

A large industrial facility, likely a refinery or chemical plant, is silhouetted against a vibrant orange and yellow sunset sky. Thick, dark smoke or steam billows from a tall chimney on the right side of the frame.

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?



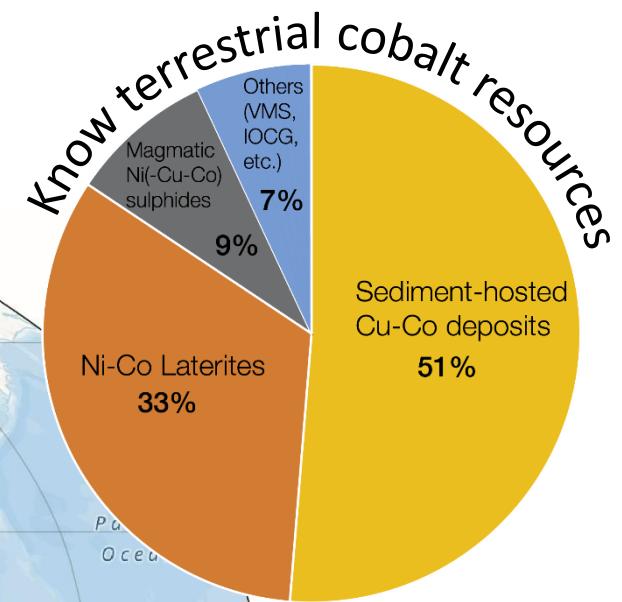
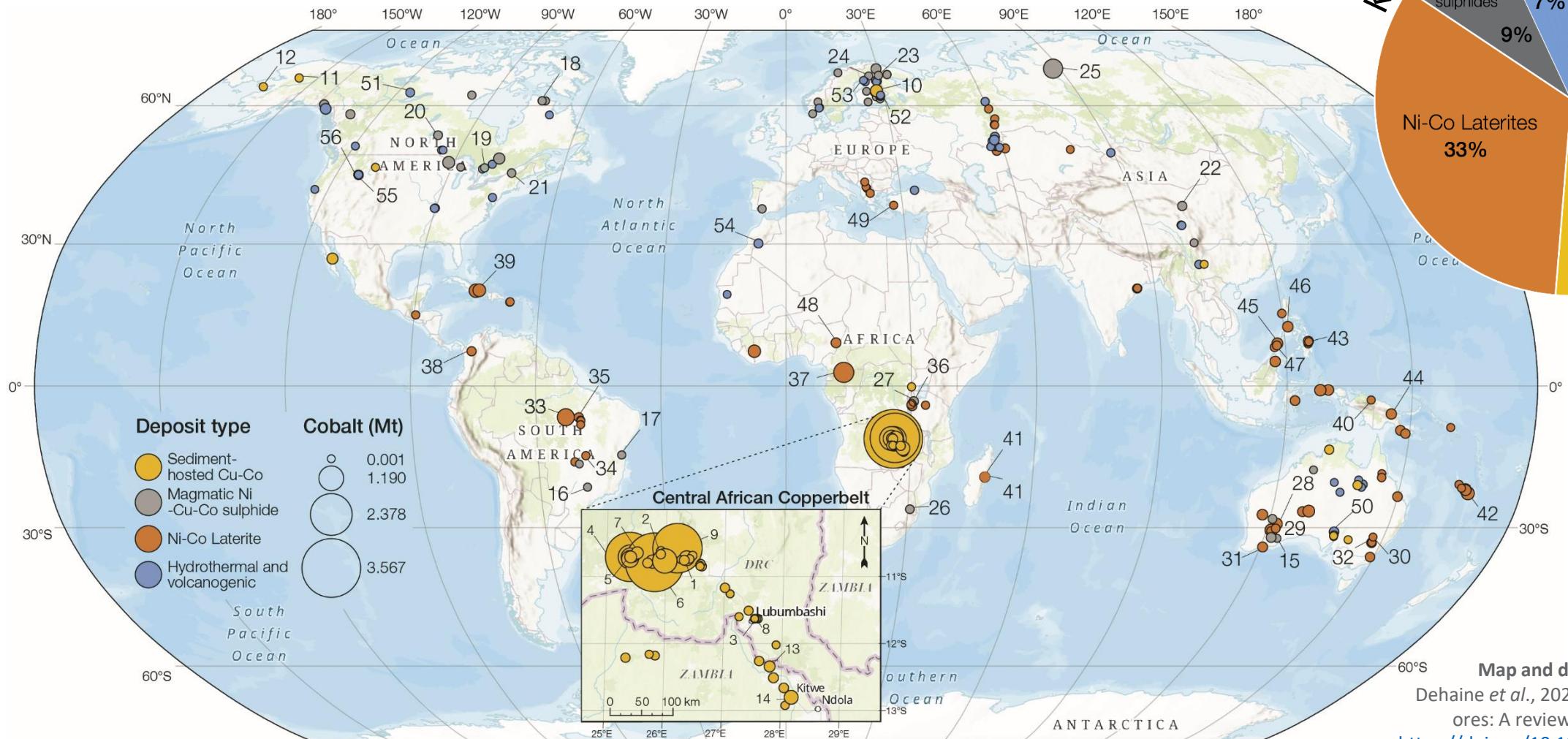
Will cobalt demand exceed supply?



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



COBALT RESOURCES



Map and deposits list available from:
Dehaine et al., 2021. Geometallurgy of cobalt
ores: A review. *Minerals Engineering* 160
<https://doi.org/10.1016/j.mineng.2020.106656>

COBALT MINERALS

COMMON COBALT-BEARING MINERALS WITH MAIN PROPERTIES

Deposit Type
Stratiform Sediment Hotted Cu-Co
Ni-Co Laterite
Magmatic Ni-Cu-Co Sulphide deposits
Hydrothermal and volcanogenic

Mineral Name	Group	Formula	Weight percent			Hardness	Avg. S.G.	Avg. Magnetic Susceptibility (10^{-6})	Acid solubility			Example Deposit
			Co	Ni	Cu				HCl	HNO ₃	H ₂ SO ₄	
Primary Co minerals												
Skutterudite	Arsenide	(Co,Ni)As _{3-x}	17.95	5.96	-	5.5-6	6.5	151.8	H			Bou Azzer (Morocco), Skutterud Mines (Norway)
Smaltite	Arsenide	CoAs _{3-x} , x=[0.5,1]	28.2	-	-	5.5-6	6.5	38.0	I	H	I	Bou Azzer (Morocco),
Safflorite	Arsenide	(Co,Fe)As ₂	21.25	-	-	4-5	7.1	73.8				Elizabeth mine (Romania)
Cobaltite	Sulpharsenide	CoAsS	35.52	-	-	5.5	6.33	49.7	I	H	I	Sudbury (Canada), Broken Hill, (NSW, Australia)
Alloclasite	Sulpharsenide	(Co,Fe)AsS	26.76	-	-	5	6.17		S			Elizabeth mine (Romania), Silverfields mine (ON, Canada)
Glaucodot	Sulpharsenide	(Co,Fe)AsS	26.76	-	-	5	5.95	854.6		D		Håkansboda (Sweden)
Carrollite	Sulphide	Cu(Co,Ni) ₂ S ₄	28.56	9.48	20.53	4.5-5.5	4.65	108.6	I	S		Chambishi, Copperbelt, (Zambia), Carroll County (MD, USA)
Linnaeite	Sulphide	Co ²⁺ Co ₂ ³⁺ S	57.95	-	-	4.5-5.5	4.8	532.0		S	D	Bou Azzer (Morocco), Noril'sk (Russia)
Siegenite	Sulphide	(Ni,Co) ₃ S ₄	14.51	43.36	-	5-5.5	4.65	179.2				Jungfer Mine (Germany)
Cattierite	Sulphide	CoS ₂	47.89	-	-	4.5	4.8-5	1012.4				Shinkolobwe (DRC)
Willyamite	Sulphide	(Co,Ni)SbS	20.78	6.90	-	5.5	6.76					Broken Hill (Australia)
Co-pentlandite	Sulphide	(Co,Ni,Fe) ₉ S ₈	67.40	-	-	4.5	5.22					Langis mine (ON, Canada)
Secondary Co minerals												
Erythrite	Arsenate	Co ₃ (AsO ₄) ₂ 8H ₂ O	29.53	-	-	1.5-2	3.12	1660.2	S	I	I	Bou Azzer (Morocco), Daniel Mine (Germany)
Roselite	Arsenate	Ca ₂ (Co,Mg)(AsO ₄) ₂ ·2(H ₂ O)	9.95	-	-	3.5	3.69		S	S	S	Rappold mines (Germany), Rosas mine (Sardinia, Italy)
Heterogenite	Oxide	CoO(OH)	64.10	-	-	3-5	4.3	255.6				Katanga province (DRC)
Asbolane	Oxide	(Ni,Co) _{2-x} Mn ⁴⁺ (O,OH) ₄ · nH ₂ O	3.30	9.85	-	6			S			Koniambo Massif, Goro (New Caledonia)
Co-Lithiophorite	Oxide	(Al,Li,Ni,Co)(Mn,Fe,Mg)O ₂ (OH) ₂	<5.99	xx	-							Koniambo Massif, Goro (New Caledonia)
Kolwezite	Carbonate	(Cu,Co) ₂ (CO ₃)(OH) ₂	17.84	-	39.05	4	3.97					Musonoi, Kamoto, Mupine and Mashamba West mines (DRC)
Sphaerocobaltite	Carbonate	CoCO ₃	49.55	-	-	3-4	4.1		S			Tenke-Fungurume (DRC), Schneeberg district (Germany)

