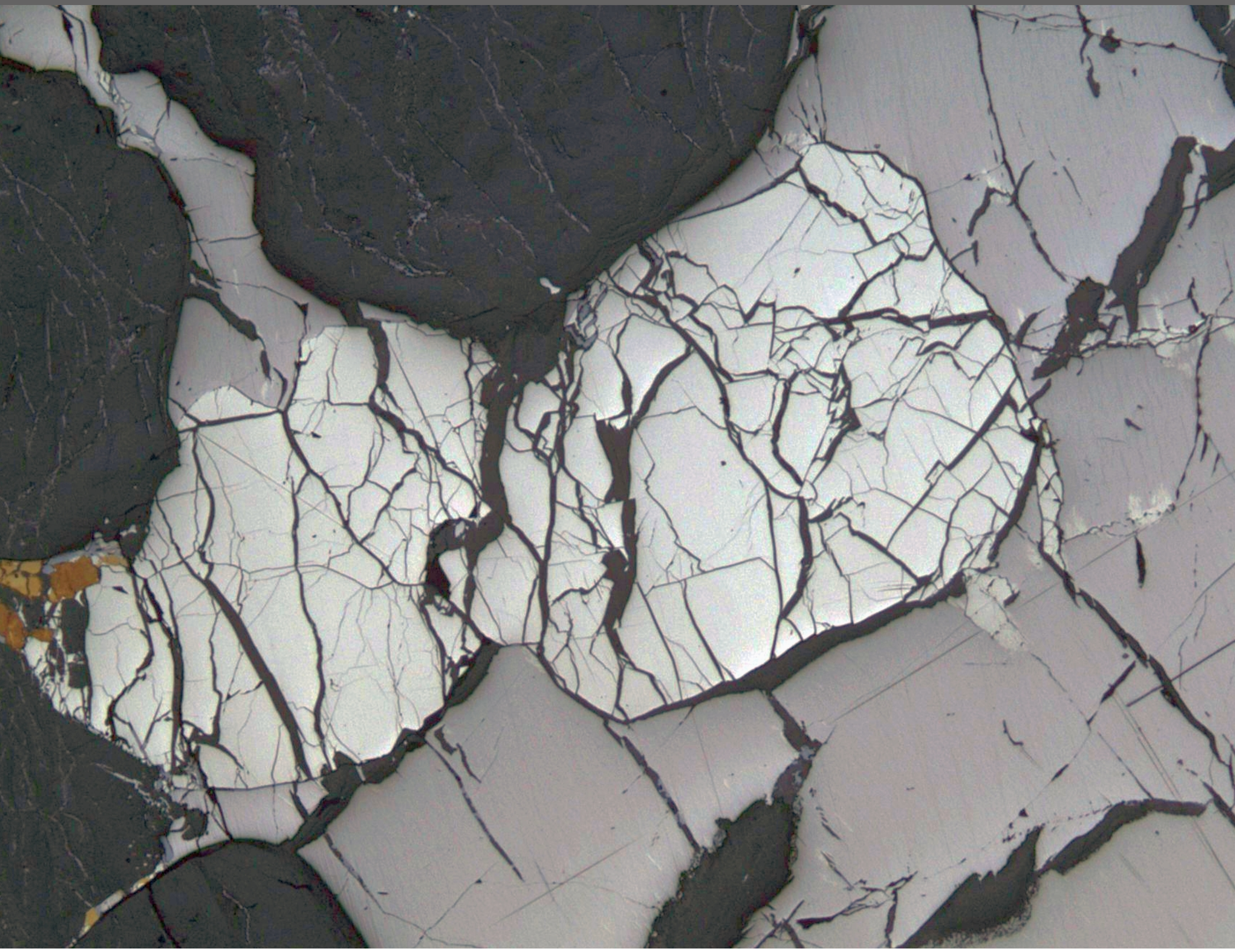
Geological Survey of Finland

2021

Analysis of Finnish battery mineral deposits with special emphasis on cobalt

Tuomo Törmänen and Pekka Tuomela

GTK Open File Research Report 29/2021



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Analysis of Finnish battery mineral deposits with special emphasis on cobalt

Unless otherwise indicated, the figures have been prepared by the author of the publication.

Front cover: Sulphide minerals from the magmatic Rytky Ni-Cu-Co deposit south of Kuopio. two mm-sized pentlandite grains (centre, creamy white) with 1.4% Co with brownish pyrrhotite with very low Co-content (<0.01%). Photo: Tuomo Törmänen, GTK.

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Compared to many other base metals such as nickel, copper and zinc, the world production of cobalt is relatively low at 140 kt. However, it has many important industrial applications, such as special steels and alloys, catalysts and chemicals, and especially rechargeable Li-ion batteries, which currently account for half of Co usage. The world primary production of Co is dominated by the Democratic Republic of Congo (DRC), with 70% of production, while China produces 50% of refined Co, mostly sourced from the DRC. Both the EU and the Finnish government have recently recognized the dependence of the manufacturing sector on imports from outside the EU. Currently, Finland is the only primary Co-producing country in Europe and an important producer of refined Co in the world (10%).

