GEOMETALLURGY OF COBALT:

Global aspects & a Finnish case study

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COBALT FACTS & FIGURES

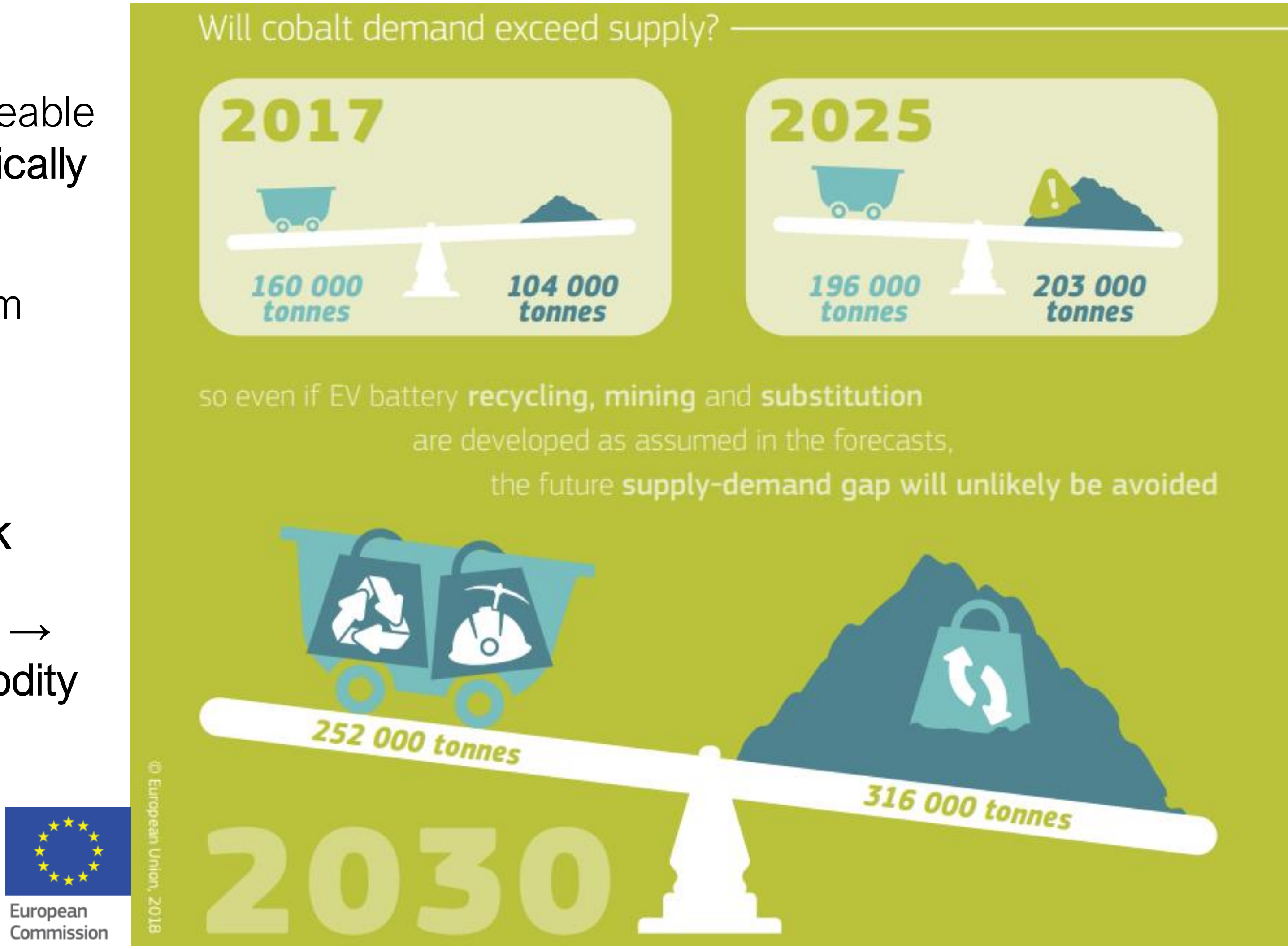
60% of the Co production goes to rechargeable batteries → **Essential for a technologically advanced low carbon society**

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?



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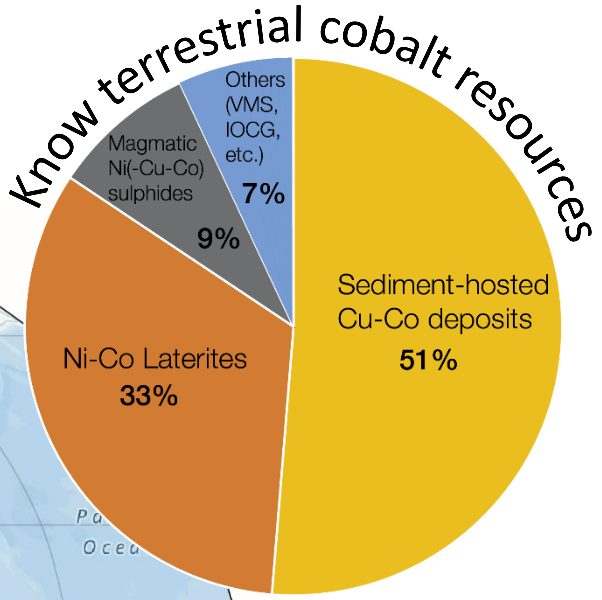
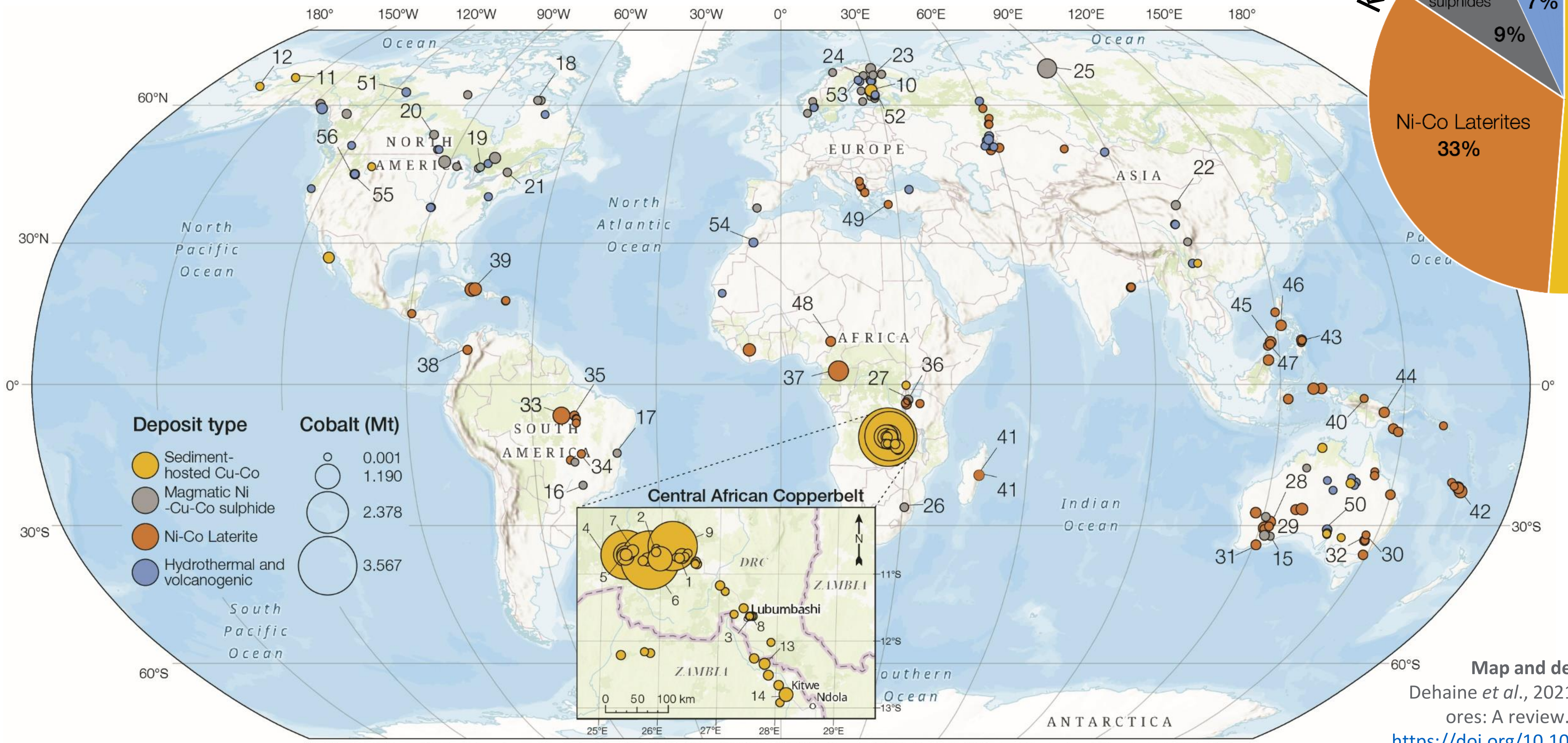
COBALT RESOURCES