+ 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:

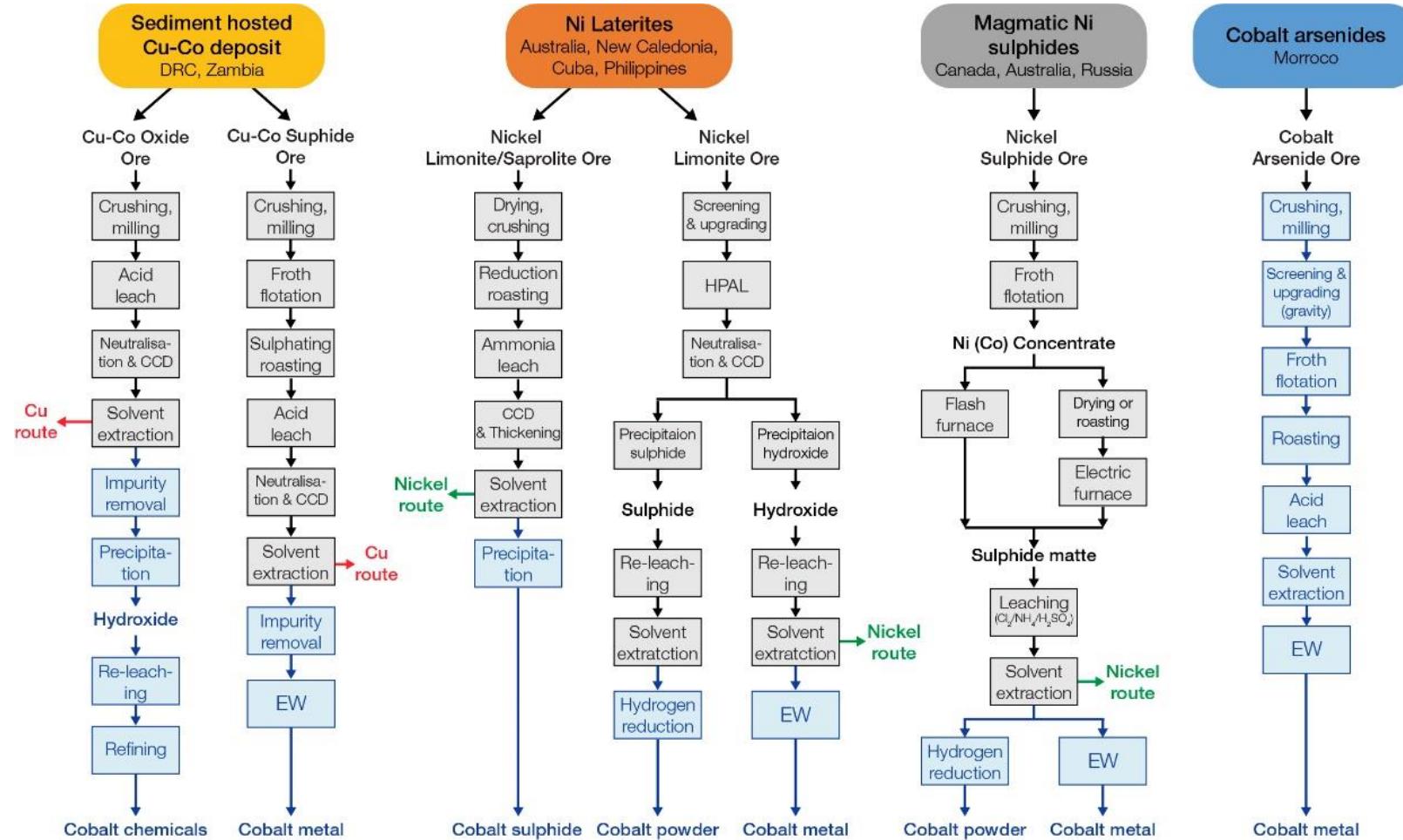
- Leach-SX-EW (oxides)
- Flotation-Leach-SX-EW (mixed/sulphides)
- Heap-leach

- Ni-laterites:

- Caron ammonia leach process
- High Pressure Acid Leaching (HPAL)
- Rotary Kiln Electric Furnaces (RKEF)

- Magmatic Ni sulphides:

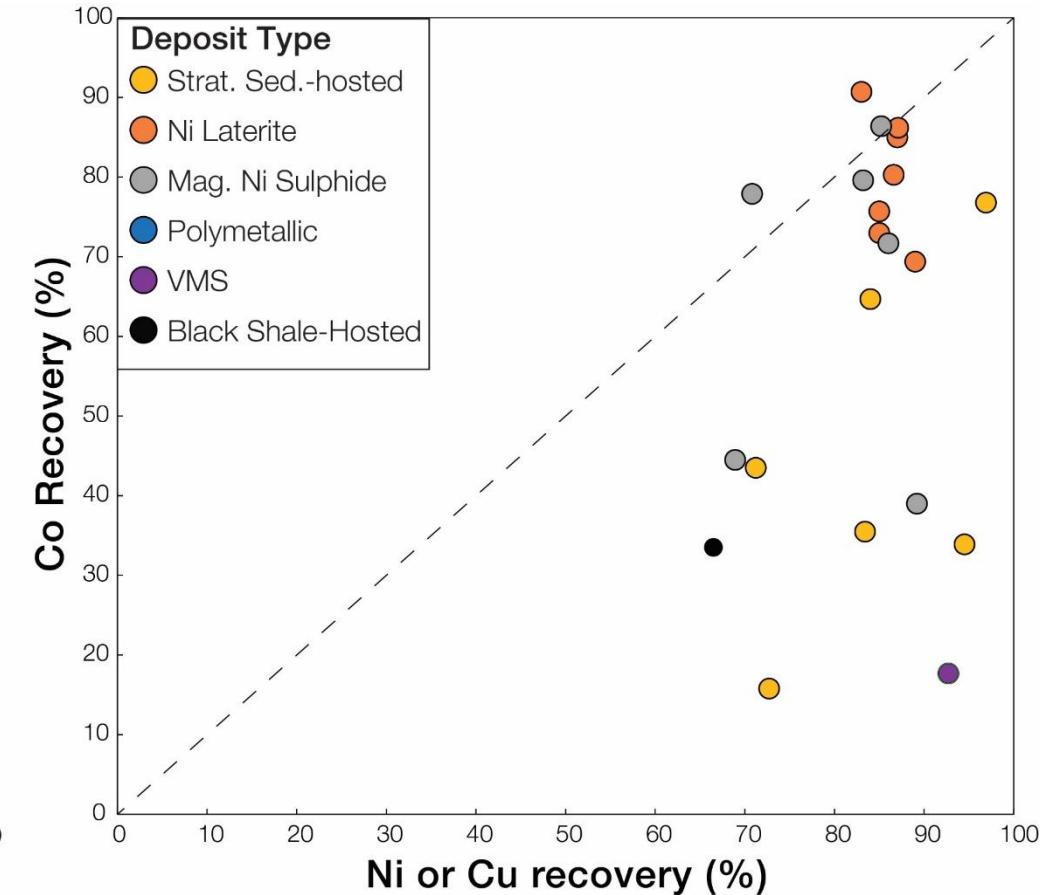
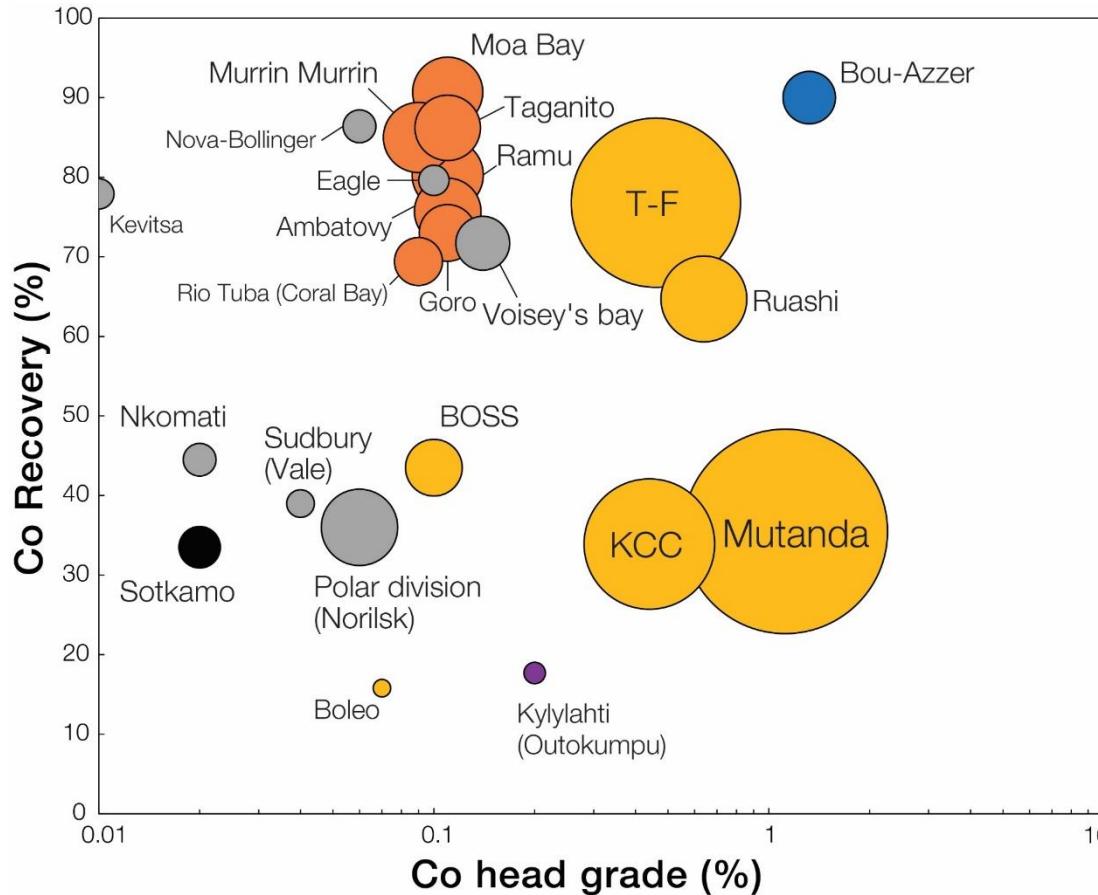
- Flotation