Finland hosts multiple types of ore deposits containing cobalt. In the past, most of the cobalt was produced from Svecofennian mafic intrusion-hosted Ni-Cu deposits and Outokumpu-type Cu-Zn-Co-Ni deposits. Currently, cobalt is produced by the Kevitsa (Boliden) Ni-Cu mine and Sotkamo (Terrafame) black schist-hosted Ni-Zn-Cu-Co mine. Identified cobalt resources amount to a total of 487 000 t, of which about 60% is contained in the Sotkamo deposit. Other significant deposit types and deposits include magmatic Ni-Cu deposits (Kevitsa, Sakatti), Kuusamo-type Au-Cu-Co deposits (Juomasuo) and Fe-Cu-Au deposits (Hannukainen).

In this report, we provide data on different deposit types, the main minerals hosting cobalt, concentrate data, downstream processing options for different concentrate types, the exploration potential, as well as brief summary of data on lithium and graphite deposits and their potential. The information has mostly been gathered from publicly available databases and from the literature.

Keywords: cobalt, cobalt deposits, cobalt minerals, flotation, pyrometallurgy, hydrometallurgy, biohydrometallurgy, exploration, undiscovered deposits

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Appendix 1: List of co deposits with tonnage data
Appendix 2: List of li and graphite deposits

1 INTRODUCTION

Both the European Union and the Finnish Government have recently recognized the strategic importance and the enormous business potential of lithium-ion batteries and their value chain. As the industry is currently dominated by Asian players, Europe is in danger of missing these business opportunities and is becoming increasingly dependent on the foreign supply of both raw materials and end products. In addition to business considerations, this is clearly also a supply security risk. As far as Finland is concerned, the Finnish mining sector currently produces battery metals such as copper, nickel and cobalt, and metallurgical industries refine these metals based on both domestic and imported raw materials.

Work Package 1 of the BATCircle project aims to evaluate Finnish battery mineral deposits, especially Co-bearing deposits, determine the mineralogical hosts for cobalt, and estimate the known resources and potential for future resources (e.g., estimation of undiscovered resources). A global overview is also presented (section 2) for background information.

2 COBALT: DEPOSITS, PRODUCTION AND USAGE – A GLOBAL PERSPECTIVE

Cobalt is a metallic element with similar electrochemical properties, for instance, to manganese, iron and nickel, and can therefore substitute these elements in many minerals. The average cobalt content of the Earth's crust is 0.003 wt% (or 30 parts per million, ppm), which is similar to other base metals (copper 0.0025 wt%, nickel 0.0056 wt% and zinc 0.0065 wt%) (e.g., Wedepohl 1995, Taylor & MacLennan 1995). Like nickel, the highest cobalt contents occur in MgO-rich mafic–ultramafic rocks (0.005–0.01 wt%), whereas sedimentary and granitic rocks contain lower amounts of cobalt (0.002 and 0.0003 wt%, respectively).

2.1 Cobalt deposit types

Cobalt rarely forms its own deposits, but it occurs as a minor constituent in a number of ore deposit types, typically with grades from 0.01 to 0.2 wt%. Globally, the most important deposits are stratiform sediment-hosted Cu-Co deposits (or sedimentary rock-hosted stratiform Cu-Co deposits), which produce 63% of the world's cobalt, followed by lateritic Ni-Co deposits (20%) and magmatic Ni-Cu-(Co-PGE) deposits (14%) (Fig. 1). In addition, cobalt occurs in a number of other deposit types, such as in some volcanogenic massive sulphide (VMS) deposits, iron oxide copper gold (IOCG) deposits, and certain Au(-Cu-Co) deposits. The so-called 5-element vein deposits and other vein-type deposits (e.g., Bou Azzer, Morocco) are the only deposit types in which cobalt can be the main commodity with percent-level concentrations (Mudd et al. 2013, Slack et al. 2017).

