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

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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), industry (metallurgy, refining) and technical 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 profitable 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.

Les matières premières de batteries (cobalt, lithium, graphite, nickel) sont essentielles pour une société technologiquement avancée à faible empreinte carbone. La plupart de ces matières premières sont produites dans une poignée de pays, ce qui entraîne des risques d'approvisionnement ainsi que des problèmes environnementaux et éthiques (minage artisanal, travail des enfants). La Finlande, avec ses ressources minérales (gisements et mines), son industrie (métallurgie, raffinage) et son expertise technique (savoir-faire, automatisation), dispose de l'écosystème idéal pour relever le défi de l'amélioration de la chaîne d'approvisionnement des matières premières nécessaires à la fabrication des batteries rechargeables et devenir une source durable de ces matières premières pour l'Europe. L'extraction rentable de ces dernières, dans un marché concurrentiel, dépend de certaines propriétés des minerais qui influencent la performance des procédés de valorisation et sont directement liées à la géologie et la minéralogie du gisement. Par conséquent, l'approche géométallurgique, qui combine les informations géologiques et métallurgiques pour améliorer la gestion des ressources, optimiser leur extraction et réduire les risques techniques, est l'approche multidisciplinaire clé pour relever le défi d'une production domestique européenne durable et responsable des matières premières de batteries.

Las materias primas usadas en baterías (cobalto, litio, grafito, níquel) son críticas para una sociedad tecnológicamente avanzada con tendencia a reducir las emisiones de carbono. La mayoría de estas materias primas se producen en un puñado de países, lo que conlleva riesgos de suministro y problemas ambientales y éticos (minería artesanal, trabajo infantil). Finlandia, con sus recursos minerales (depósitos y minas), su industria (metalurgia, refinación) y su experiencia técnica (know-how, automatización), tiene el ecosistema ideal para enfrentarse al desafío de mejorar la cadena de suministro de materias primas de baterías y garantizar una fuente sostenible de estas materias primas para Europa. La extracción rentable de estas materias, en un mercado competitivo, es una función compleja de ciertas propiedades minerales clave que determinan el rendimiento del proceso de extracción y están directamente asociados a la geología del depósito y la mineralogía del mineral. Por lo tanto, el enfoque geometalúrgico, que combina información geológica y metalúrgica para mejorar la gestión de recursos, optimizar su extracción y reducir los riesgos técnicos, es el enfoque multidisciplinario clave para enfrentar el desafío de una producción nacional europea sostenible y responsable en materias primas para la fabricación de baterías.

Introduction

With the "electric revolution" almost upon us, rechargeable batteries are likely to be the next key enabling technology for the transition towards a fossil fuel-free future for humankind. Batteries are essential for our high-tech devices (such as smartphones, tablets and laptops), our mobility through electric vehicles (EVs), and for our general energy supply (energy storage systems). The battery production industry will be challenged by predicted increased demand in the foreseeable future. While the vast majority of the batteries for EVs are currently manufactured in Asia, European car companies have expressed their interest in producing domestically with local battery manufacturing capabilities. Whilst more efficient recycling of materials will be achieved in the foreseeable future, as proposed by the concept of the circular economy, battery raw materials (*e.g.*, cobalt, lithium, graphite, and nickel), which represent about 50% of the costs of the battery cells, still need to be extracted from natural resources to meet