CURRENT COBALT RECOVERY PRACTICE

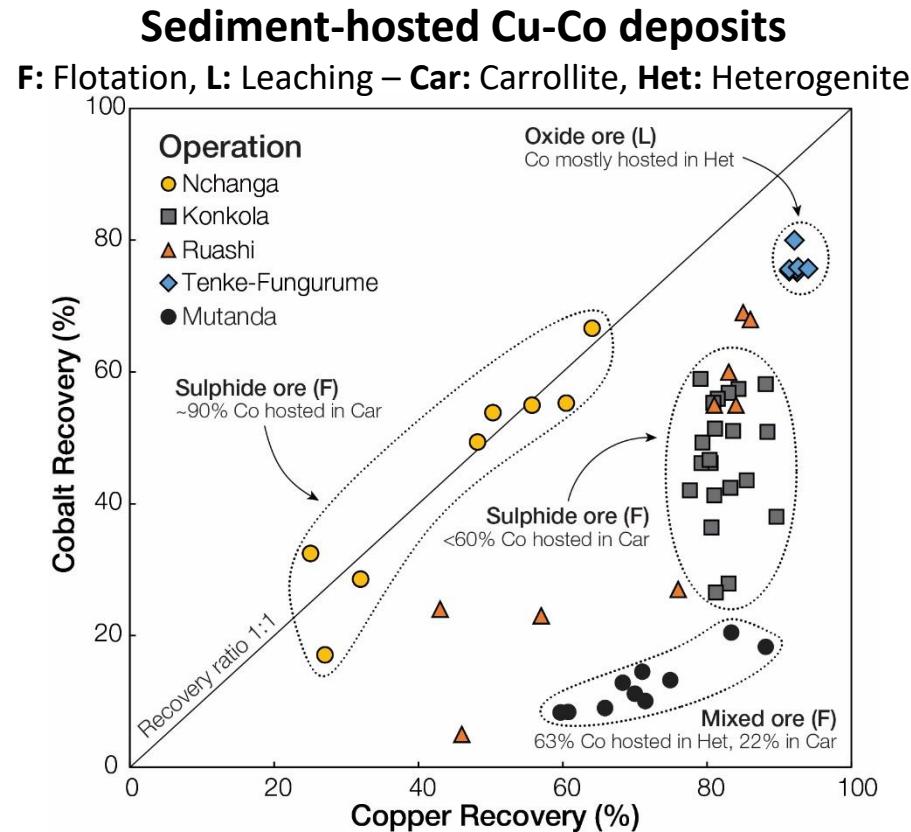
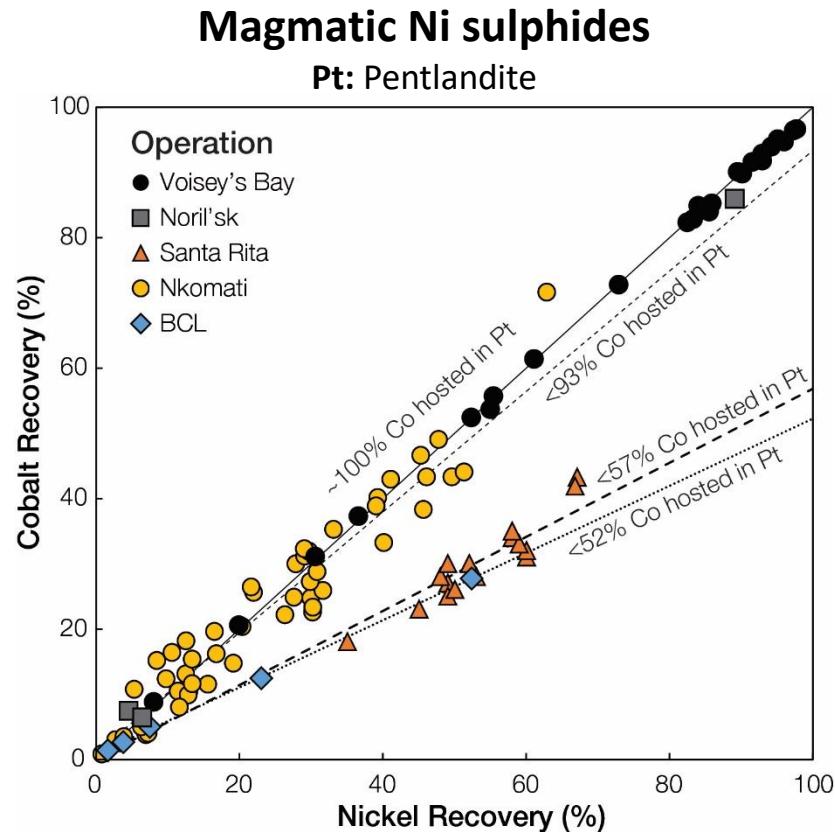
COBALT PRODUCTION DATA

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



CURRENT COBALT RECOVERY PRACTICE

IMPORTANCE OF ORE MINERALOGY



Lab/Pilot +
Industrial
Data

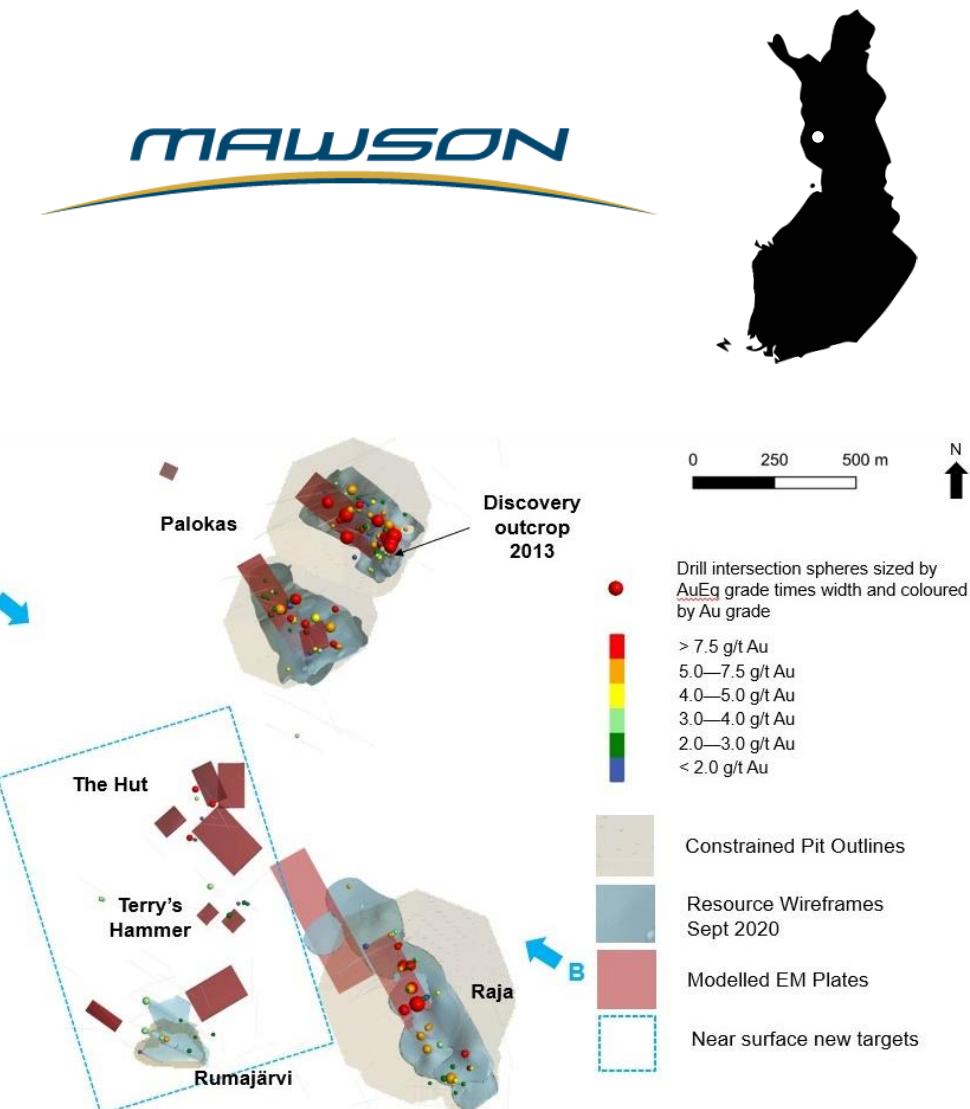
Dehaine *et al.*, 2021.
Geometallurgy of cobalt
ores: A review. *Minerals*
Engineering 160
<https://doi.org/10.1016/j.mineng.2020.106656>