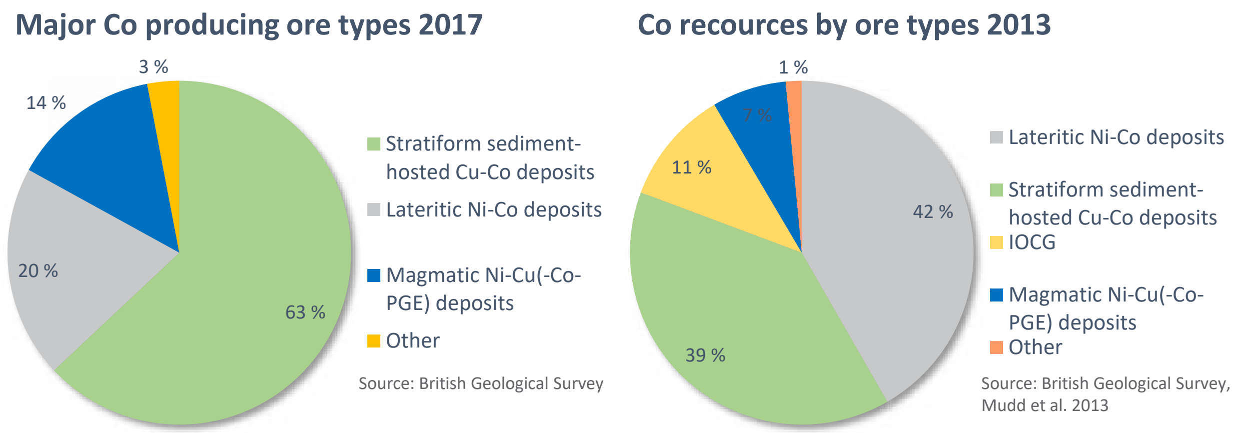

Fig. 1. Major ore types from which cobalt is produced (2017) and Co resources (2013).

Some examples of global Co deposits are presented in Table 1 and typical Co minerals and Co-bearing minerals in Table 2.

Table 1. Global examples of Co-bearing deposit types; grade-tonnage data for the main metal and Co.

Deposit	Country	Tonnage (Mt)*	Cu grade (wt%)	Co grade (wt%)	Contained Co (t)
Stratiform sediment-hosted Cu-Co deposit					
Tenke Fungurume	DRC	824	2.95	0.29	2 390 000
Kisanfu	DRC	96	2.084	0.587	564 000
Chambishi	Zambia	200	2.021	0.077	15 8000
Nama	Zambia	186	0.04	0.059	74 600
Opuwo	Namibia	112	0.41	0.11	126 100
Lateritic Ni-Co					
Deposit	**Country**	**Tonnage (Mt)**	**Ni grade (wt%)**	**Co grade (wt%)**	**Contained Co (t)**
Ravensthorpe	Australia	197**	0.60	0.03	59 100
Punta Gorda	Cuba	310	1.32	0.11	341 000
Ambatovy	Madagascar	228	0.9	0.08	180 000
Mindoro	Philippines	344	0.86	0.11	383 000
Caldag	Turkey	33	1.13	0.07	23 000
Magmatic Ni-Cu(-Co-PGE) deposits					
Mt Keith	Australia	225	0.53	0.01	22 500
Savannah North	Australia	10.2	1.7	0.12	12 700
Voice's Bay	Canada	31	2.12	0.13	39 000
Eagle	USA	4.6	4.2	0.1	1400
Jinchuan	China	515	1.1	0.019	98 000
Other deposit types					
Windy Craggy (VMS)	Canada	298	Cu=1.4	0.07	208 000
Mount Oxide (IOCG)	Australia	25	Cu=0.901	0.084	21 000
Black Bird (metasediment-hosted Cu-Co-Au, Black Bird type)	USA	7	Cu=1.15	0.74	52 000
Bou Azzer (vein type)	Morocco	5.7	Ni=1	1	57 000
Nick (black shale)	Canada	?	Ni=5.5	0.026	?

*Resources+reserves, ** Reserves. Data source: Slack et al. 2017, company web sites, S&P Global Market Intelligence 2018, Gadd & Peter 2018.

Stratiform sediment-hosted Cu-Co deposits

These types of deposits are the most important source of cobalt and the second most important source of copper. They typically occur as sulphide zones a few metres in thickness parallel to layering in the host sedimentary rocks, typically forming fairly large tonnage deposits ranging from a few million tonnes to several hundreds of millions of tonnes. Most of the deposits are found within the Central African Copperbelt, stretching from Zambia to the DRC, with relatively few deposits occurring elsewhere. The DRC deposits tend to be more Co-enriched, typically grading >0.1 wt% Co, with some deposits having Co grades between 0.5 and 1 wt% (Hitzman et al. 2017, Slack et al. 2017), whereas the Zambian deposits and deposits elsewhere typically contain 0.01–0.06 wt% Co.

Table 2. Main cobalt minerals and Co-bearing minerals.