World topographic and hillshade base layers from Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

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

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COBALT MINERALS

COMMON COBALT-BEARING MINERALS WITH MAIN PROPERTIES

Deposit Type

- Stratiform Sediment Hoted Cu-Co
- Ni-Co Laterite
- Magmatic Ni-Cu-Co Sulphide deposits
- Hydrothermal and volcanogenic

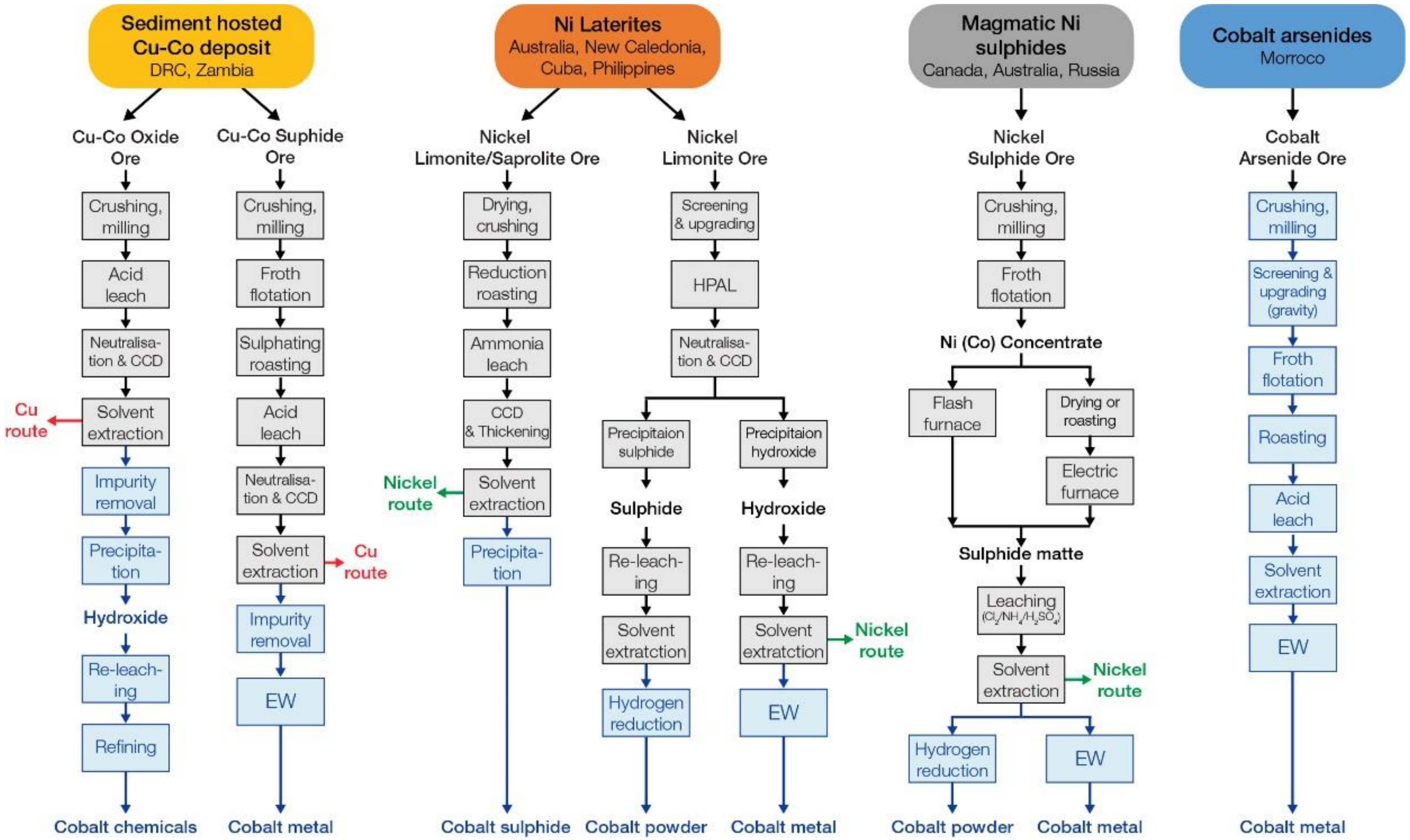
Mineral Name	Group	Formula	Weight percent			Hardness	Avg. S.G.	Avg. Magnetic Susceptibility (10^{-6})	Acid solubility			Example Deposit
			Co	Ni	Cu				HCl	HNO_3	H_2SO_4	
						Primary Co minerals						
Skutterudite	Arsenide	$(Co,Ni)As_{3-x}$	17.95	5.96	-	5.5-6	6.5	151.8		H		Bou Azzer (Morocco), Skutterud 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	$Cu(Co,Ni)_2S_4$	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	$(Ni,Co)_3S_4$	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	$(Co,Ni,Fe)_9S_8$	67.40	-	-	4.5	5.22					Langis mine (ON, Canada)
						Secondary Co minerals						
Erythrite	Arsenate	$Co_3(AsO_4)_28H_2O$	29.53	-	-	1.5-2	3.12	1660.2	S	I	I	Bou Azzer (Morocco), Daniel Mine (Germany)
Roselite	Arsenate	$Ca_2(Co,Mg)(AsO_4)_2\cdot 2(H_2O)$	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	$(Ni,Co)_{2-x}Mn^{4+}(O,OH)_4 \cdot nH_2O$	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



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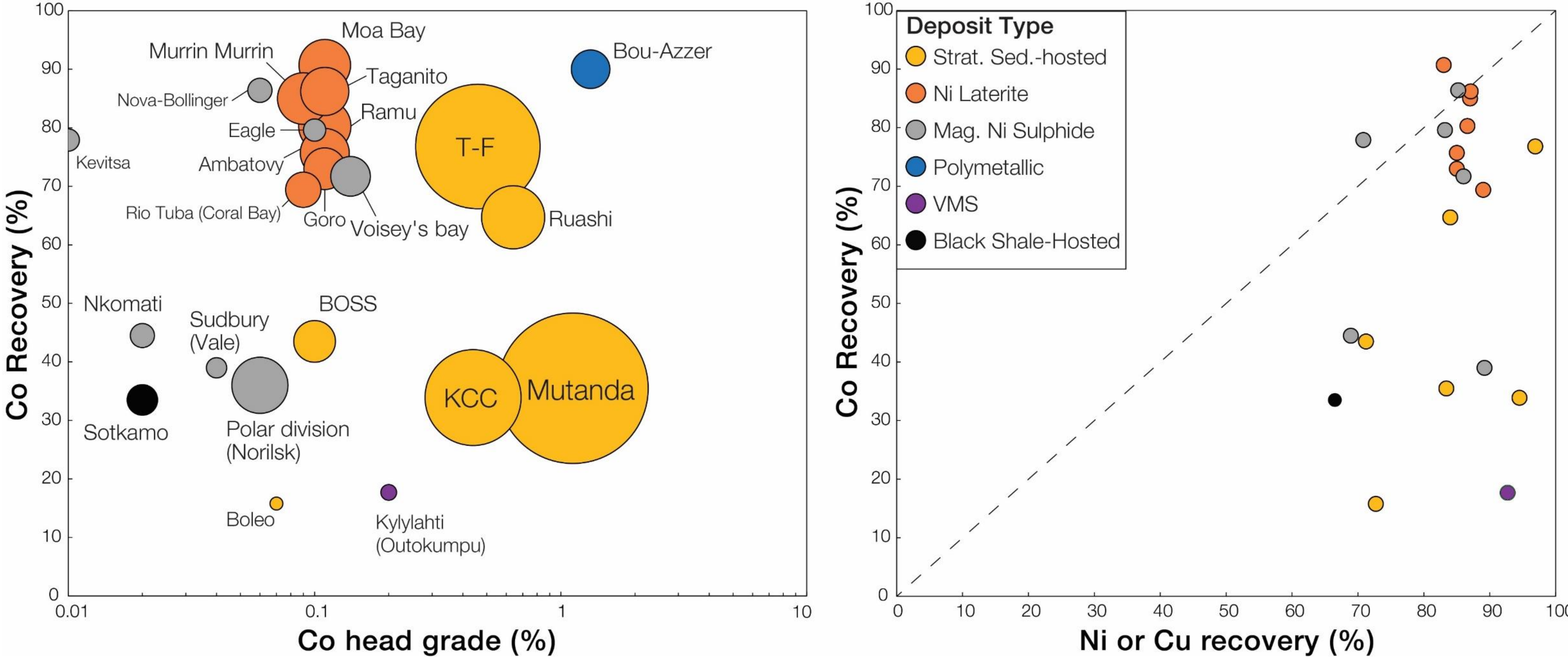
CURRENT COBALT RECOVERY PRACTICE