→ 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

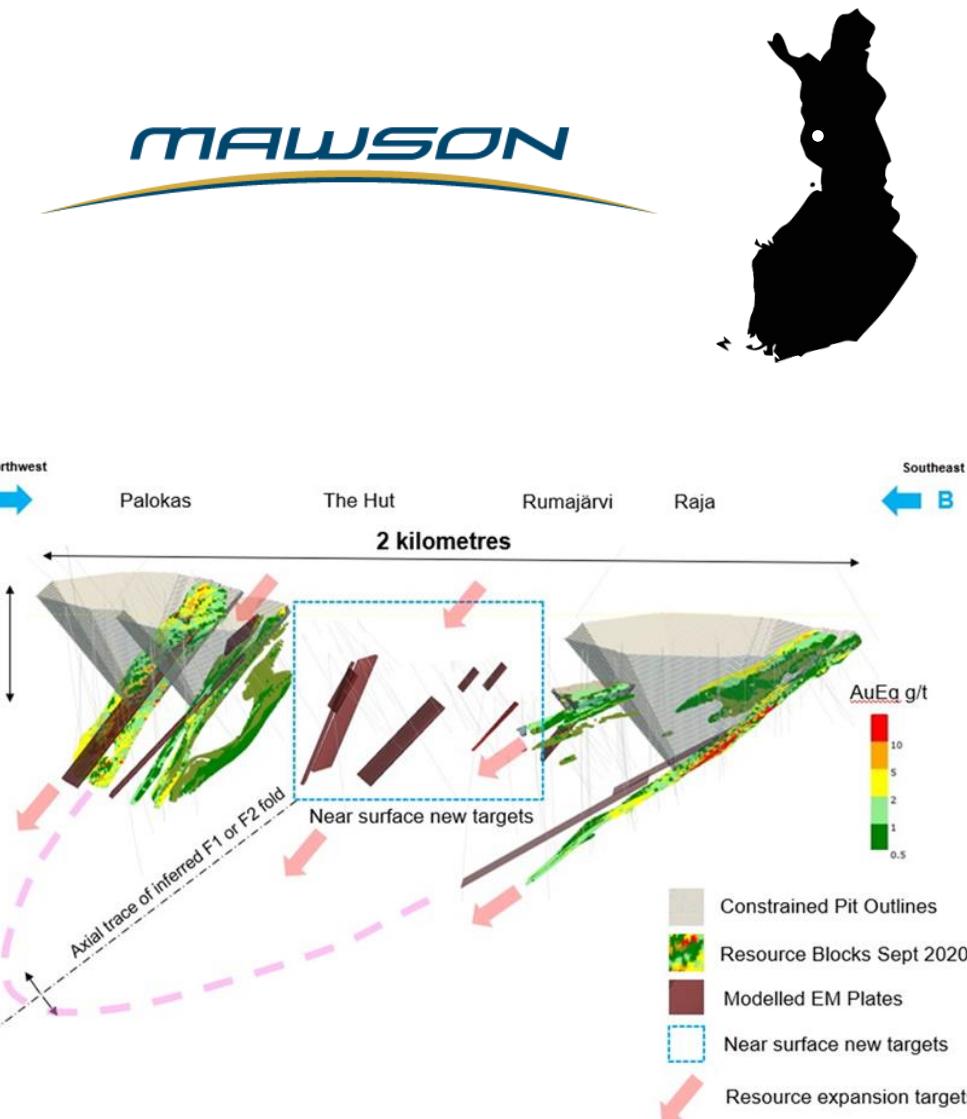
- **Location:** The Rajapalot Au-Co project is located in the northern part of the Paleoproterozoic Peräpohja belt,
- **Resources:** 2020 Inferred Mineral Resource (IMR) estimated at **9.0 Mt @ 2.1 g/t Au & 570 ppm Co** (Ni43-101),
- **Deposit type:** Stratabound disseminated & hydrothermal mineralisation, 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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RAJAPALOT AU-CO PROJECT

BATCIRCLE GEOMETALLURGICAL PROGRAM



BF BATCircle project (WP1) → Evaluate Finnish battery mineral deposits (especially Co) by developing a **geometallurgical decision-making methodology**.

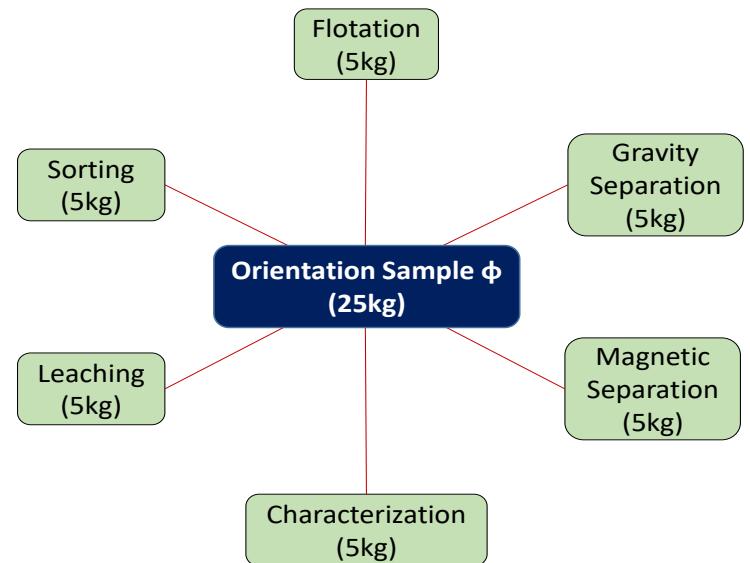
Geometallurgical orientation study:

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:

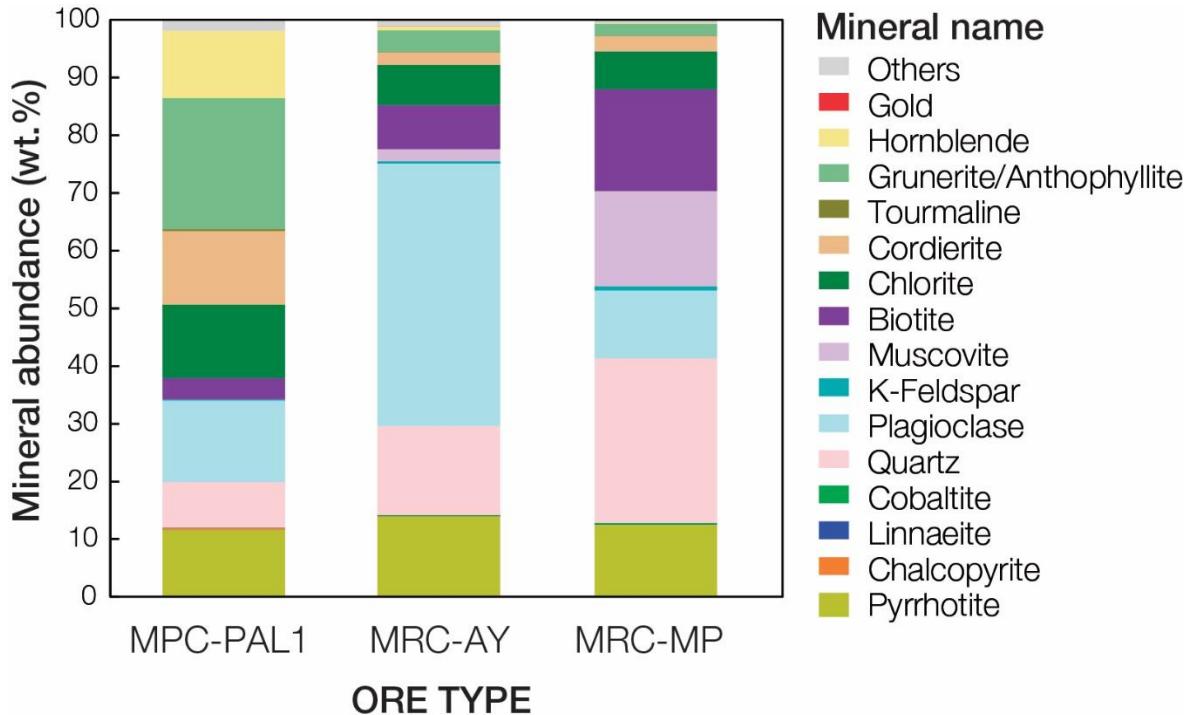
- What are the main **geometallurgical characteristics** of each ore type?
- Is there a clear **distinct process behavior** between the ore types?
- Is there a **mineralogical control** on the process behavior of these ore types?