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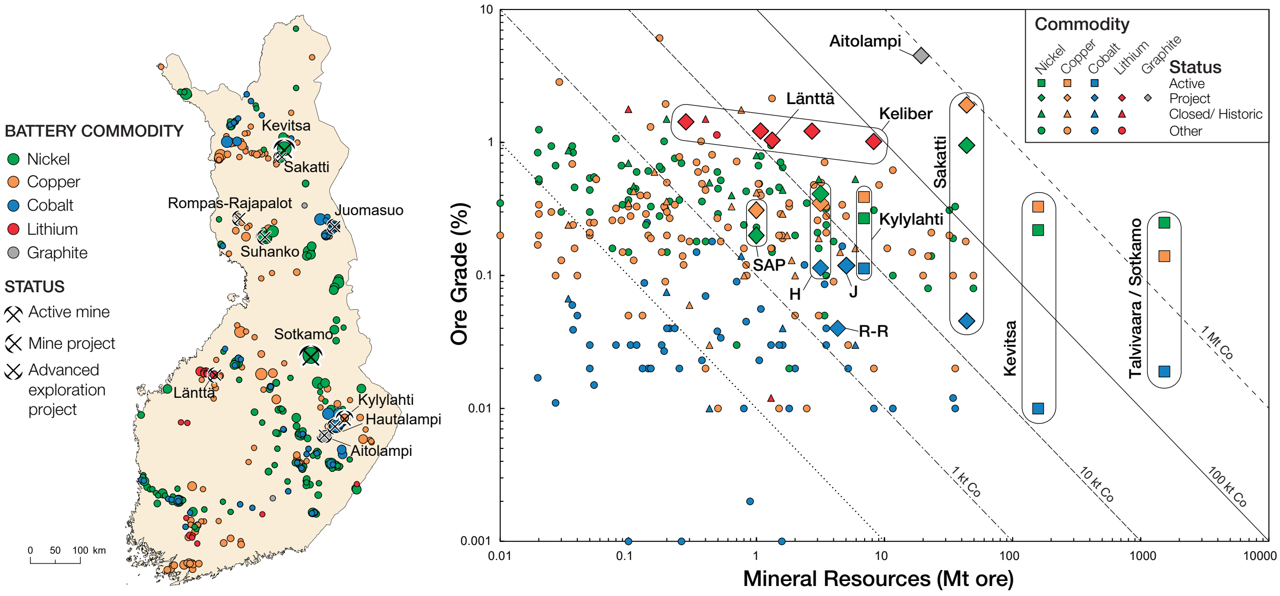

Figure 1: Finnish battery mineral deposits. Left: Map of the battery mineral deposits of Finland. Right: Resource grade-tonnage relationship by mining status with main operating mines and projects highlighted. H: Hautalampi, J: Juomasuo, R-R: Rompas-Rajapalot and SAP: Suhanko Arctic Platinum.

our growing societal needs. Raw material production has therefore an important role in enhancing the competitiveness of the European battery production. Currently the production of battery raw materials is concentrated in a few countries outside the EU, especially for cobalt and graphite, with about 70% of the global cobalt supply coming from the Democratic Republic of Congo (DRC) and 64% of the global graphite supply from China (USGS, 2020). Hence, the effective and efficient recovery of these minerals to supply the required battery ecosystem is fast becoming a strategic priority for Europe. Finland is one of the most important EU countries supplying battery raw materials to the EU market, meeting 66% of the EU demand for cobalt ores and concentrates and 16% of the demand for nickel (European Commission, 2018).

Battery minerals in Finland are found in a variety of mineral deposit types, often polymetallic, especially for nickel (Ni), copper (Cu) and cobalt (Co). To determine whether battery raw materials can be profitably recovered (as a main or by-product) from these deposits, one must assess three key factors: (i) the amount of material that can be mined and recovered as a marketable product; (ii) their typical recovery efficiency (which depends on the technologies used for recovery) and (iii) the relative costs and benefits of battery raw material (by-product) recovery (Mudd *et al.*, 2013). All of these factors are a complex function of key ore properties; they are directly linked to the deposit type and ore mineralogy and drive extraction process performance. These complex considerations can be linked through the development of integrated approaches supported by the discipline called *geometallurgy*. Geometallurgy could be considered as the next generation of mineral processing, where more effective recovery is achieved and a better understanding is reached of what waste products are produced. This allows more sophisticated stewardship of ore deposits and better management of waste, where future re-mining of tailings dams and waste dumps will be an activity in the circular economy.

The Finnish-based circular ecosystem of battery metals consortium (BATCircle), led by Aalto University, aims at improving the manufacturing processes of the mining industry, metals industry and battery chemicals, and increasing the recycling of lithium-ion batteries. The goal is to strengthen the cooperation between companies and research organisations in Finland and to find new business opportunities. Within this framework, the Geological Survey of Finland (GTK) is developing integrated solutions for Finnish battery mineral resources through the application of a geometallurgical approach to key battery minerals exploration projects in Finland.