COBALT PRODUCTION DATA

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



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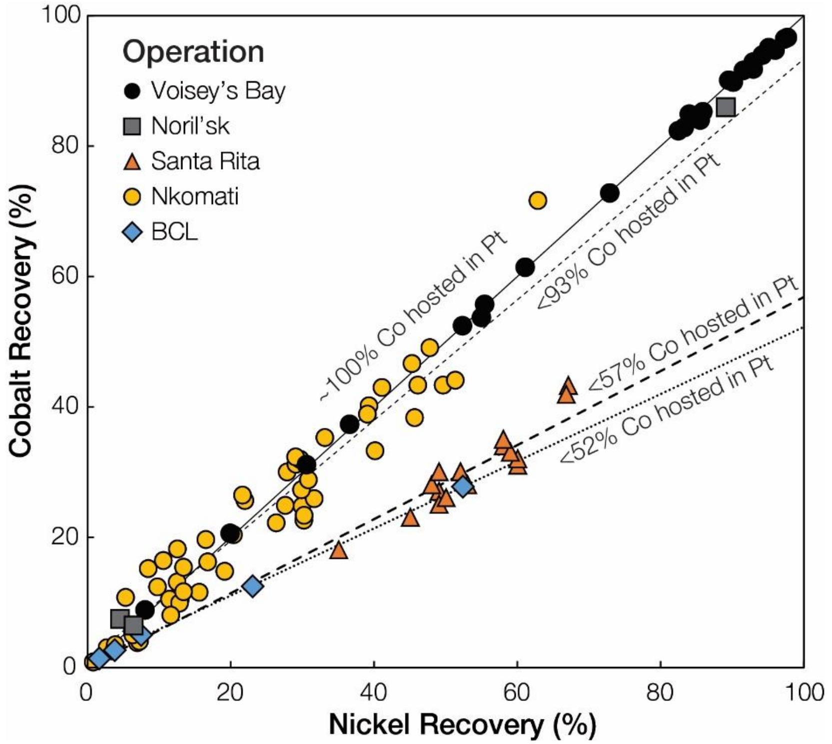
CURRENT COBALT RECOVERY PRACTICE

IMPORTANCE OF ORE MINERALOGY

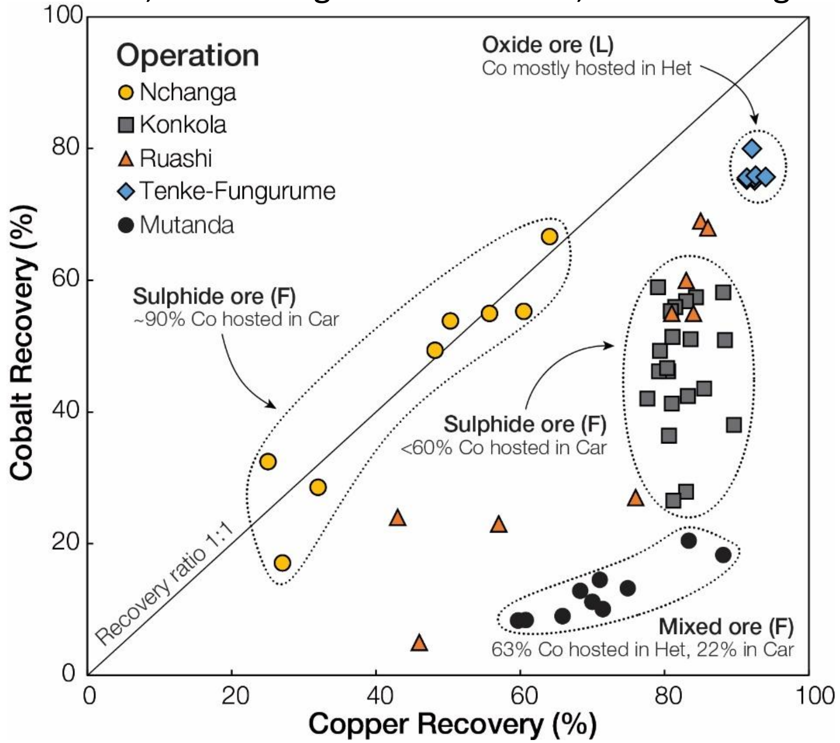
Magmatic Ni sulphides

Pt: Pentlandite



Sediment-hosted Cu-Co deposits

F: Flotation, **L:** Leaching – **Car:** Carrollite, **Het:** Heterogenite



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

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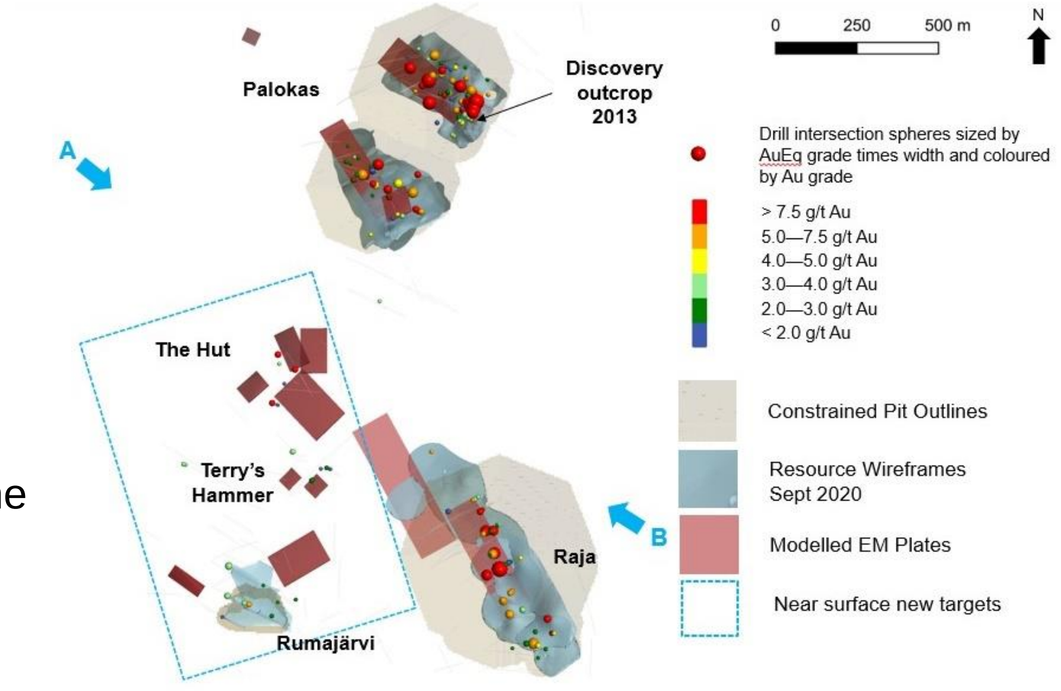
RAJAPALOT AU-CO PROJECT