Mineral	Formula	Co content (wt%)	Occurrence (global/Finnish deposits)
Cobalt sulphides			
Cobaltpentlandite	$(Co,Ni,Fe)_9S_8$	10–60	Oku, Kuusamo, Rajapalot, minor
Linnaeite	$Co^{2+}Co_2^{3+}S_4$	40–60	Rare–minor, Rajapalot, Oku
Carrolite	$Cu(Co,Ni)_2S_4$	35–38	DRC, rare in Finnish deposits
Siegenite	$(Ni,Co)_3S_4$	13–26	DRC, rare in Finnish deposits
Cattierite	CoS_2	42–48	DRC, rare in Finnish deposits
As-S minerals			
Cobaltite	(Co,Fe,Ni)AsS	20–35	Common minor to trace mineral in several deposit types (magmatic Ni, Oku, Kuusamo-Rajapalot)
Alloclasite	(Co,Fe)AsS	10–29	Rare
Glaucodot	(Co,Fe)AsS	10–20	Rare
Gersdorffite	(Ni,Fe,Co)AsS	0–10	Orthomagmatic Ni deposits, minor
Arsenopyrite	FeAsS	<0.01–5	Common minor to trace mineral
Safflorite	$(Co,Fe)As_2$	10–30	Rare
Skutterudite	$(Co,Ni)As_3$	20–30	Rare
Löllingite	$FeAs_2$	<0.01–5	Rare
Co-containing sulphides			
Pentlandite	$(Ni,Fe)_9S_8$	<0.5–3.27	Common in magmatic Ni-deposits
Millerite	NiS	0.2–2	Minor–trace, important in some magmatic Ni-deposits
Violarite	$Fe^{2+}Ni_2^{3+}S_4$	0.2–3	Minor–trace, important in some magmatic Ni-deposits
Pyrite	FeS_2	<0.01–3	Common in all sulphidic ore deposits
Pyrrhotite	$Fe_{(1-x)}S$	<0.01–0.3	Common in all sulphidic ore deposits
Chalcopyrite	$CuFeS_2$	<0.01–0.2	Main Cu sulphide, rarely Co-bearing
Cubanite	$CuFe_2S_3$	<0.01	Common minor Cu-phase, rarely Co-bearing
Sphalerite	(Zn,Fe)S	<0.01–0.6	Main Zn sulphide, Co-bearing in Oku-type deposits
Other			
Erythirite	$Co_3(AsO_4)_2 8H_2O$	30	Bou Azzer, laterites, not found from Finland
Heterogenite	CoOOH	64	DRC, laterites, not found from Finland
Kolwezite	$(Cu,Co)_2(CO_3)(OH)_2$	30	DRC, not found from Finland

Oku = Outokumpu-type Cu-Zn-Co-Ni deposits.

These types of deposits have not been found in Finland, although some recent geological research and exploration results in the Peräpohja belt have induced speculation about the presence of sediment-hosted Cu deposits within the belt (e.g., Kyläkoski et al. 2012).

Lateritic Ni-Co deposits
These deposits form via the weathering of ultramafic rocks in tropical to subtropical climates over a long time period. In the weathering process, elements such as iron, nickel and cobalt are enriched in the weathered material, while many other elements are leached away. Mined laterites typically contain >1 wt% Ni and generally low but variable Co-contents between 0.01 and 0.1 wt%. The tonnage range is similar to the sediment-hosted Cu-Co type. Some lateritic Ni-Co deposits also occur in Europe (Greece, Kosovo, Serbia, Poland, Russia, Ukraine) (Hitzman et al. 2017, Slack et al. 2017), and possibly one paleolateritic Ni occurrence in Finland, but nothing is known about its Co content.

Magmatic Ni-Cu-(Co-PGE) sulphide deposits
This is a fairly common and important deposit type for Ni and Cu that is found on every continent, in Europe, mostly occurring in the Nordic countries (Finland, Sweden and Norway) and in NW Russia (Kola Peninsula). Typical Ni and Cu grades are between 0.5 and 2 wt% and Co is between 0.01 and 0.06 wt%. Cobalt grades closely follow the total sulphide content and especially the Ni grades, as most of the Co (typically 80–90%) occurs in pentlandite, which is usually the main Ni carrier, so that some high-grade Ni deposits with >2 wt% Ni can contain 0.1–0.2 wt% Co. These deposits are highly variable in size and generally relatively small, from 1–10 Mt, but the largest deposits can be in the hundreds of megatonnes, and some areas, such as Sudbury in Canada and Noril'sk-Talnakh in Russia, host combined resources in the order of a billion tonnes (including past production) (Hitzman et al. 2017, Slack et al. 2017). The Kevitsa Ni-Cu deposit is the only currently mined deposit of this type in Finland.

Other deposit types
As stated above, in addition to the major Co-producing deposit types, there are a number of other deposit types that can also contain cobalt. Some VMS deposits contain elevated Co grades, typically a few hundred ppm (0.02–0.08 wt%), with some deposits reaching 0.1–0.4 wt%, such as the Outokumpu region deposits in Finland, some Russian deposits in the Urals and a few other deposits elsewhere. Supracrustal rock-hosted Au-Cu-Co deposits typically contain 0.1–0.3 wt% Co. The most notable deposits occur at Kuusamo and in the Black Bird district in Idaho, USA. IOCG and Fe-Cu-Co skarn deposits can contain a few hundred ppm of Co (e.g., some of the Kolari area Fe-deposits in Finland). Sulphur and carbon-rich black shales/schists can, in some cases, also be metal enriched, with elevated and in some cases economic concentrations of Ni, Cu, Zn, Mo, V, +Pt, Pd, Au, Ag and Co. They are known to occur in China, Yukon, the Czech Republic and Finland (Pagès et al. 2018, Pasava et al. 2013). One of the most notable of these is the Talvivaara deposit in Finland. The so-called 5-element vein deposits, as well as the Bou Azzer-type Ni-Co vein deposits, are generally small in tonnage but can contain %-level Co concentrations, and are the only deposit type in which cobalt is the main commodity (Hitzman et al. 2017, Slack et al. 2017).