The aim of this article is to present the Finnish battery ecosystem in terms of mineral resources and raw material production and introduce current developments to improve the battery raw material supply chain at the Finnish and EU level, through the example of the BATCircle and BATTRACE projects.

The battery ecosystem of Finland in brief

The Finnish battery ecosystem covers almost all the battery value chain with available battery mineral resources (nickel, copper, cobalt, lithium, and graphite) (Eilu, 2012); there is an active mining industry with operating mines extracting battery minerals, an active metallurgical industry (processing plants, smelters, refineries), as well as a growing manufacturing industry and internationally-renowned mining technology companies.

Battery minerals in Finland are found in a wide variety of polymetallic mineral deposit types (Eilu, 2012) such as: shale-hosted Ni-Zn-Cu-Co deposits (*e.g.*, Sotkamo); magmatic Ni-Cu-Co-PGE sulphides (*e.g.*, Kevitsa, Sakatti, Suhanko); Cu-Ni-Zn-Co(-Ag-Au) Volcanogenic Massive Sulphides (*e.g.*, Outokumpu area, Hautalampi); Li-pegmatites (*e.g.*, Syväjärvi, Läntta); Supracrustal-rock-hosted polymetallic Au-Co(-Cu) deposits (*e.g.*, Kuusamo belt, Juomasuo, Rompas-Rajapalot); and metamorphic graphite deposits (***Figure 1***, left). Most of these battery mineral deposits are small to medium-sized. However, large deposits (*e.g.*, Kevitsa, Sakatti, Aitalompi), and world-class deposits, such as the Ni-Zn-Cu-Co Sotkamo deposits (previously known as Talvivaara), also occur in Finland (***Figure 1*** and ***Table 1***). Nickel, copper and cobalt often occur together in polymetallic deposits, with Ni and Cu concentrations

Table 1: List of active battery raw material mines and projects in Finland with estimated total mineral resources (measured + indicated + inferred) and reserves (proved + probable), when available, obtained from company annual reports or website.

Operation Name	**Deposit type**	**Main Commodities**	**Tonnage (Mt)**	**Grade (%)**					**Contained Metal (kt)**					**Current Owner**	**Stage**
				Co	**Ni**	**Cu**	**Li_2O**	**TGC[a]**	**Co**	**Ni**	**Cu**	**Li_2O**	**TGC[a]**		
Sotkamo	*Shale-hosted*	*Ni, Zn, Cu, Co*	*1525.0*	*0.02*	*0.25*	*0.14*	*-*	*-*	*290*	*3813*	*2135*	*-*	*-*	*Terrafame*	*Active*
Sakatti[b]	*Magmatic*	*Cu, Ni, Co, PGE*	*44.4*	*0.05*	*0.96*	*1.90*	*-*	*-*	*20*	*426*	*845*	*-*	*-*	*Anglo American*	*Project*
Kevitsa	*Magmatic*	*Ni, Cu, Co, PGE*	*297.5*	*0.01*	*0.23*	*0.33*	*-*	*-*	*31*	*695*	*977*	*-*	*-*	*Boliden*	*Active*
Suhanko[b]	*Magmatic*	*PGE, Au, Ni, Cu, Co*	*208.5*	*n/a*	*0.10*	*0.22*	*-*	*-*	*n/a*	*202*	*468*	*-*	*-*	*Suhanko Arctic Platinum*	*Project*
Kaustinen area	*Pegmatite*	*Li*	*23.6*	*-*	*-*	*-*	*1.04*	*-*	*-*	*-*	*-*	*246*	*-*	*Keliber Oy*	*Project*
-Syväjärvi	*Pegmatite*	*Li*	*4.8*	*-*	*-*	*-*	*1.17*	*-*	*-*	*-*	*-*	*56*	*-*	*Keliber Oy*	*Project*
-Rapasaari	*Pegmatite*	*Li*	*14.0*	*-*	*-*	*-*	*0.99*	*-*	*-*	*-*	*-*	*138*	*-*	*Keliber Oy*	*Project*
-Länttä	*Pegmatite*	*Li*	*2.4*	*-*	*-*	*-*	*0.97*	*-*	*-*	*-*	*-*	*24*	*-*	*Keliber Oy*	*Project*
-Outovesi	*Pegmatite*	*Li*	*0.5*	*-*	*-*	*-*	*1.27*	*-*	*-*	*-*	*-*	*6*	*-*	*Keliber Oy*	*Project*
-Emmes	*Pegmatite*	*Li*	*1.9*	*-*	*-*	*-*	*1.13*	*-*	*-*	*-*	*-*	*22*	*-*	*Keliber Oy*	*Project*
Kylylahti[c]	*VMS*	*Cu, Au, Zn, Ni, Co*	*0.5*	*0.16*	*0.25*	*0.33*	*-*	*-*	*1*	*1*	*2*	*-*	*-*	*Boliden*	*Closing*
Hautalampi	*VMS*	*Ni, Cu, Co, Au*	*5.4*	*0.10*	*0.44*	*0.38*	*-*	*-*	*5*	*24*	*20*	*-*	*-*	*Vulcan Hautalampi Oy*	*Project*
Rompas-Rajapalot[b]	*Orogenic (Hydrothermal, Metamorphic)*	*Au, Co*	*4.3*	*0.04*	*-*	*-*	*-*	*-*	*2*	*-*	*-*	*-*	*-*	*Mawson Resources*	*Project*
Juomasuo[b]	*Orogenic (Hydrothermal, Metamorphic)*	*Au, Co*	*5.0*	*0.12*	*-*	*-*	*-*	*-*	*6*	*-*	*-*	*-*	*-*	*Latitude 66 Oy*	*Project*
Aitolampi[d]	*Metamorphic*	*Graphite*	*19.3*	*-*	*-*	*-*	*-*	*4.50*	*-*	*-*	*-*	*-*	*878*	*Beowulf Mining plc*	*Project*