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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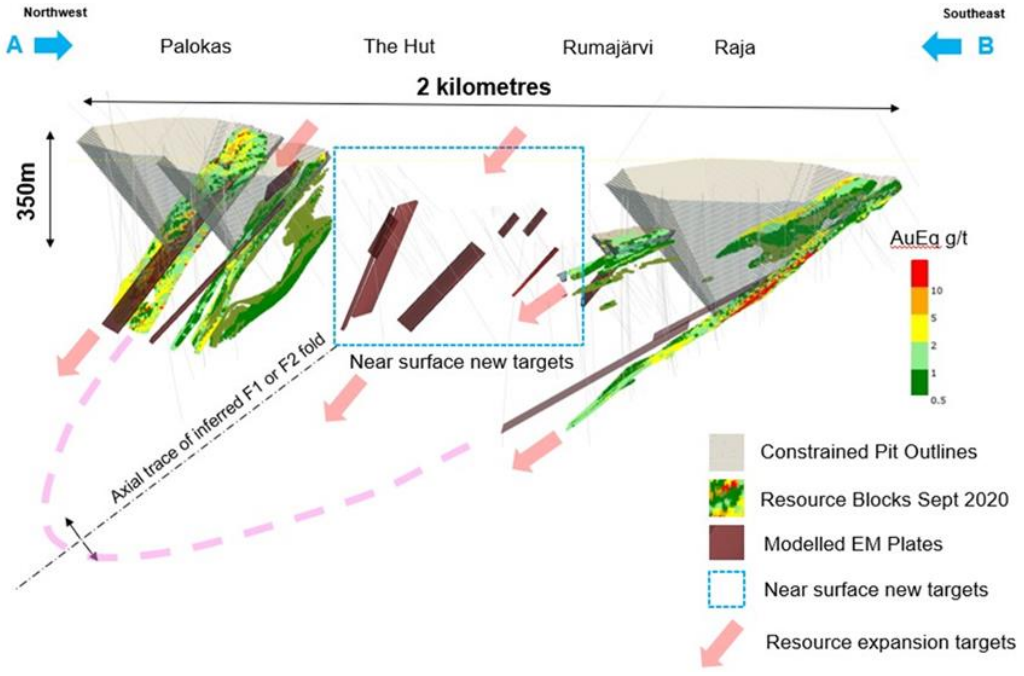


RAJAPALOT AU-CO PROJECT
BATCIRCLE GEOMETALLURGICAL PROGRAM

BATCircle

BUSINESS FINLAND

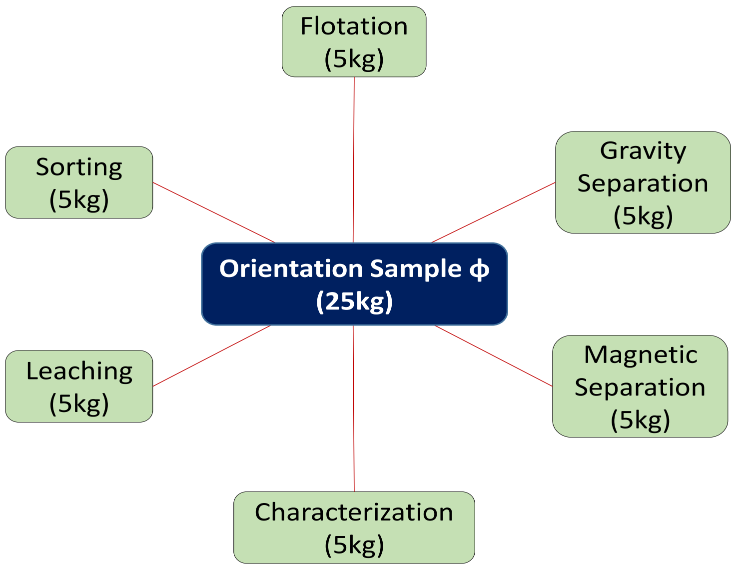
BF **BATCircle project** (WP1) → Evaluate Finnish battery mineral deposits (especially Co) by developing a **geometallurgical decision-making methodology**.

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.

(MRC-AY and MRC-MP:) 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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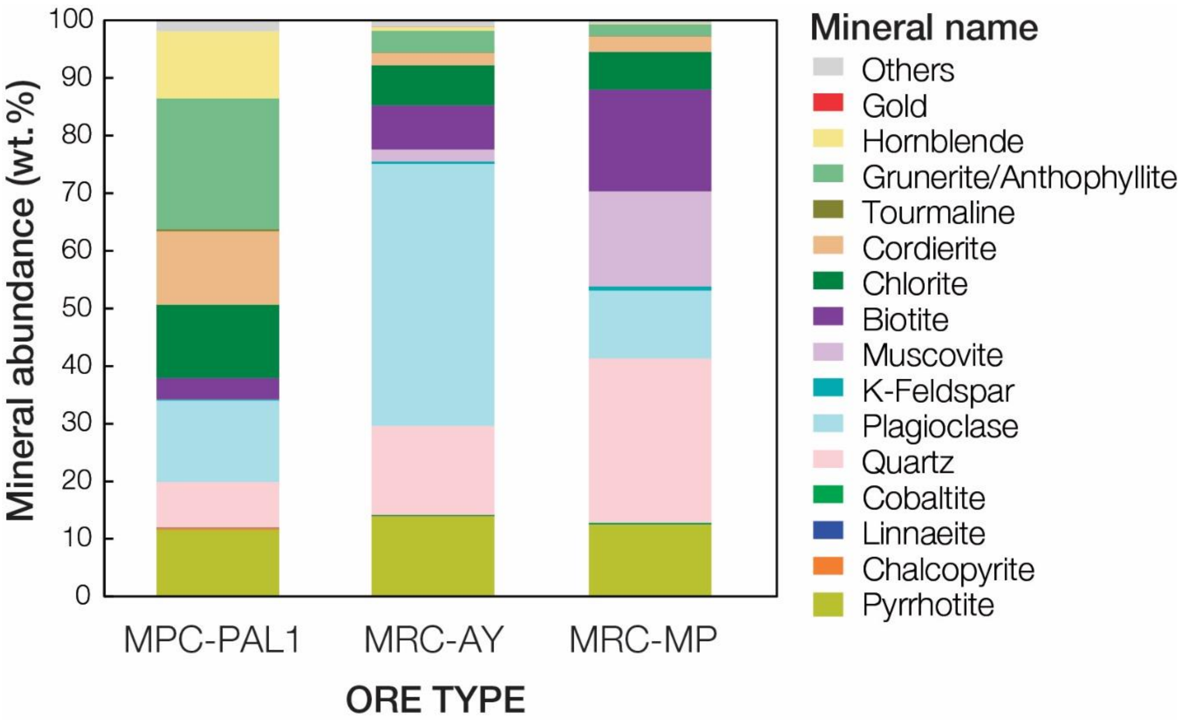
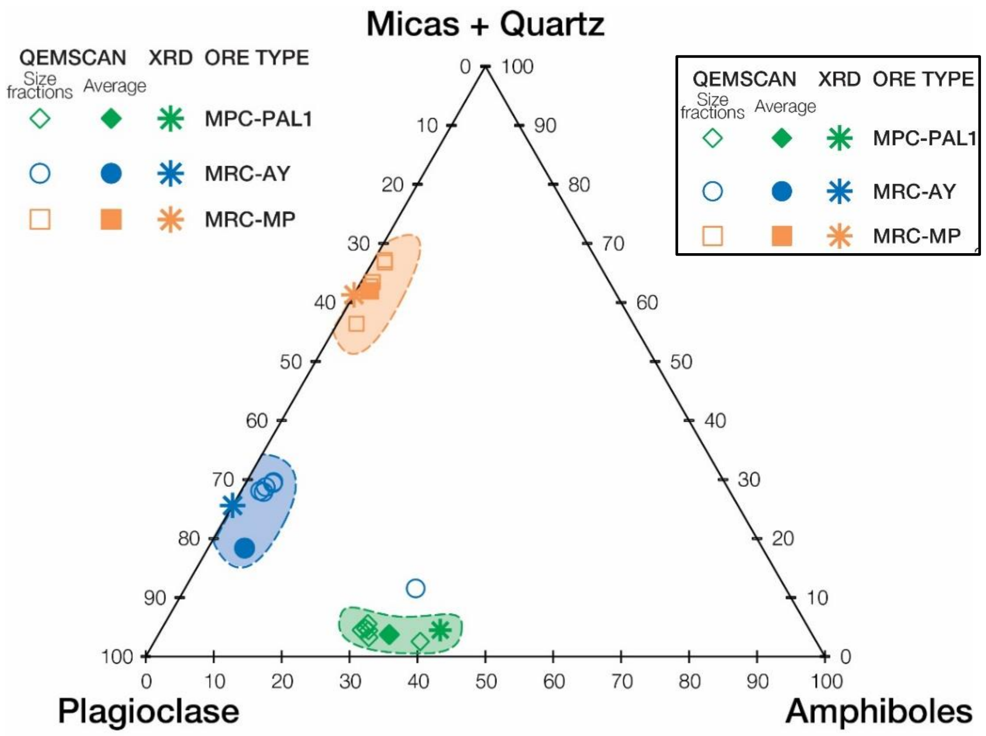
BULK ORE MINERALOGY