2.2 Cobalt production

Cobalt is a relatively minor metal in terms of production volume (140 000 t in 2019) compared with many other base metals (Ni: 2.7 Mt, Zn: 13 Mt, Cu: 20 Mt). Cobalt production has steadily increased from 33 000 t in 2000 to 140 000 t in 2019 (Fig. 2) (USGS 2020). The world mine production of Co is dominated by the Democratic Republic of the Congo (DRC), which in 2019 produced about 100 000 t of cobalt, representing 70% of world production. The share of the rest of the Co-producing countries is between 1–4% (1 400–6 000 t). The annual Co-production of Finnish mines has been about 1 300–1 400 t in recent years, representing about 1% of world production. In comparison, only about 10 000 t was produced through recycling (Roberts & Gunn 2014). Known global Co resources and reserves, excluding marine resources, were 18 Mt in 2018, 10 Mt (55%) of which were located in the DRC. Other countries with significant resources (>0.3 Mt) include Australia, Tonga, Canada, Zambia, Cuba, Finland and Papua New Guinea (Fig. 4).

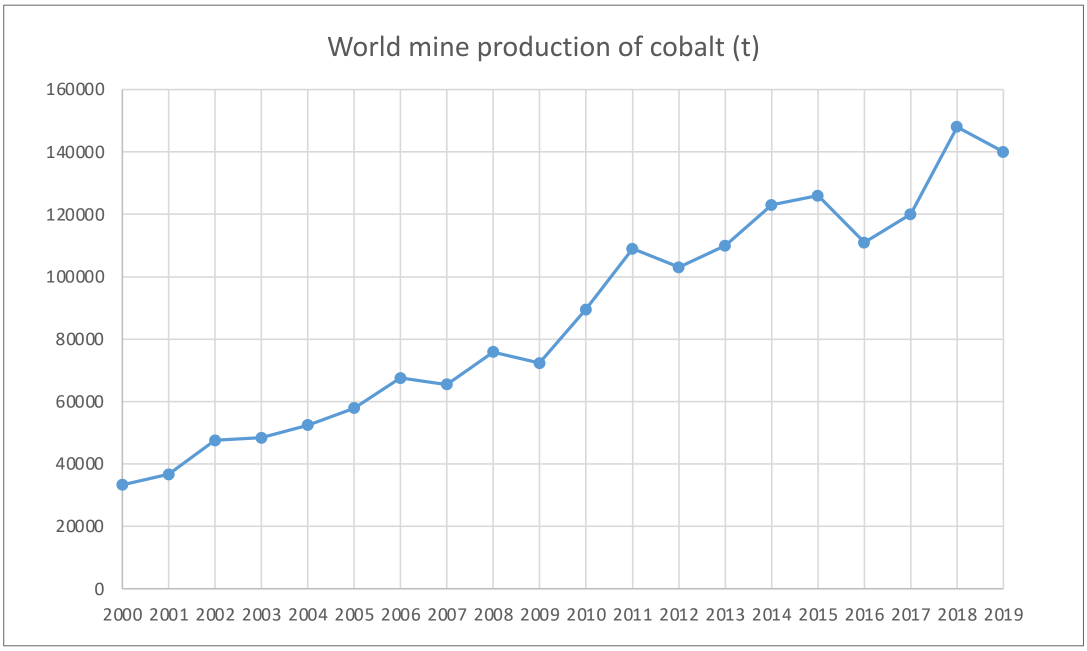

Fig. 2. Cobalt mine production (t) from 2000 to 2019 (source: USGS 2020).

The cobalt produced from mines is usually contained in an intermediate product, i.e., a Ni-Co sulphide concentrate, cobalt oxides, hydroxides or sulphates. However, laterite Ni-Co ore has been shipped from mines directly to outside refining.

Refined Co production, i.e., the production of metallic cobalt products (ingots, powders, briquettes, cathodes and rounds) and purified cobalt salts, oxides and hydroxides, is dominated by China, whereas the major mine producer, the DRC, has very little refined Co production (Fig. 3). Finland is also a major refined Co producer, with a 13% share in 2016 (Fig. 3), along with some other European countries (Belgium 6.5%, Norway 3.5%).