[a] Total Graphite Carbon ("TGC")
[b] Total mineral resources only
[c] Mineral reserves only as Boliden planned the mine closure for autumn 2020. Previous estimate (2018): 8.2 Mt @ 0.16 %Co, 0.27 %Ni and 0.8 4%Cu
[d] Indicated+ Inferred mineral resources only

being an order of magnitude higher than that of Co, thus explaining its by-product status in currently active mining operations. Despite the wide heterogeneity between the distinct Ni-Cu-Co-hosting deposit types, there is a relatively small number of minerals that currently are or historically have been mined for these metals, like pentlandite ($(Fe,Ni,Co)_9S_8$), chalcopyrite ($CuFeS_2$), cobaltite (CoAsS) but also pyrite (FeS_2) which may contain significant proportions of cobalt and nickel.

Today in Finland there are ten active mines and exploration projects, at various stages of development, three of which (*i.e.*, Sotkamo, Kevitsa and Kylylahti) produce nickel, copper and cobalt concentrates, which are mostly refined locally to supply the EU market. The Boliden Kevitsa and Kylylahti mineral processing plants rely mainly on froth flotation to produce nickel and copper concentrates, following a typical process for magmatic Ni-Cu sulphide ores (Boliden, 2018), while the Sotkamo process is based on one-of-a-kind bio-heap leaching process. The latter is a unique and energy-efficient way to extract metals with about 40% less greenhouse gas emissions and 20% less energy consumption than the average for nickel production (Terrafame, 2018).

With four operating smelters and refineries (***Table 2***), Finland is the biggest nickel producer and the only country with its own cobalt production in the EU (European Commission, 2018). A range of battery materials is currently produced by these plants, notably nickel matte, cathodes, briquettes and salts, copper cathodes and cobalt chemicals. A Ni-Co sulphate plant is under construction by BASF in collaboration with Nornickel, while a lithium hydroxide plant is at the feasibility stage with Keliber Oy which will process concentrates from the company's own mines.