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

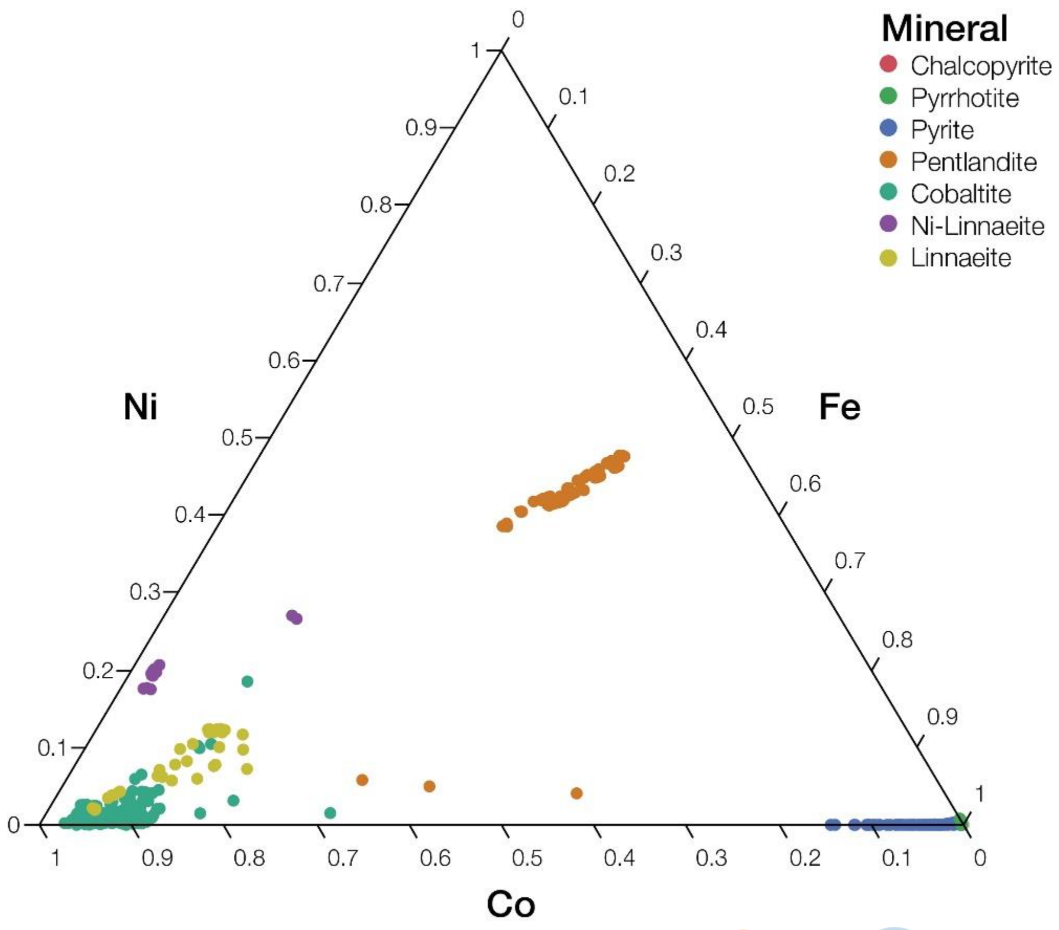
RAJAPALOT AU-CO PROJECT

COBALT MINERALS – COBALT CONTENT

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

- **Cobaltite** (Cob) - CoAsS
- **Linnaeite** (Lin) - $Co^{2+}Co^{3+}{}_2S_4$
- **Ni-rich Linnaeite** (Ni-Lin) - $(Co,Ni)_3S_4$
- **Cobaltian Pyrite** (Py) - $(Fe,Co)S_2$
- **Cobaltian Pentlandite** (Pt) - $(Co,Fe,Ni)_9S_8$
- + traces in pyrrhotite (Po) and chalcopyrite (Cpy)

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



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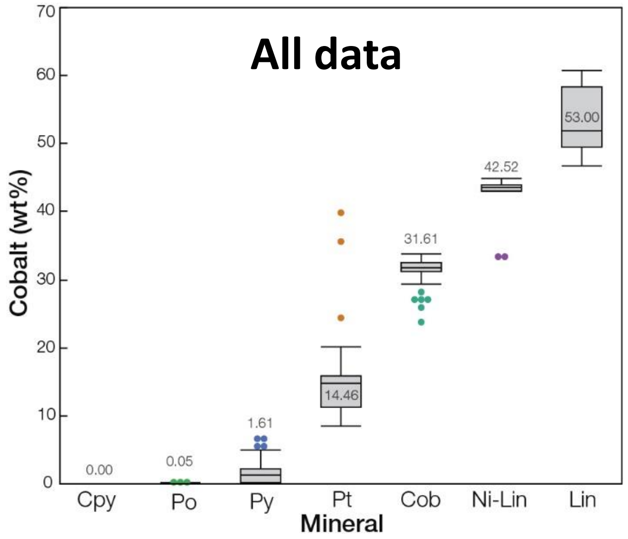
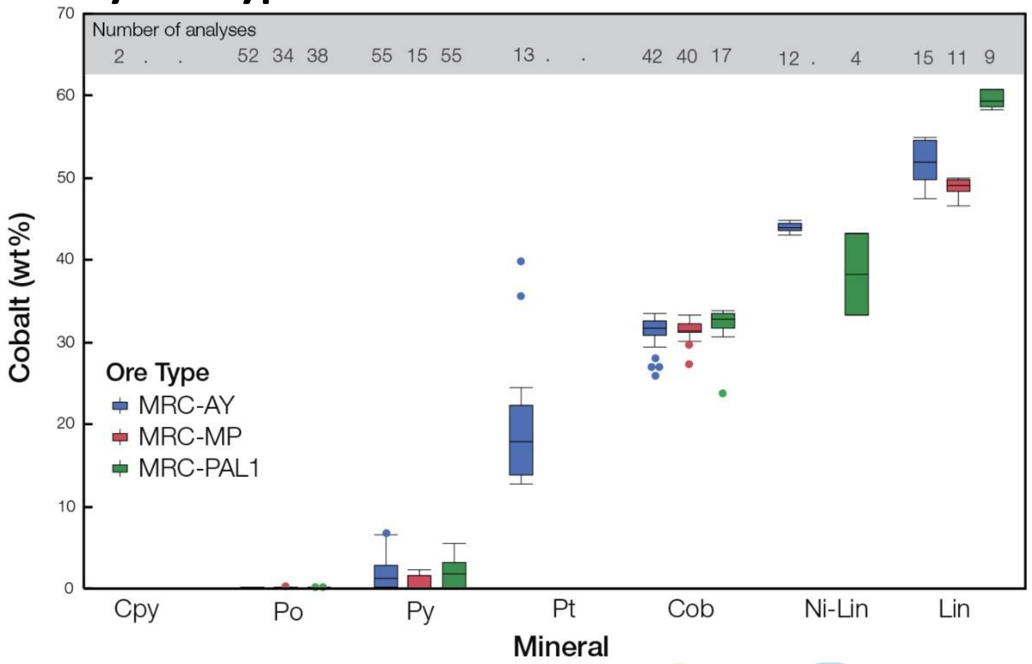
➢ **Cobalt content in cobaltite is relatively constant** regardless of the ore type,

