrated into the 3D model.
AN INTEGRATED APPROACH FOR OPTIMISATION AND TRACEABILITY ALONG THE BATTERY MATERIALS VALUE CHAIN
Battery minerals from Finland: Improving the supply chain for the EU battery industry using a geometallurgical approach

Qoetia Delinova, lanessa A. Hiltunen, Jari Niemi, Henrik Olofsson, and Allan R. Butcher

Abstract

Battery raw materials (copper, nickel, and cobalt) are manufactured in a variety of ways using advanced clean-metal extraction technologies.

Projects

www.batcircle.fi/

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www.linkedin.com/company/battrace-project/

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