Although there have been efforts to attract large battery cell manufacturers to Finland, there is currently no large-scale battery cell fabrication plant in Finland

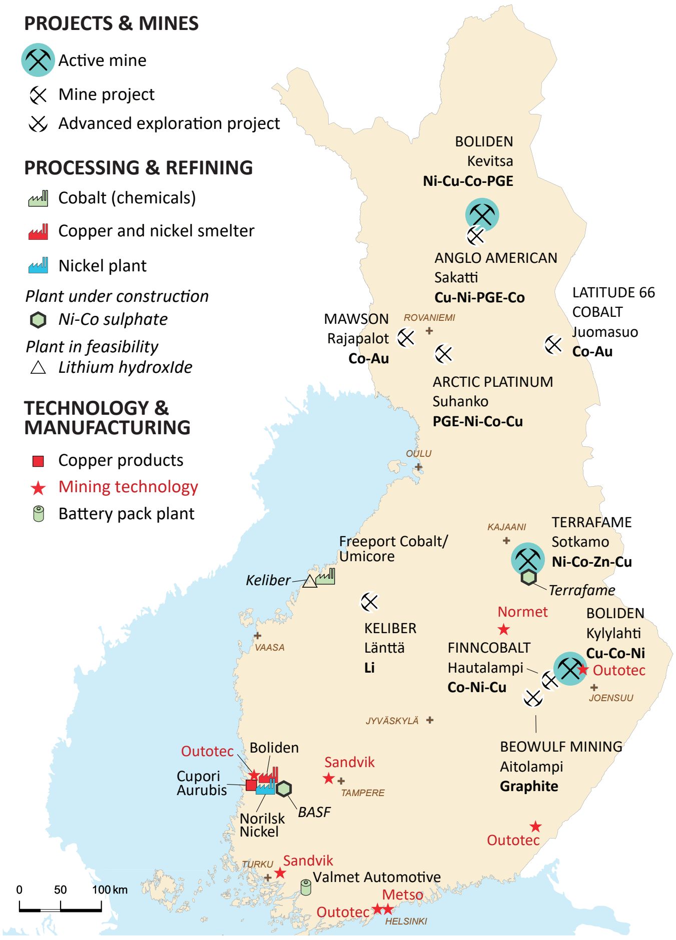

Figure 2: Overview of the Finnish battery ecosystem: battery mineral deposits, projects and mines, processing plants, smelters and refineries, as well as mining technology centres.

Table 2: List of active and future battery mineral refineries in Finland.

Industrial operation	***Main Commodity***	***Product(s)***	***Current Owner***	***Stage***
Kokkola	*Co*	*Cobalt chemicals and catalysts*	*Freeport/ Umicore*	*Operating*
Sotkamo	*Ni, Co*	*NiCoS mixed sulphide, Cu sulphide* *+ Ni-Co sulphate*	*Terrafame*	*Operating* *+ in extension*
Nornickel Harjavalta	*Ni, Cu, PGMs*	*Ni cathodes, briquettes & salts, Co chemicals*	*Norilsk Nickel*	*Operating*
Boliden Harjavalta	*Cu, Ni, Ag, Au*	*Cu cathode, Ni matte*	*Boliden*	*Operating*
BASF Harjavalta	*Ni, Co*	*Ni-Co sulphate*	*BASF*	*Under construction*
Keliber project	*Li*	*Li hydroxide*	*Keliber Oy*	*In feasibility*

(the European Battery factory in Varkaus closed in 2013). However, a new Li-ion battery assembly plant was launched in 2019 in Salo by Valmet Automotive to produce battery pack systems for EVs and moving machinery applications.

Figure 2 shows an overview of the Finnish battery ecosystem with mineral resources, chemical manufacturing plants and mining technology company offices and research centres. In addition to the aforementioned key assets, the strong R&D knowledge and know-how in the mining, chemical, and recycling industry, with notable mining and processing machinery manufacturers (Outotec, Metso) and access to cheap sustainable energy make Finland a potential platform for rechargeable battery manufacturing (Finnish Mineral Group - FMG, 2018) and one of the top locations in the world for mining investments (Stedman *et al.*, 2019). According to the FMG, Finland has the potential to meet the material needs of one large electric vehicle battery (EVB) factory, producing precursor and active cathode materials for the batteries of over 500,000 EVs annually.

Geometallurgy to improve the battery raw material value chain

Geometallurgy: What and why?