➢ **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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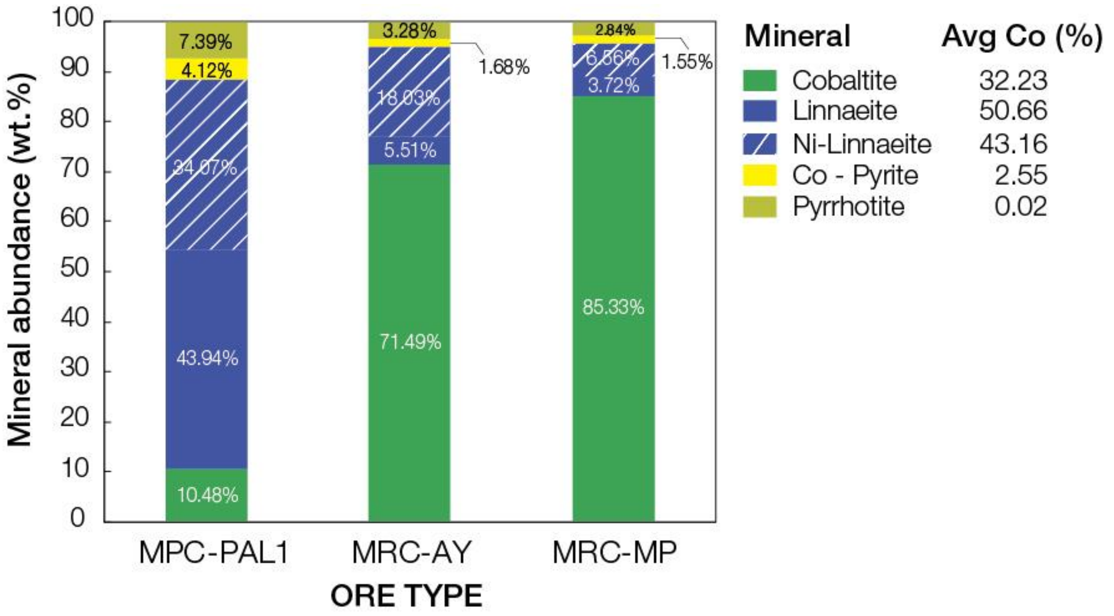
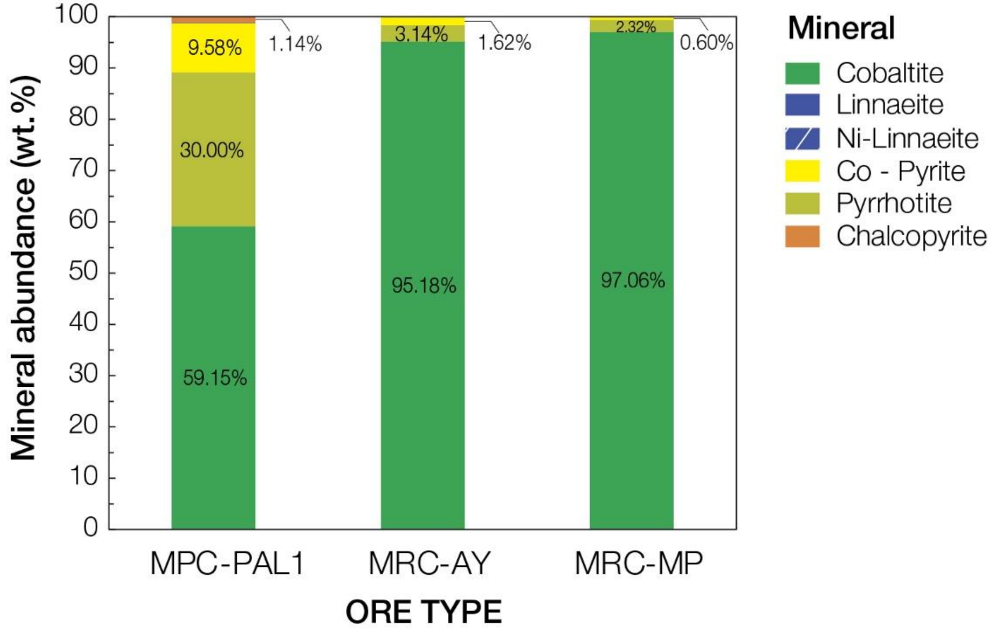
COBALT & ARSENIC DEPORTMENT

Cobalt deportment



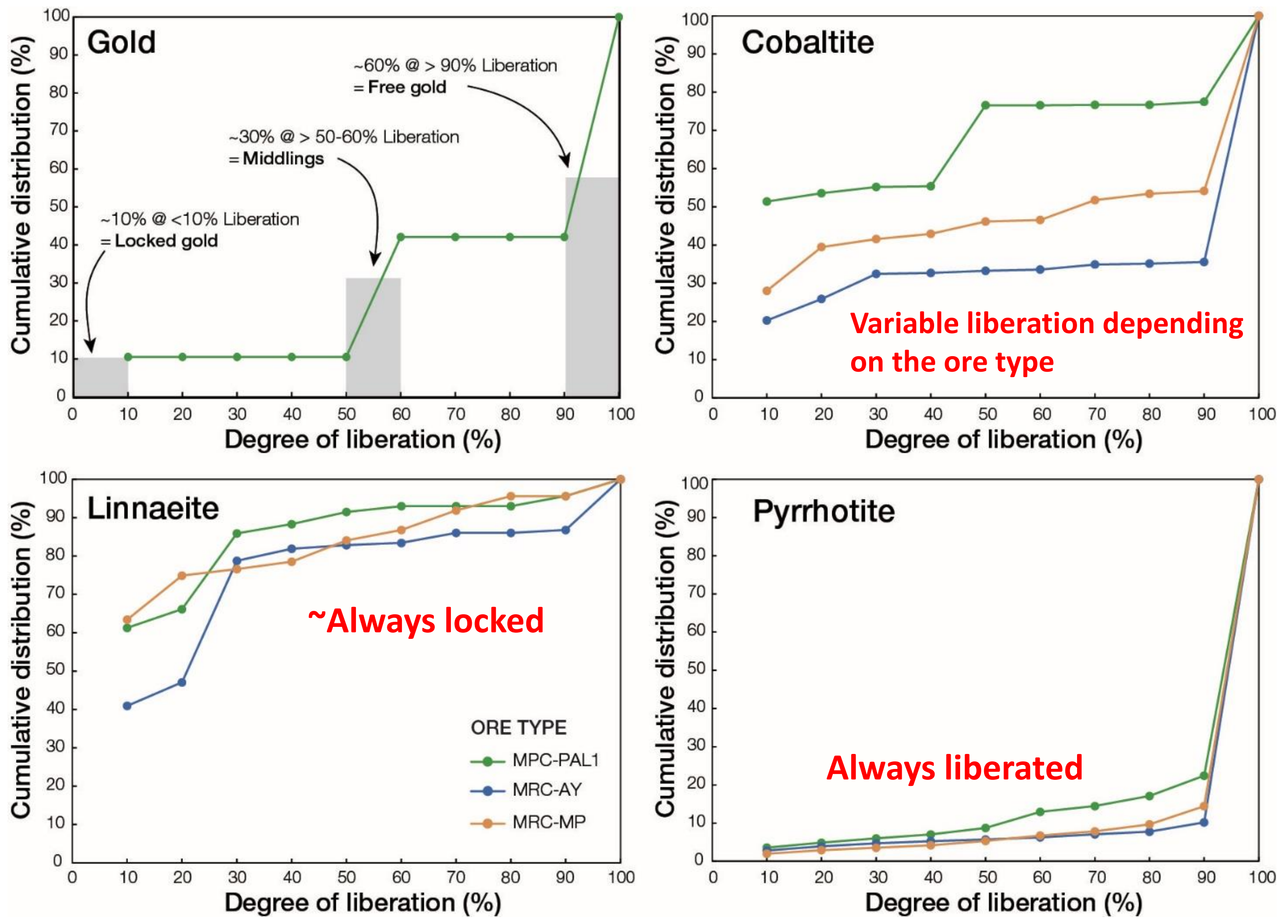
Arsenic deportment



- 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.