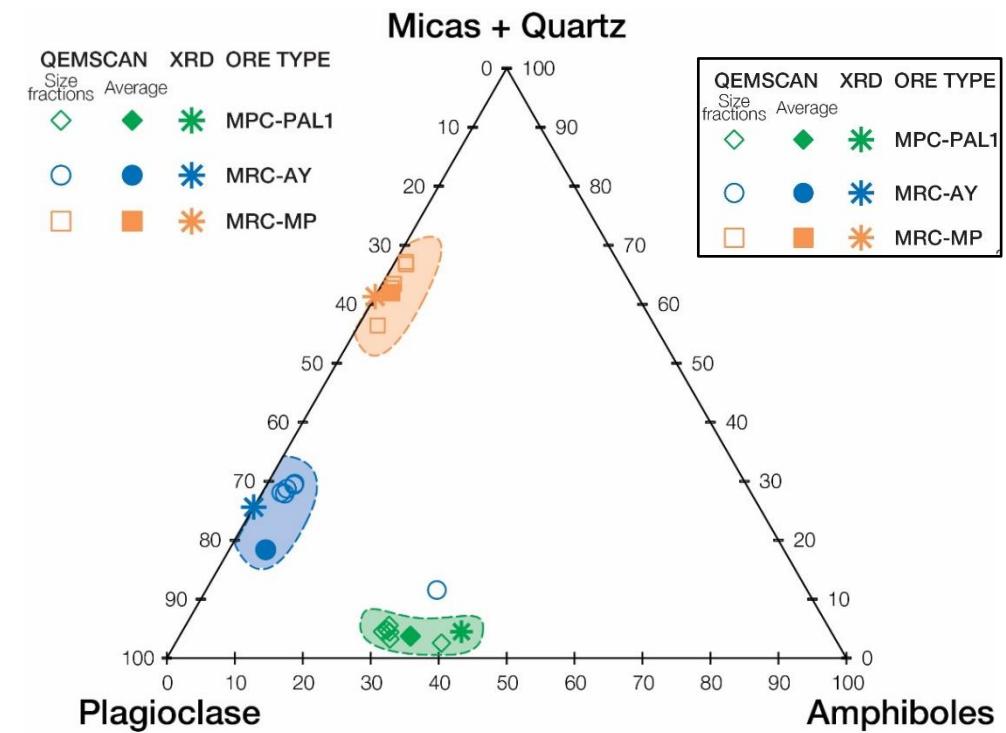
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BULK ORE MINERALOGY

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

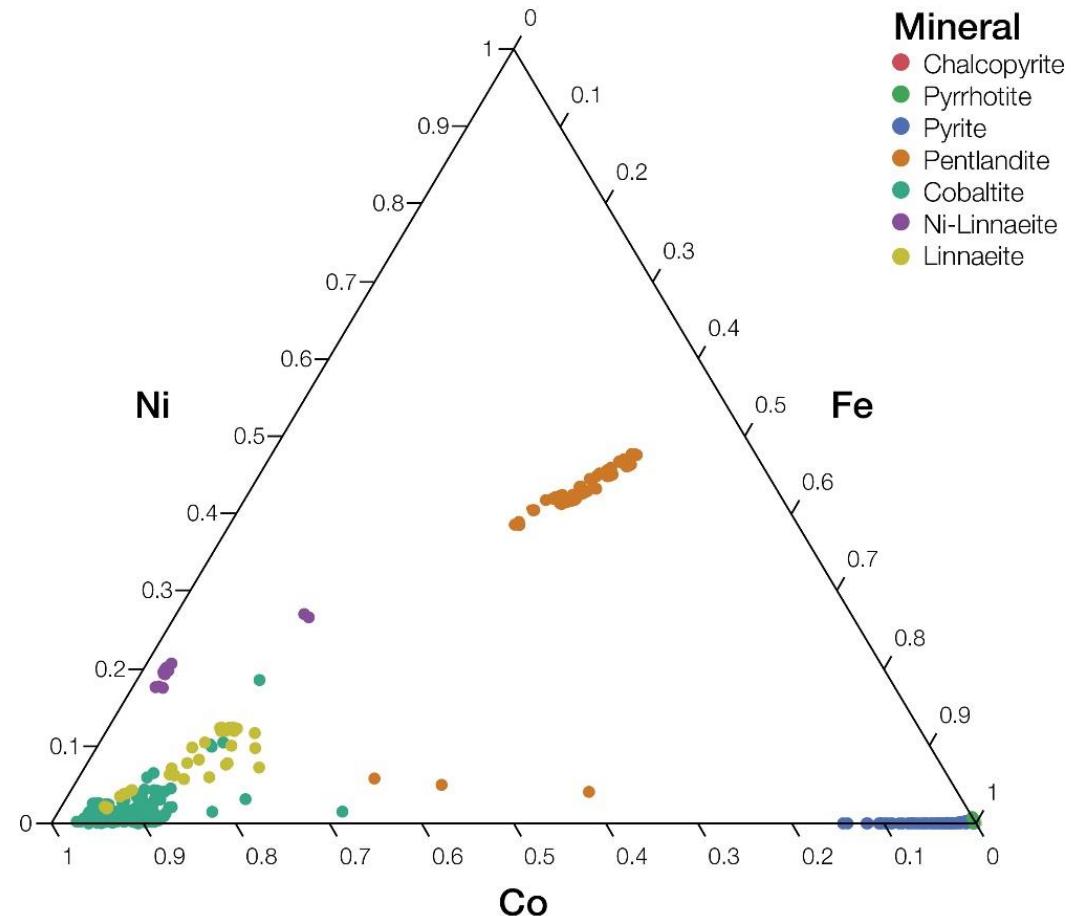
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COBALT MINERALS – COBALT CONTENT

Cobalt found in several minerals (by order of importance):

- **Cobaltite (Cob)** - CoAsS
- **Linnaeite (Lin)** - $\text{Co}^{2+}\text{Co}^{3+}_2\text{S}_4$
- **Ni-rich Linnaeite (Ni-Lin)** - $(\text{Co},\text{Ni})_3\text{S}_4$
- **Cobaltian Pyrite (Py)** - $(\text{Fe},\text{Co})\text{S}_2$
- **Cobaltian Pentlandite (Pt)** - $(\text{Co},\text{Fe},\text{Ni})_9\text{S}_8$
- + traces in pyrrhotite (Po) and chalcopyrite (Cpy)

Ni-Fe-Co plot for sulphide minerals (EPMA)



RAJAPALOT AU-CO PROJECT

COBALT MINERALS – COBALT CONTENT

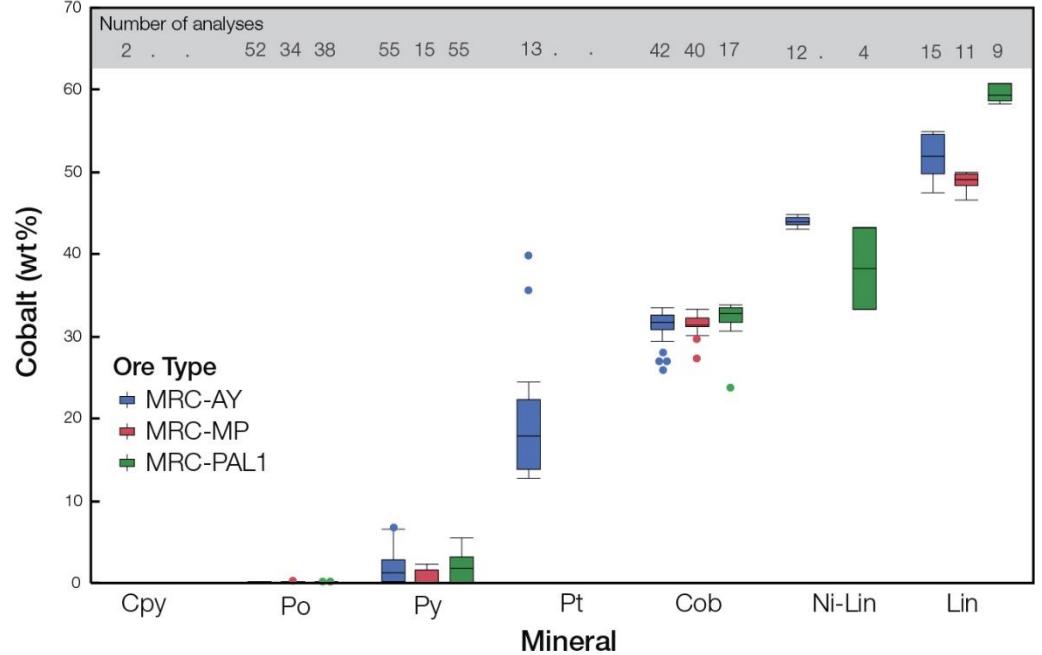
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- Cobalt content in cobaltite is relatively constant regardless of the ore type,
- Cobalt content in Linnaeite is highly variable depending on the ore-type