As cobalt is mainly a by-product in most of the deposit types, the refining process generally focuses on maximizing the recovery of the main metal(s), typically Cu and Ni. This results in quite significant losses of Co to tailings (waste). According to Mudd et al. (2013), Co recoveries vary between 10% and 90% and are typically between 25% and 75%, with considerable variation even within the same deposit type. This is mostly related to Co-mineralogy, i.e., whether cobalt occurs as a major or minor constituent in recoverable oxides or sulphides or in undesired or unrecoverable minerals. This can be exemplified by magmatic Ni-Cu sulphide deposits, where the main sulphide minerals are pyrrhotite ($Fe_{(1-x)}S$), pentlandite ($(Ni,Fe)_9S_8$) and chalcopyrite ($CuFeS_2$), with generally 80% of the sulphides being pyrrhotite and 5–10% each being pentlandite and chalcopyrite. Typically, about 80% of Co is carried by pentlandite and the rest occurs in pyrrhotite. In the nickel flotation process, the aim is to achieve a sufficiently high Ni content (>8 wt%) with a reasonable Ni recovery (~75–85%). This is achieved by supressing silicate gangue minerals and also pyrrhotite. In the process, some of the Ni and Co is lost to the tailings in pentlandite, which passes through the flotation for various reasons, and also in pyrrhotite, which typically also contains unrecoverable fine-grained pentlandite exsolutions. The end result is that up to 50% of Co is lost to tailings. Consequently, some mining operations, especially in the DRC, have resulted in considerable secondary Co-resources in the tailings, with up to 113 Mt containing 1.49% Cu and 0.32% Co (e.g., Petavratzi et al. 2019).

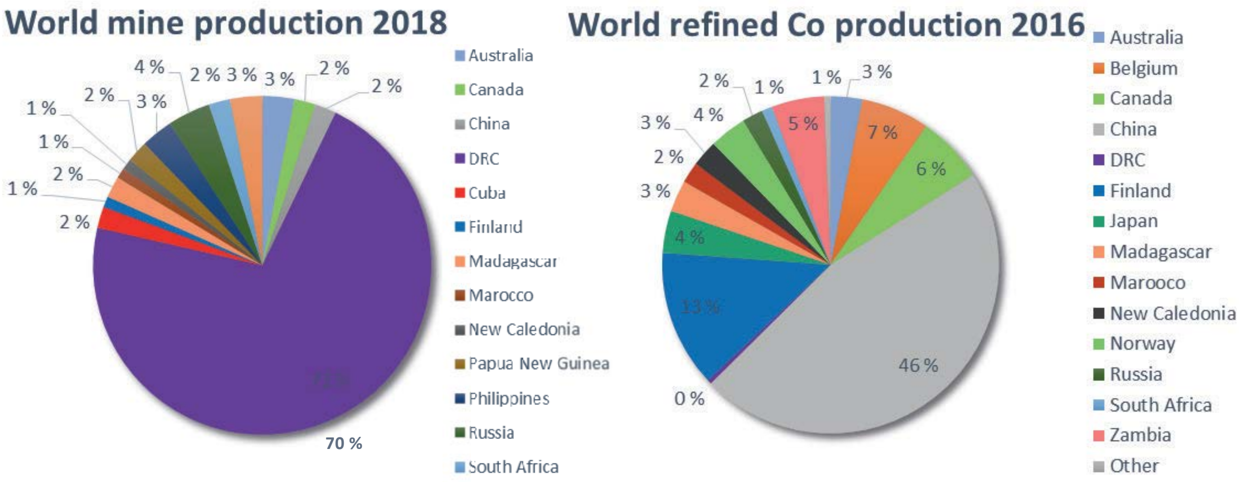

Fig. 3. Cobalt mine production (2018) and refined Co production (2016) by country (source: USGS 2020).

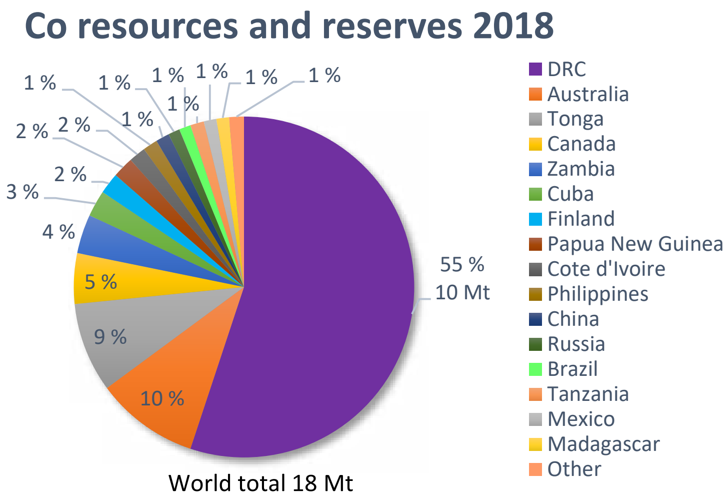

Fig. 4. Global Co resources and reserves in 2018 (data source: S&P Global Market Intelligence 2018, USGS 2020, this study).