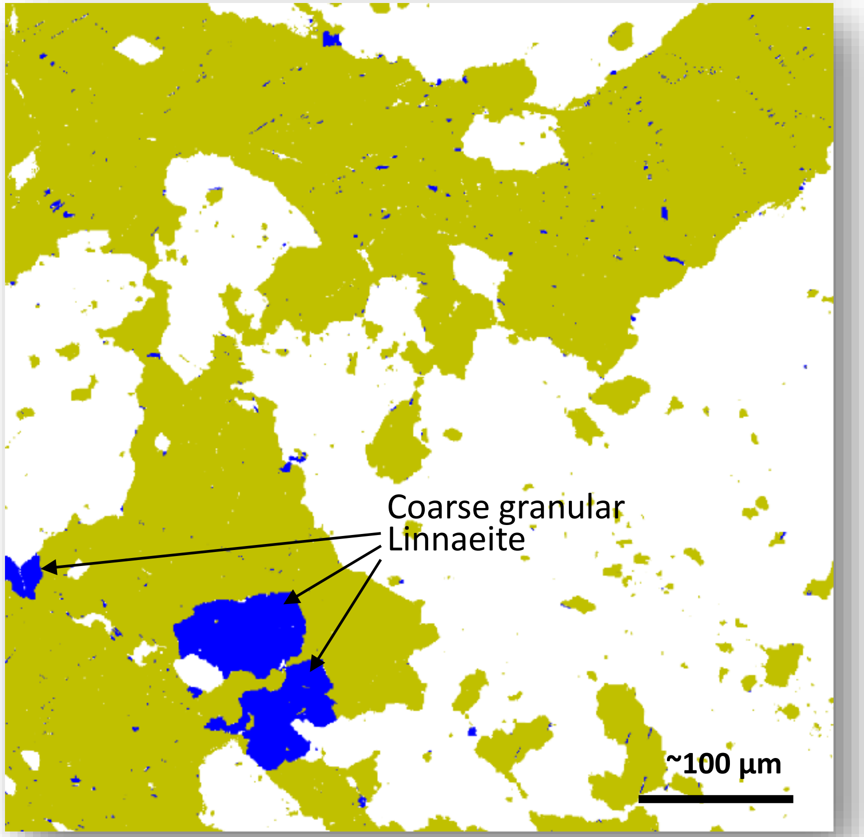
RAJAPALOT AU-CO PROJECT

KEY MINERALS LIBERATION BY ORE TYPE



QEMSCAN Mineral map (Palokas)

Pyrrhotite & linnaeite only



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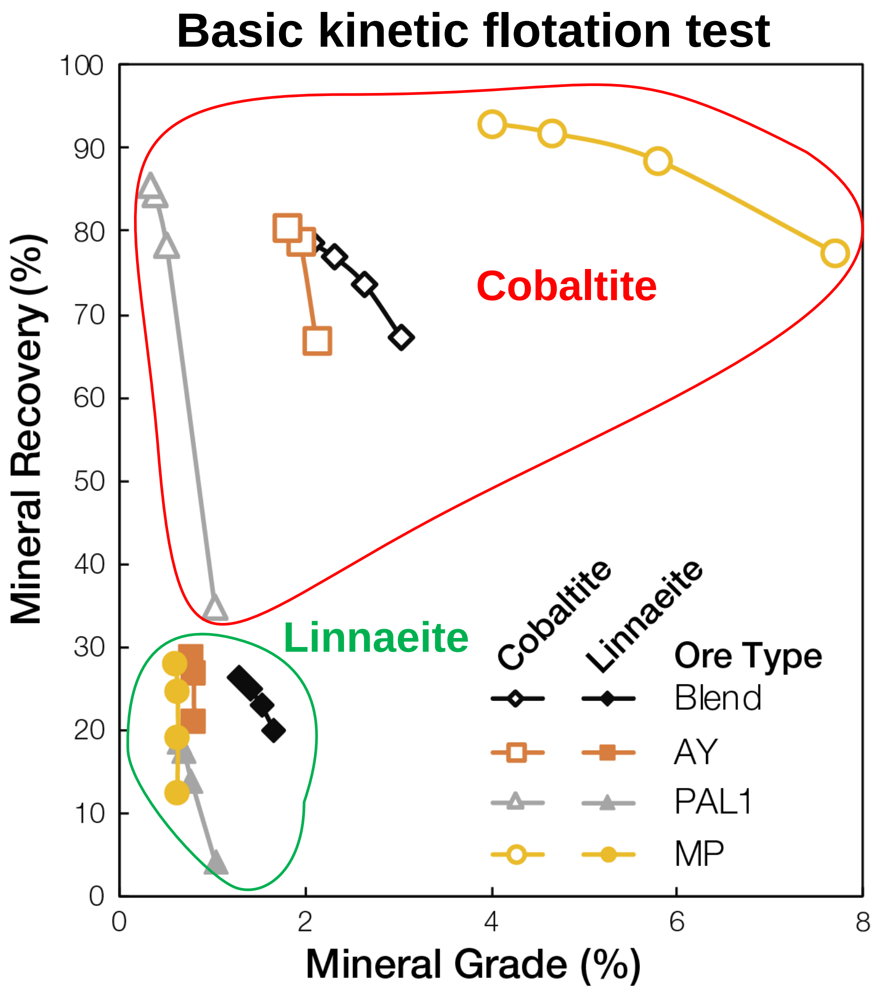
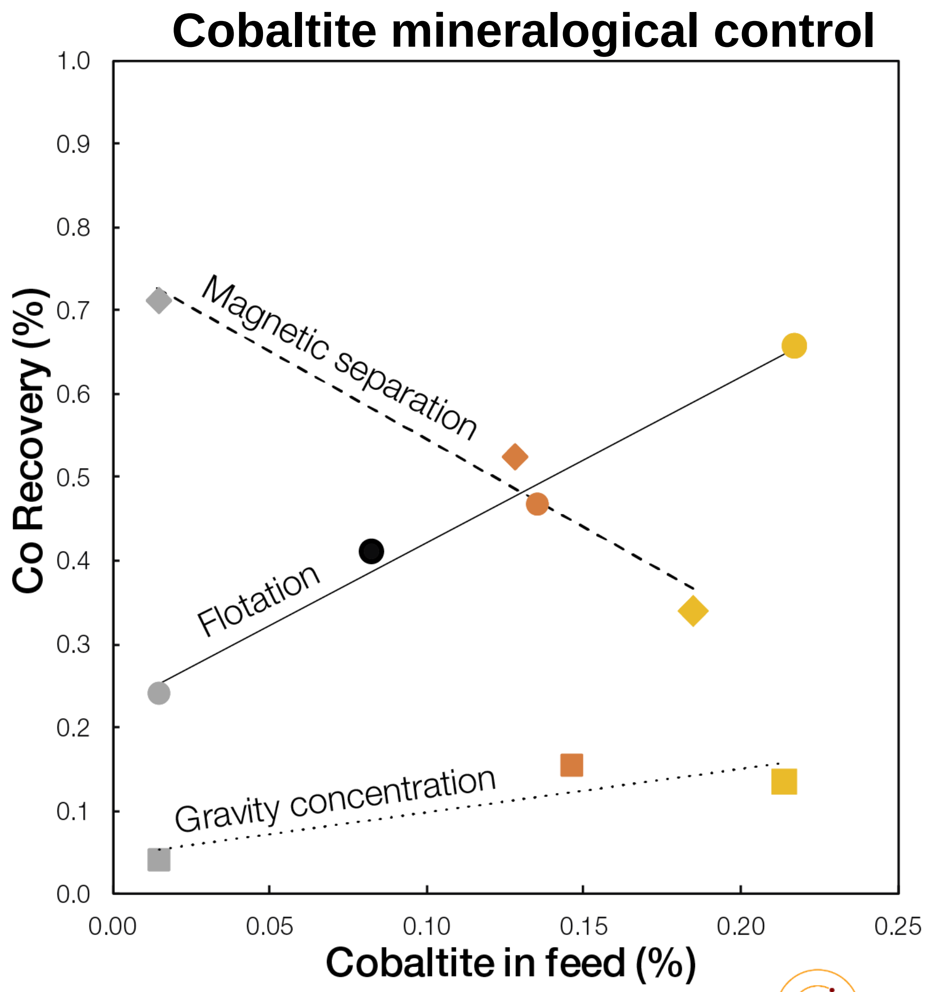
MINERALOGICAL CONTROL ON COBALT RECOVERY