Cobalt content
in sulphide
minerals
(EPMA)

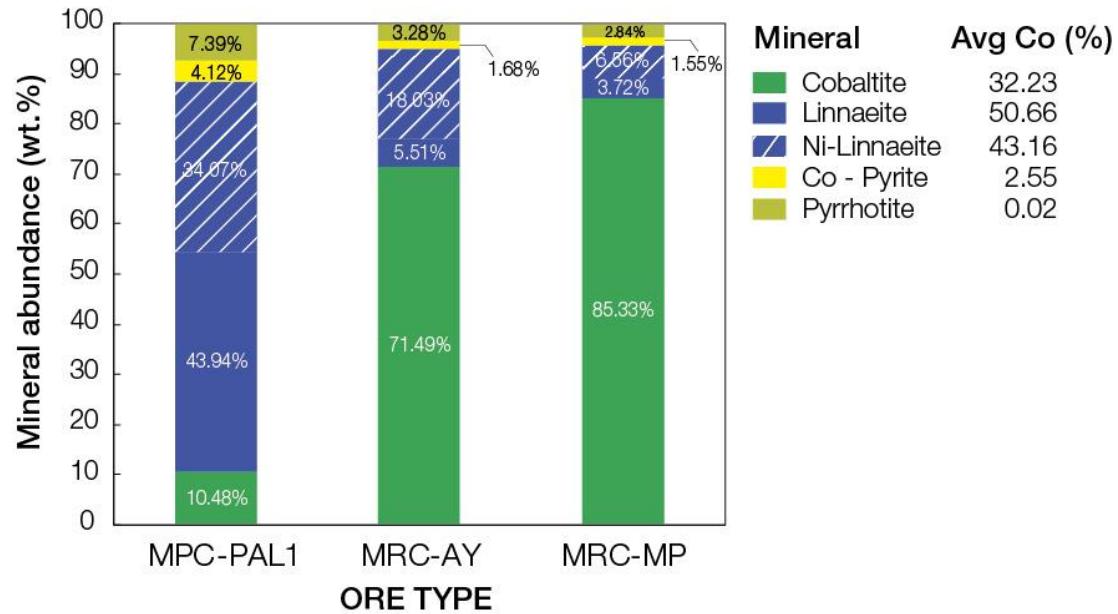
By ore-type



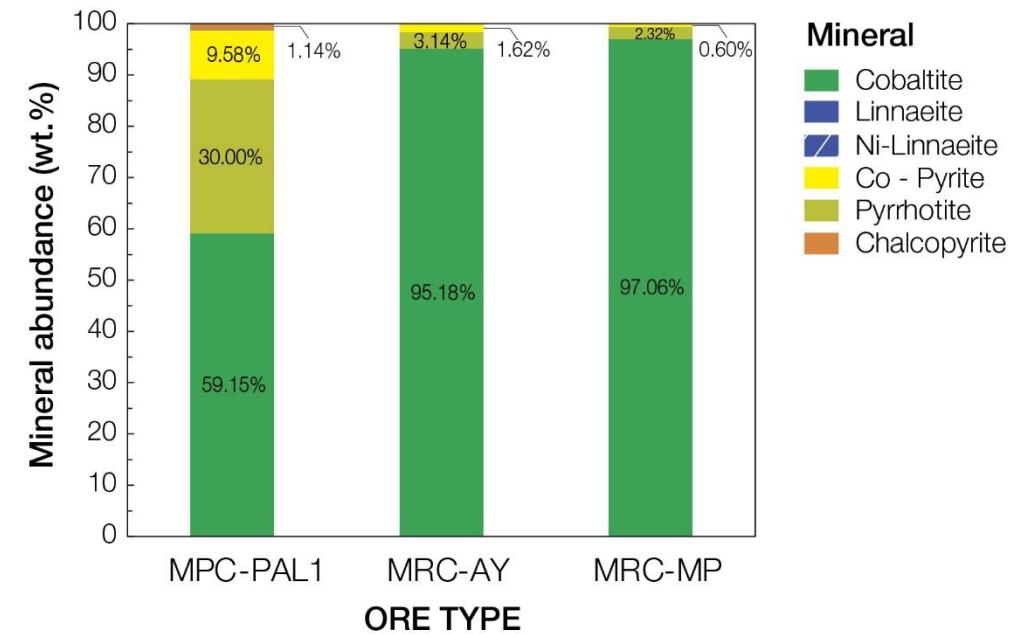
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COBALT & ARSENIC DEPORTMENT

Cobalt deportment



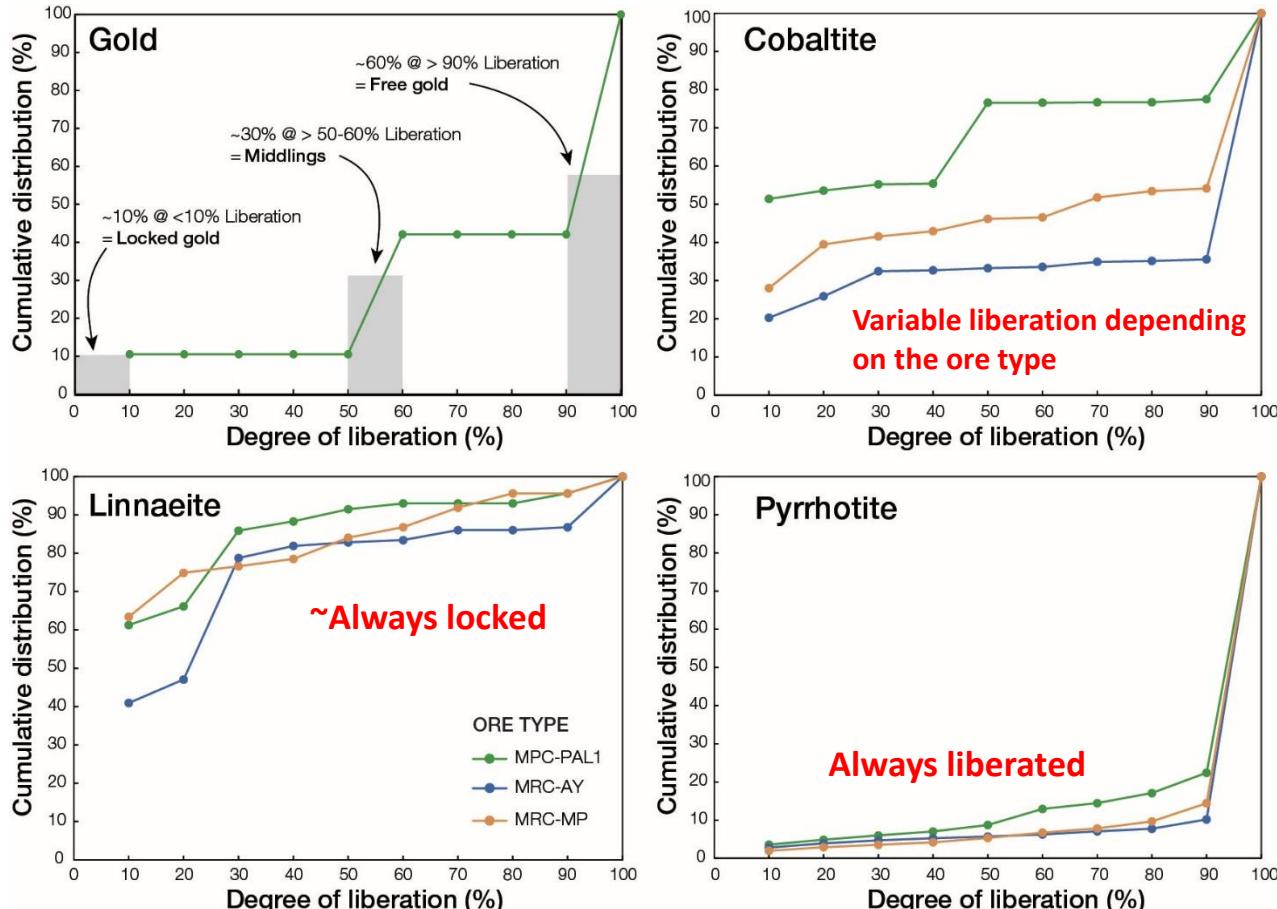
Arsenic deportment



- 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.