Public reporting of Mineral Resources, Reserves and the CRIRSCO codes

CRIRSCO (the Committee for Mineral Reserves International Reporting Standards), which was formed in 1994, is a grouping of representatives of organizations that are responsible for developing mineral reporting codes and guidelines. There are several national and regional reporting codes in use, for instance PERC in Europe, JORC in Australia, NI 43-101 in Canada and SME in USA. In short, based on the reporting codes, a mineral occurrence can be classified as belonging to one of three groups: Exploration Results (Exploration Target), Mineral Resources and Mineral Reserves (Fig. 5). Exploration Target is, in general terms, an estimation of the exploration potential of a mineral deposit for which there is insufficient data to make a mineral resource estimate. Mineral Resource is a concentration or occurrence of material of economic interest in or on the Earth's crust in such a form, quality and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade or quality, continuity and other geological characteristics of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge, including sampling. Mineral Resources are subdivided, in order of increasing geological confidence, into the categories Inferred, Indicated and Measured. Mineral Reserve is the economically mineable part of a Measured and/or Indicated Mineral Resource. It is further divided into Probable and Proved Mineral Reserves.

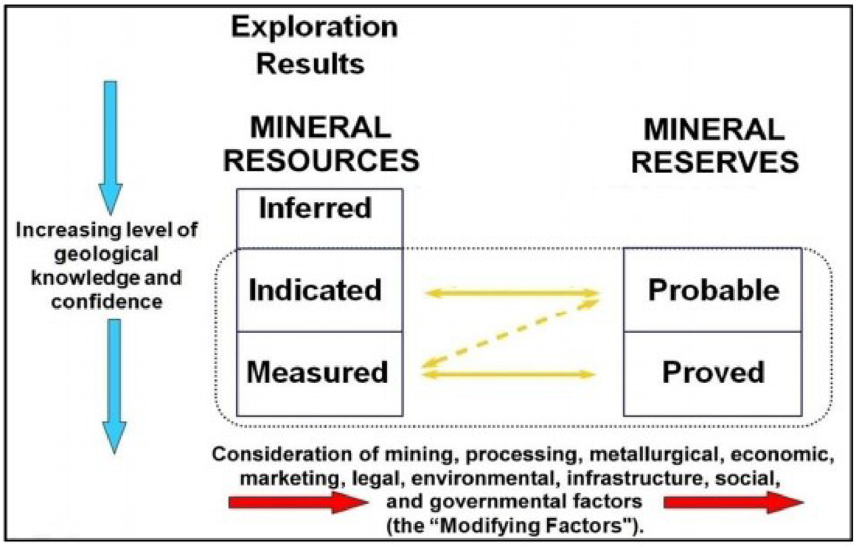

Fig. 5. Classification of mineral deposit estimates (CRIRSCO internal reporting template 2019).

2.3 Cobalt usage

Cobalt uses can be divided into two main groups: metallurgical and chemical applications. Metallurgical applications include superalloys used in the aerospace industry, nuclear reactors, power plants and gas turbines, other alloys and carbides used in cutting tools, and cobalt magnets (Al-Ni-Co and Nd-Fe-B(-Co)) used in wind turbines, hard disk drives, sensors, actuators and magnetic resonance imaging. In 2006, these accounted for about 45% of cobalt use, whereas in 2017 their share had dropped to about 30% (Fig. 6). Cobalt chemicals are used as catalysts in natural gas and refined petroleum product manufacture, plastics manufacture and the chemical industry. Cobalt salts are used in dyes and pigments in pottery, enamels, inks and glass. Cobalt metal and various compounds, such as cobalt antimony, cobalt boron, cobalt germanium and others, are used in numerous electronic products that contain integrated circuits, processors, digital storage and semi-conductors. The highest increase in cobalt use has been as a cathode material in the manufacturing of rechargeable Li-ion batteries (LIB). Cobalt is used in lithium-cobalt-oxide (LCO), lithium-manganese-oxide (LMO) and lithium-nickel-manganese-cobalt-oxide (NMC), as well as nickel-cadmium and nickel-metal hydride batteries. In 2006, these accounted for 22% of Co use, whereas in 2017 they accounted for 46–49% of global Co usage. In terms of tonnage, this means an increase from 15 000 t in 2006 to 55 000 t in 2017. For reference, the world mine production of Co in 2006 was 67 500 t. Consumer electronic devices account for 80% of the demand for LIBs and electric and hybrid vehicles for 20%.

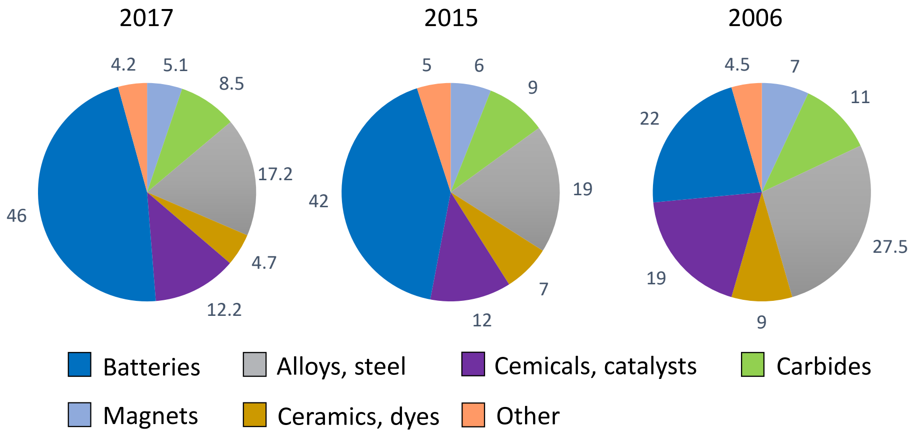

Fig. 6. Major cobalt using technologies/products. Also indicated is the world mine production of cobalt. Sources: USGS 2020, Roskill, Cobalt Institute.