Geometallurgy is a multi-disciplinary approach that links geological, mining and metallurgical information to improve resource management, optimise process performance, and reduce technical risks (Lund and Lamberg, 2014). Geometallurgy systematically integrates planning practices to maximise resource efficiency of future or existing mining operations to create a spatial model for production planning and management (Dehaine *et al.*, 2019; Michaux and O'Connor, 2020). It also incorporates the principles of process mineralogy and material characterisation as tools for predictive metallurgy (Bowell *et al.*, 2011). Geometallurgy is an evolutionary step forward in mineral processing, where the process behaviour of minerals can guide engineering design. The competitive edge that geometallurgy provides is related to the dynamic relationship between different ore types and the target process response. The outcome is an understanding as to what minerals control which process response, and why poor recovery might happen. This allows more proactive planning in design and operation.

There are three main methods used for battery minerals extraction - physical separation (gravity, magnetic); flotation and hydrometallurgy. The processes involved and the flowsheets employed are typically unique to each deposit and ore type. Mineralogy is the main, if not the most important, geometallurgical ore property, as it drives the ore processing requirements (e.g. leaching vs flotation, leaching agent, flotation collector, etc.). However, mineralogy is not the only characteristic of interest. Indeed, there are other geometallurgical ore properties that influence process performance, such as: physical properties of the ore (hardness, grindability, and particle size), which control comminution behaviour and ore reactivity; gangue mineralogy, which

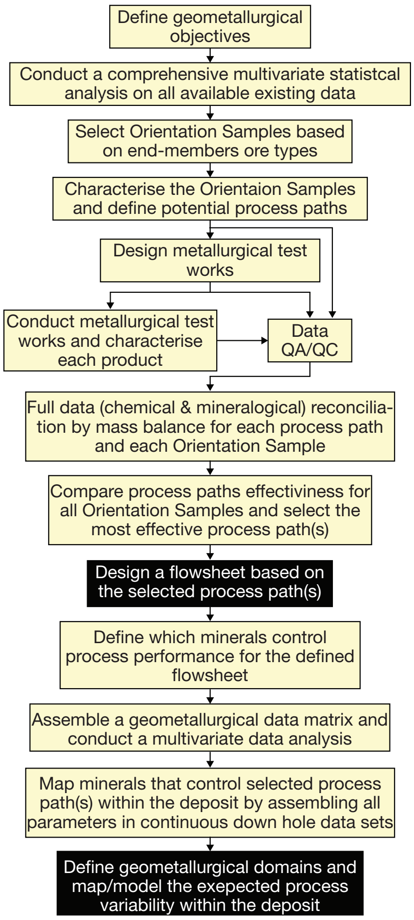

Figure 3: Simplified BATCircle geometallurgical program workflow.

influences acid consumption and flotation performance; mineral associations and liberation of metal-bearing minerals, which control their susceptibility to leaching and flotation; and the amount of impurities, which may reduce final product quality. These geometallurgical properties can be the determining factor for the selection of the processing route (flotation vs leaching) since they directly affect operating costs and recoveries of hydrometallurgical projects.

BATCircle: A geometallurgical program for battery mineral deposits

As mentioned before, the BATCircle project has been designed to be based around the concept of a Circular Ecosystem of Battery Metals. One main task of the project is the development of a geometallurgical program for battery mineral resources of Finland for which two case studies have been selected, the Rompas-Rajapalot Au-Co and Suhanko PGE-Au-Ni-Cu-Co projects. A concept or protocol was developed for each deposit type, set of geological and mineralogical characteristics, and acquired raw material specification requirements (***Figure 3***).

The basic experimental procedure for the geometallurgical programs is structured as follows:

1. **Define geometallurgical objectives** and assess all the available data from the deposit to date in terms of geology, mineralogy and process test characterisation. **Conduct a comprehensive multivariate statistical study** on all available data.
2. **Select a number of samples that show end-member ore types** (Orientation Samples). These samples should reflect the variety of mineralogy and textures encountered within the deposit at their extremes. This means that any other ore sample could be in theory regarded as a combination of these extreme ore types as far as their metallurgical response is concerned.
3. **Characterise each Orientation Sample** in terms of commercial chemistry (target metal grades, penalty elements) and mineralogy (mineral grades, grain sizes, liberation and associations). **Define potential process paths** based on characterisation results.
4. For each Orientation Sample, **conduct a series of metallurgical tests** (gravity separation, flotation, leaching) that could be made up into several parallel process paths. **Characterise the products of each test** with the same methods used to characterise the process test products in context of the relationship between the Orientation Study and the following Mapping Study.
5. For each Orientation Sample, and for each process path, a **full data reconciliation is done**. This includes **a mineralogical reconciliation** to determine what minerals separated into what product stream. This will establish the mineralogical controls over process behaviour for each separation process.
6. Then **compare all the process separation methods and all process paths for all Orientation Samples**. Assess which process path is the most effective in the context of multiple target metals. Trade-off comparisons between polymetallic recovery process paths can then be made in engineering and economic contexts, where mineralogy defines the outcome. **Select the best process paths** that yielded the best performance and that would recover the most economical combination of target elements. Of these process paths, select the one considered to be the final best result to design the process flowsheet.
7. For the Orientation Samples, **define what minerals controlled the most effective process paths**. These minerals will form the basis of the Mapping Study.
8. **Assemble all the available geological, mineralogical and metallurgical data in a geometallurgical data matrix** and **conduct a multivariate data analysis**, focusing on the target minerals from Step 7. Assess the statistical structures and relationships for each target mineral. Then assemble all parameters that control and influence the selected process paths into a continuous down-hole setting on individual drill cores into one single data matrix.
9. **Use cross-correlation of different data types to define domains of process behavior.** In doing so, **geometallurgical domains can be defined** and process response variability can be quantified.

For each case study, the above geometallurgical program will provide (i) an understanding of what mineralogy controls process separation behaviour of battery minerals, (ii) an estimate of the best engineering process path for each target valuable mineral/metal in each ore type, and then for all ore types together, (iii) an estimate of the best engineering process path for several valuable minerals/metals and (iv) a geometallurgical experimental procedure to study battery minerals.

Overall, the expected outcomes of the BATCircle project are:

- A comprehensive assessment of Finnish battery metal deposits, including polymetallic (e.g. Ni-Co-Cu), lithium and graphite deposits, not limited to tonnage and grades but including mineralogical and geometallurgical information with an emphasis on mineralogical properties that have a significant effect on the processing methods;

- A geometallurgical experimental and analytical procedure, a decision making methodology for battery mineral ores, and a geometallurgical library for the tested deposit types that can later be expanded;
- A strategic development plan for the development of Finnish battery mineral resources in a complete battery ecosystem. This can be used as a tool to support planning e.g., government initiatives supporting the ecosystem or business development planning.

Responsible sourcing

Ensuring sustainability all along the raw materials value chain has been a growing concern for the mining industry in recent years, especially in Europe. Achieving competiveness through sustainability is one of the key potential advantages of Europe. Raw materials traceability along the supply chain – from exploration, discovery, mining, to downstream uses – is a prerequisite to sustainability certification and compliance.

Currently, the vast majority of the world's cobalt supply is produced in the Democratic Republic of Congo (DRC) as a by-product of copper. According to the Government's own estimates, 20% of the cobalt currently exported from the DRC comes from artisanal mining in the southern part of the country, which often involves child labour (Amnesty International, 2016). Through independent traders this cobalt is then sold on to larger China-based companies via their local subsidiaries, which then supply some of the world's leading electronics companies, making cobalt likely to become a conflict mineral in the foreseeable future. Hence, fingerprinting battery raw materials, cobalt in particular, throughout the value chain would help improve their traceability and thus their responsible sourcing.

The BATTRACE project, currently in development, is exploring options for improving the traceability of battery raw materials at various stages of the value chain (from ore to product) using mineralogical and geochemical fingerprints (***Figure 4***). In terms of potential solutions that could help improve traceability of battery raw materials, a number of projects using digital technologies such as Blockchain or QR codes to control provenancing are being explored (RCS Global, 2017). However, these approaches are costly in terms of computing power and face technical challenges related to corruptible data input, with complex points of aggregation, mixing and processing, thus making the control of material flows challenging. Geochemical and mineralogical fingerprints, on the other hand, cannot be easily corrupted as they are often unique and inherent to the ore deposit type and location. For example, intrinsic mineralogical, geochemical and trace element contents in minerals can be used to discriminate between ore deposit types (Dupuis and Beaudoin, 2011). However, these fingerprints become less distinctive once mineral processing, metallurgy and other downstream steps of the supply chain proceed. In archaeometallurgy, for example, provenancing of raw materials used to manufacture tools can be established using trace elements patterns and lead isotopes ratios (Pernicka, 2014). Regardless of the processes involved in the treatment of ores (roasting, smelting, alloying or dissolution), the isotopic composition remains constant, making it an ideal fingerprint for metal sourcing. Such an approach has been successfully applied to conflict minerals in Africa (coltan, tin) but limited to ores and concentrates, i.e., upstream supply chain (Melcher *et al.*, 2008).