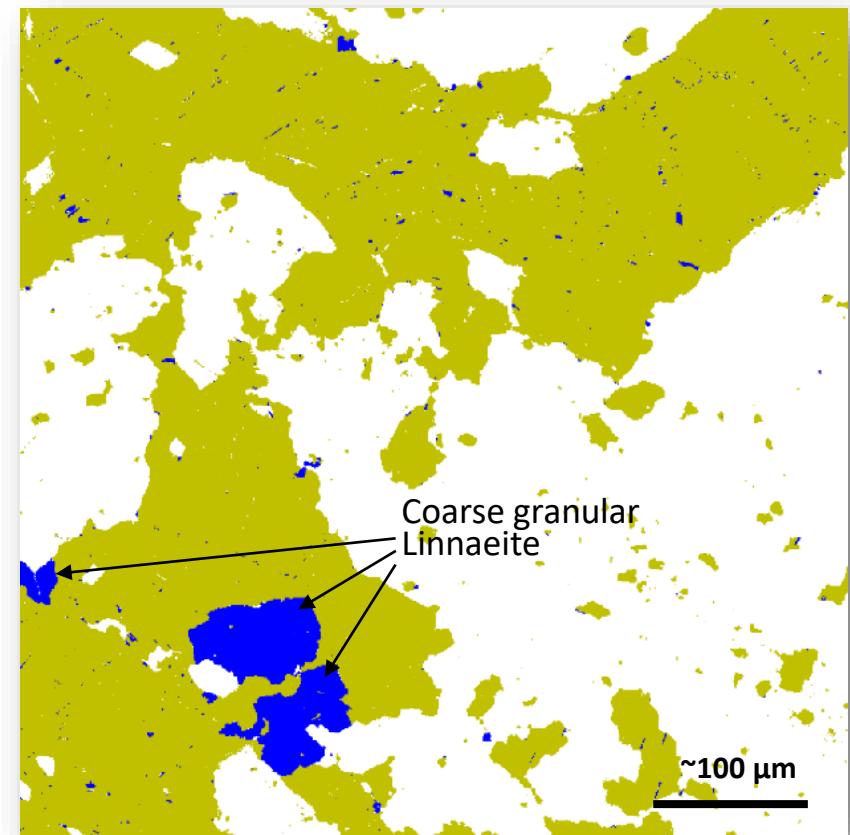
RAJAPALOT AU-CO PROJECT

KEY MINERALS LIBERATION BY ORE TYPE



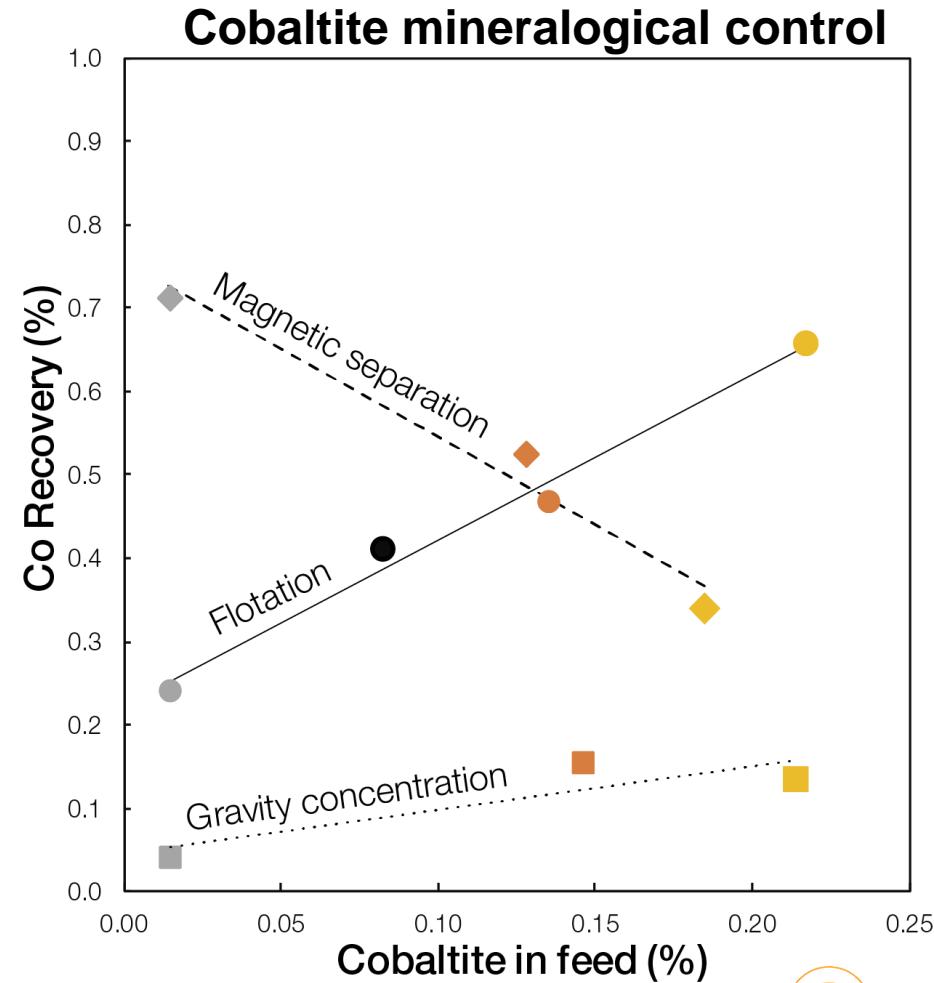
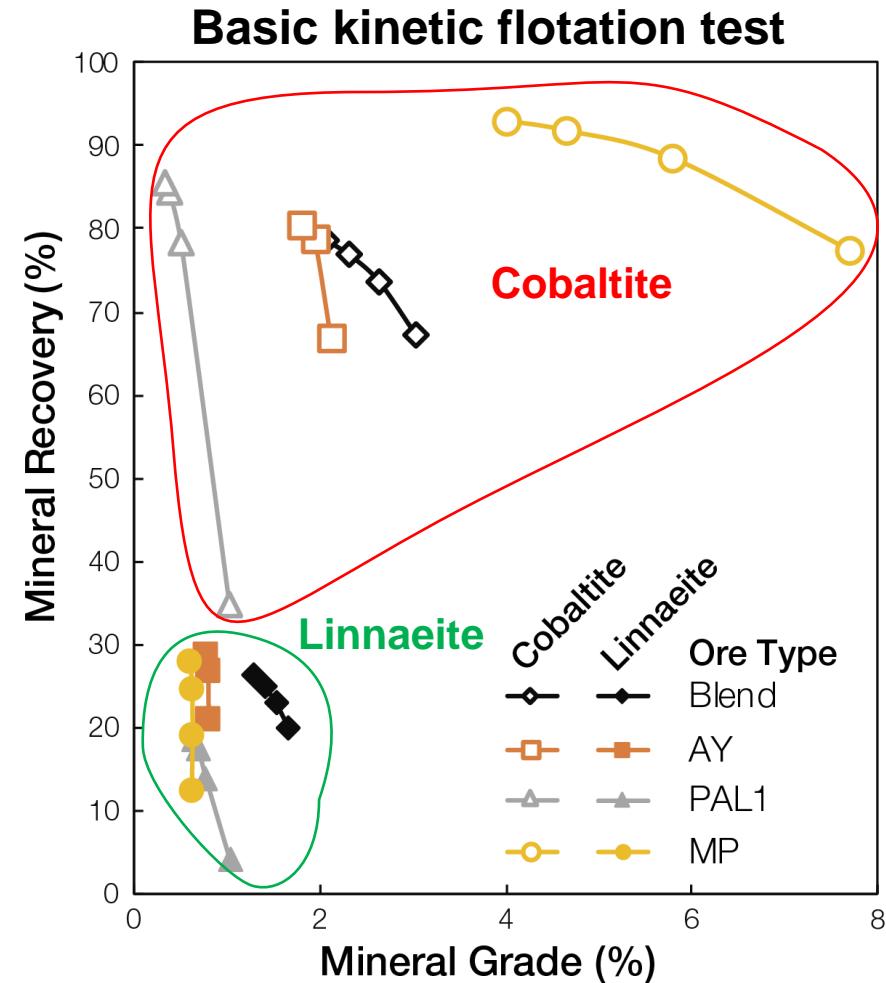
QEMSCAN Mineral map (Palokas)