RAJAPALOT AU-CO PROJECT

CONCLUSIONS

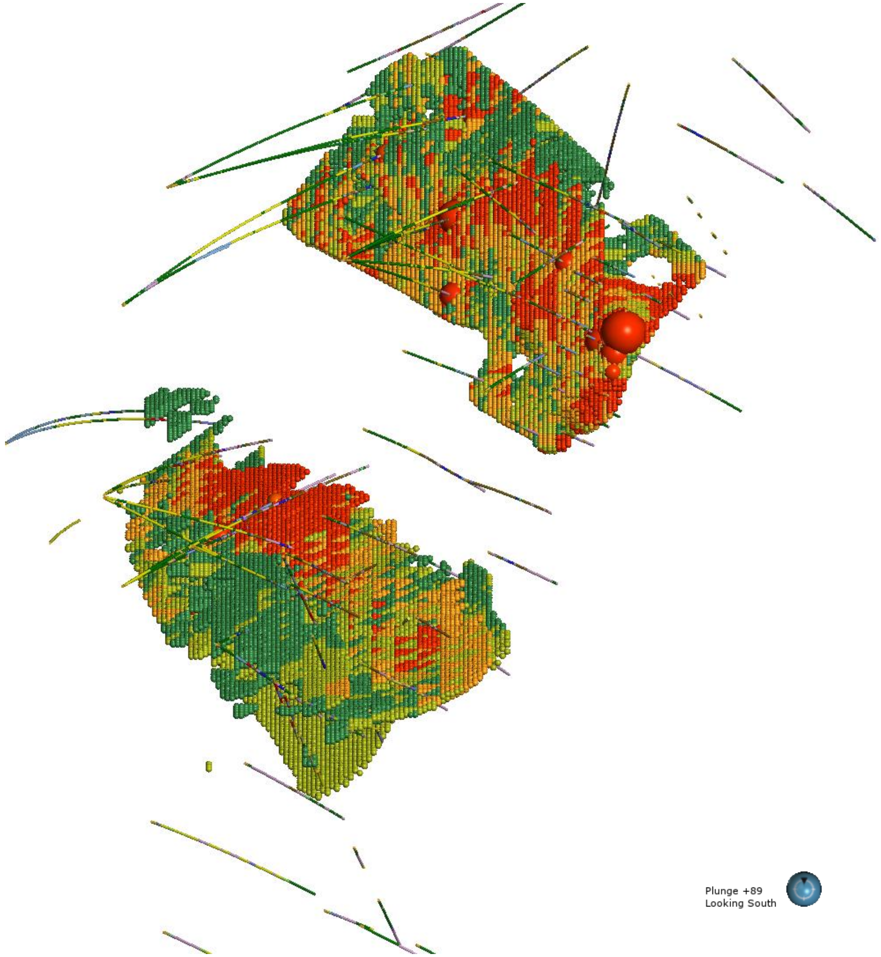
The 3 ore types show a distinct:

- 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),

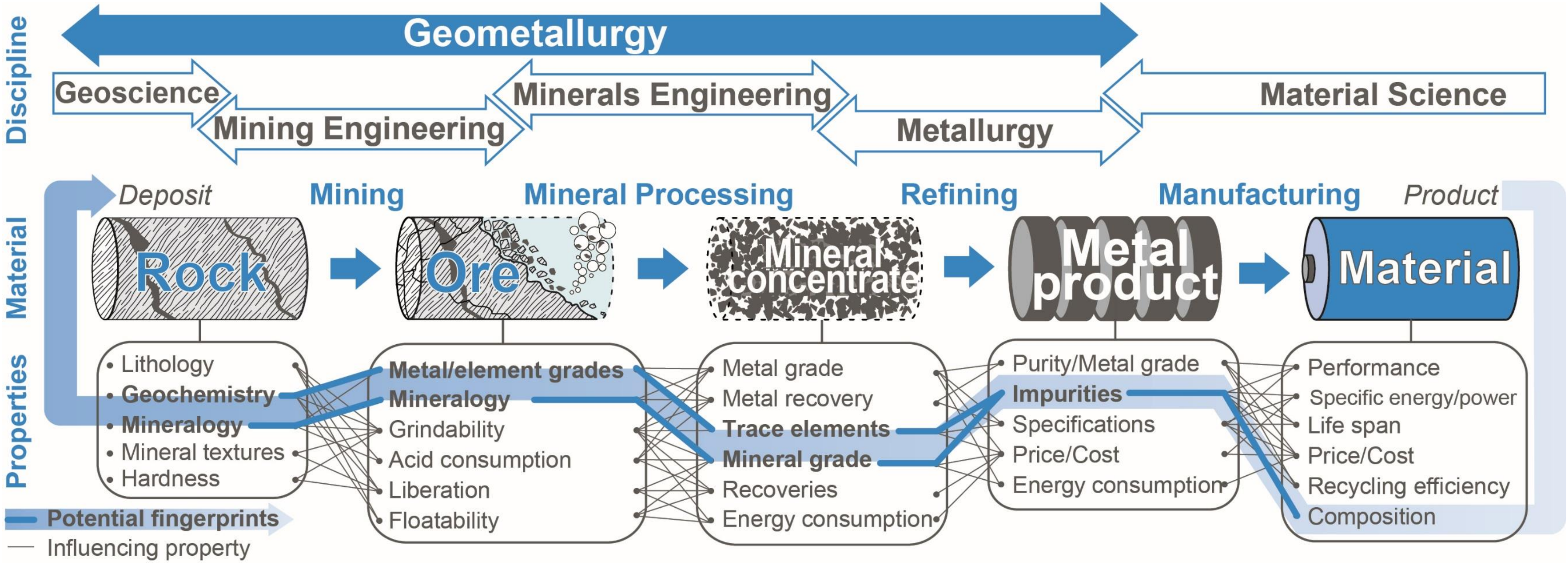
Mineralogical control:

- 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



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FURTHER READING…

PROJECTS

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www.batcircle.fi/

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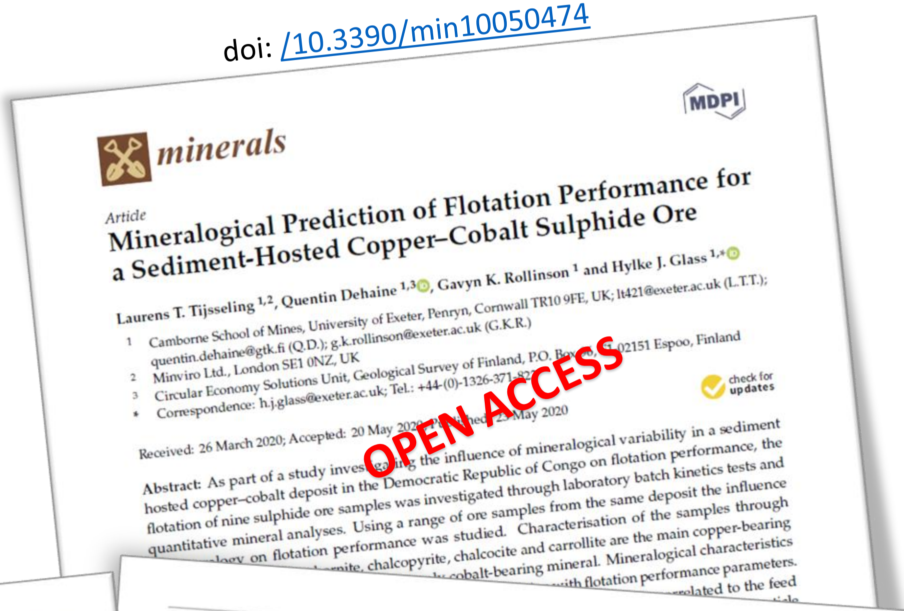
PUBLICATIONS



doi: [/10.3390/min10050474](https://doi.org/10.3390/min10050474)

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

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KIITOS!

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