The battery minerals resources of Finland offer a source of sustainable and responsible battery raw materials that could reduce the dependence of the EU on importation for some battery raw materials. However, for those raw materials that cannot be produced in sufficient amounts, there is clearly an urgent need to embrace these ideas and move towards more transparent and traceable raw materials flows along the battery raw material value chain. In this context, the BATTRACE project is being developed to improve the traceability of battery raw materials and therefore enhance sustainability and responsibility issues connected to their production and gain a competitive advantage.

Conclusion

Finland, with its available mineral resources (battery mineral deposits and operating mines), metallurgical industry (processing plants, smelters, refineries), and its technical expertise (know-how, automation, low-price clean energy), has the ideal ecosystem to tackle the challenge of improving the battery raw materials supply chain and securing a sustainable, conflict-free, source for Europe.

From battery mineral hosting rocks to a final battery product (*e.g.*, cathodes) different types of materials (*e.g.*, ores, minerals, metals) flows are treated all along the value chain, and each of these materials is characterised by key different properties (***Figure 4***). Quantifying the relationships between these properties at the different stages of the

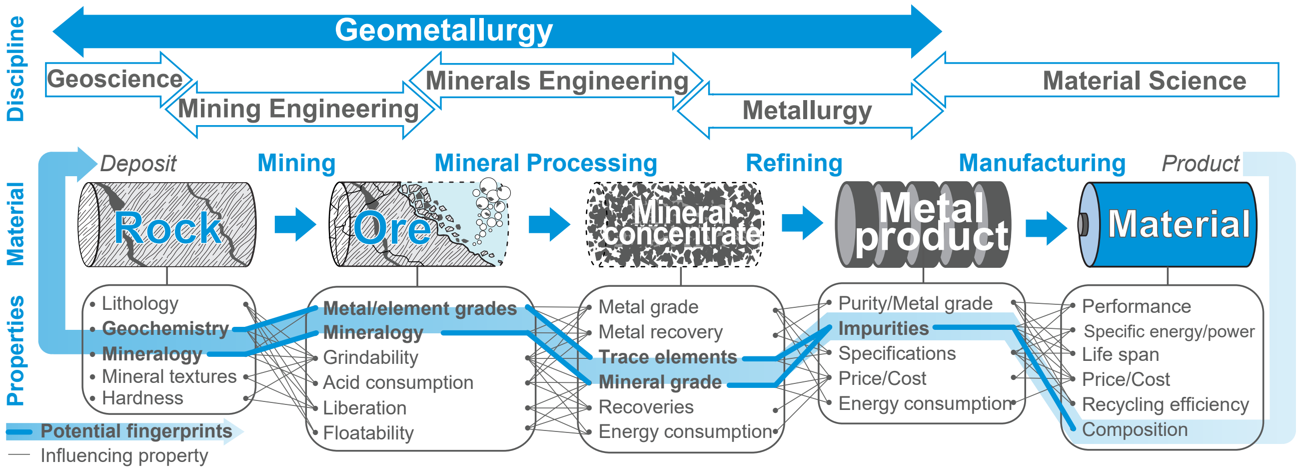

Figure 4: Geometallurgy: an integrated approach for optimisation and traceability along the battery materials value chain.

value chain through the application of an integrated geometallurgical approach will allow the optimisation of the whole mine value chain and the battery materials supply chain. Some of the properties (*e.g.*, trace elements, isotopes) may have the potential to be used as fingerprints to trace the origin of the battery materials at different stages of the value chain. Ongoing projects like BATCircle and BATTRACE seek to apply this integrated approach to optimise the battery supply chain using the Finnish ecosystem. This will support efficient as well as sustainable and responsible production through tracing battery materials all along the value chain.

Acknowledgments

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