Pyrrhotite & Linnaeite only



RAJAPALOT AU-CO PROJECT

MINERALOGICAL CONTROL ON COBALT RECOVERY



RAJAPALOT AU-CO PROJECT

CONCLUSIONS

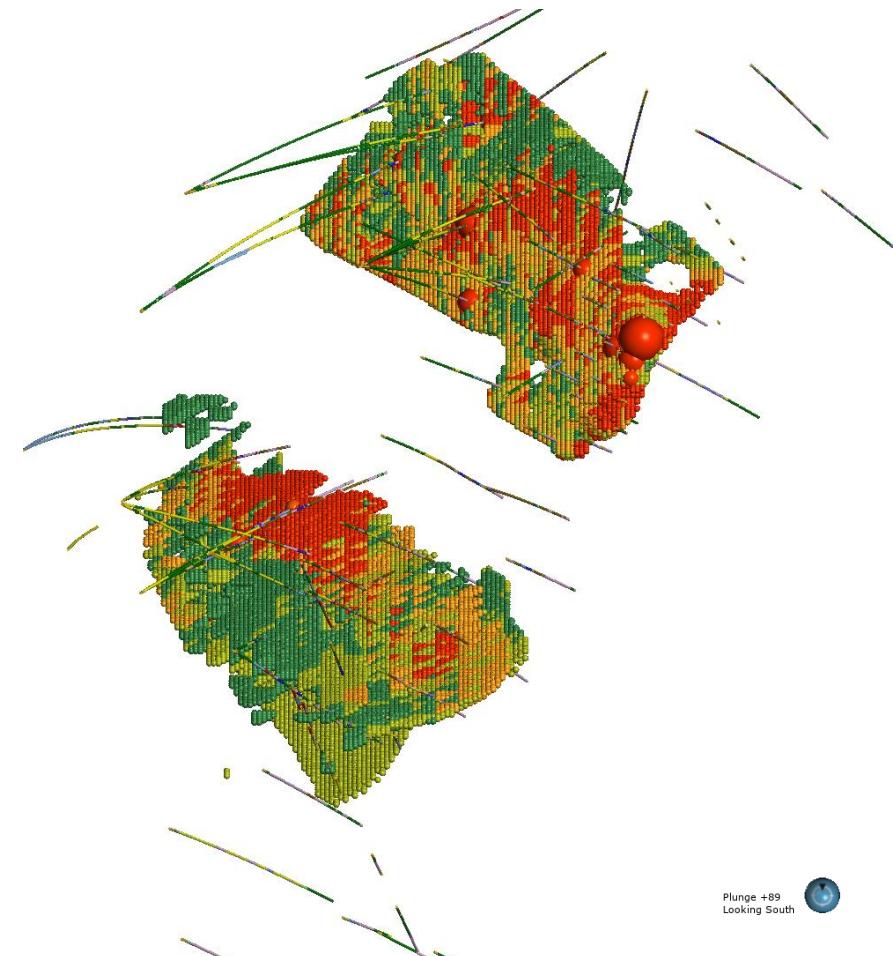
The 3 ore types show a distinct:

- 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),

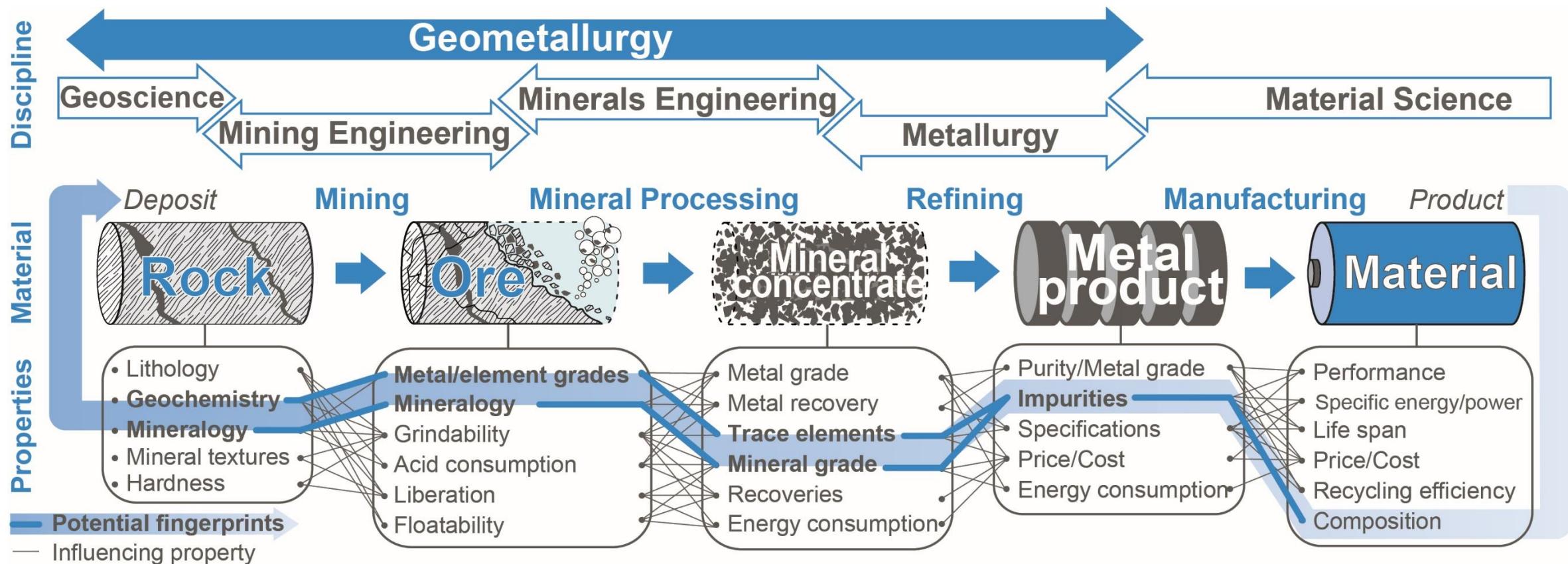
Mineralogical control:

- 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.

Mineralogical 3D model – Cobaltite/Linnaeite ratio



AN INTEGRATED APPROACH FOR OPTIMISATION AND TRACEABILITY ALONG THE BATTERY MATERIALS VALUE CHAIN



FURTHER READING...

PROJECTS



www.batcircle.fi/

PUBLICATIONS

Battery minerals from Finland: Improving the supply chain for the EU battery industry using a geometallurgical approach

Quentin Dehaine*, Simon P. Michaux, Jussi Pokki, Mari Kivinen and Alan R. Butcher

Battery raw materials (cobalt, lithium, graphite, and nickel) are essential for a technologically-advanced low-carbon society. Most of these commodities are produced in just a few countries, which leads to supply risk as well as environmental and ethical issues. Finland, with its available mineral resources (deposits and mines), nical expertise (know-how, automation), has the ideal ecosystem to tackle the challenge of improving the rechargeable battery raw materials supply chain and securing sustainable sources for Europe. The probable extraction of these commodities in a competitive market is a complex function of key ore properties that drive extraction process performance and are directly linked to deposit geology and ore mineralogy. Hence, geometallurgy – which combines geological and metallurgical information to improve resource management, optimise extraction, and reduce technical risks – is the key multidisciplinary approach to tackling the challenge of sustainable and responsible EU domestic production of battery raw materials.

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[doi:\[10.5281/zenodo.3938855\]\(https://doi.org/10.5281/zenodo.3938855\)](https://doi.org/10.5281/zenodo.3938855)

Topical - Mineral raw materials

BATTRACE



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[doi:\[10.1016/j.mineng.2020.106656\]\(https://doi.org/10.1016/j.mineng.2020.106656\)](https://doi.org/10.1016/j.mineng.2020.106656)

ARTICLE INFO

Keywords:
Cobalt
Geometallurgy
Mineralogy
Flotation
Leaching

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Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Geometallurgy of cobalt ores: A review

Quentin Dehaine^{a,b,*}, Laurens T. Tijsseling^{a,c}, Hylke J. Glass^a, Tuomo Törmänen^b, Alan R. Butcher^b

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Article

Mineralogical Prediction of Flotation Performance for a Sediment-Hosted Copper-Cobalt Sulphide Ore

Laurens T. Tijsseling^{1,2}, Quentin Dehaine^{1,3}, Gavyn K. Rollinson¹ and Hylke J. Glass^{1,4}
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Received: 26 March 2020; Accepted: 20 May 2020; Available online: 23 May 2020

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Abstract: As part of a study investigating the influence of mineralogical variability in a sediment-hosted copper-cobalt deposit in the Democratic Republic of Congo on flotation performance, the flotation of nine sulphide ore samples was investigated through laboratory batch kinetics tests and quantitative mineral analyses. Using a range of ore samples from the same deposit the influence of variability on flotation performance was studied. Characterisation of the samples through mineralogical analysis revealed the presence of pyrite, chalcopyrite, chalcocite and carrollite are the main copper-bearing and cobalt-bearing mineral. Mineralogical characteristics were correlated with flotation performance parameters.



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Novel approach for processing complex carbonate-rich copper-cobalt mixed ores via reverse flotation

Quentin Dehaine^{a,b,*}, Lev O. Filippov^{c,*}, Inna V. Filippova^c, Laurens T. Tijsseling^d, Hylke J. Glass^a
^a University of Exeter, Camborne School of Mines, Penryn, Cornwall TR10 9FE, United Kingdom
^b Geological Survey of Finland, Circular Economy Solutions Unit, FI-02151 Espoo, Finland
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KIITOS!

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