Estimates for Co use in electric vehicles in 2025 vary from about 50 000 t to 150 000 t (e.g., Alves Dias et al. 2018). Towards 2030, there are even higher estimates in place. IEA (2020) estimated that by 2030, global annual EV cobalt demand could be 140 000–225 000 t, depending on the battery chemistry in the stated policy scenario (the mean estimate being 180 000 t). The IEA sustainable development scenario (SDS) forecasts cobalt demand of 300 000–460 000 t (the mean estimate being 375 000 t) by 2030, again depending on the battery chemistry. The SDS scenario for 2030 would require almost three times the current overall cobalt production only to satisfy the EV demand, not counting all the other uses for cobalt. It is to be noted that during the past year, EV sales have globally risen faster than what was forecasted just a few years ago. These figures clearly raise questions concerning how the supply side can respond to the constantly growing demand, despite the fact that battery chemistries are being developed to operate with smaller relative amounts of cobalt. This typically causes greater demand for nickel, which is similarly undersupplied in the long term, especially when considering sustainable sourcing from operations with a low carbon footprint (sulphidic nickel deposits). In principle, there are no easy solutions to meet the growing LIB demand for the required commodities. Further discussion on this topic is, however, beyond the scope of this study.

3 KNOWN FINNISH BATTERY MINERAL DEPOSITS

This chapter summarizes the known battery mineral deposits in Finland. In most cases, only resources are reported, as reserve data are not available. The resource data are a combination of the measured, indicated and inferred tonnage and grade. The reserve and resource summary is based on the GTK Metso database and Fennoscandian Ore Deposits Database (FODD), which are based on respective company reporting. Updated company mineral reserve and resources reports (end of 2020) were available for this summary. Table 3 presents a compilation of the most significant Co-containing deposits, including active mines, past-producing mines and unexploited deposits. For some of the deposits (namely in the Suhanko area), the Co tonnage has been estimated by GTK based on available public Co-grade data. All deposits included in GTK databases are summarized in Appendix 1. It needs to be noted that many of the deposits do not have CRIRSCO-compliant resources. These are referenced with the code ‘old’ (or ‘non-compliant’).

Table 3. Active mines and selected Co-containing deposits in Finland.

Deposit type	Deposit satus	Holder	Main metals	Deposit type	Resource +reserves Mt	Co (t)	Ni (t)	Cu (t)	Zn (t)	Au (t)	Pt+Pd (t)
Sotkamo	Active	Terrafame	Ni.Zn.Cu.Co	Black shale	1525	289 750	3 812 500	2 135 000	7 930 000		
Kevitsa	Active	Boliden	Ni.Cu.PGE	Magmatic Ni-Cu	307.5	30 750	663 680	1 001 930		25.9	77.9
Hannukainen	CM	Hannukainen Mining	Fe. Cu. Au.Co	IOCG	221	29 835		397 800		17.7	
Ahmavaara	NE	CD Capital	PGE. Ni. Cu	Magmatic Ni-Cu	187.77	13 144*	37 620	75 240		18.8	185.9
Konttijärvi	NE	CD Capital	PGE. Ni. Cu	Magmatic Ni-Cu	75.24	3010*	129 561	328 597		5.3	9.8
Sakatti	NE	Aglo American	Ni.Cu.PGE	Magmatic Ni-Cu	44.4	20 424	426 240	843 600		14.6	50
Kuervitikko	NE	Hannukainen Mining	Fe. Cu. Au.Co	IOCG	43	4300		81 700		3.14	
Ruossakero	NE		Ni.Cu	Magmatic Ni-Cu	35.6	5589	117 480	1352			
Pappilanmäki	NE	FinnAust Mining	Ni.Zn.Cu.Co	Black shale	34.26	4111	65 779	34 602	129 503		
Juomasuo Co	NE	Latitude 66 Cobalt	Au.Cu.Co	Kuusamo-type Au-Co	24.2	15 660		504		15.55	
Pahtavuoma	CM	Outokumpu Mining	Cu.Zn	VMS	21.1	2110		63 300	14 137		
Laukunkangas	CM	Outokumpu Mining	Ni.Cu	Magmatic Ni-Cu	5.9	1400	11 200	9800			
Haarakumpu	NE	Latitude 66 Cobalt	Au.Cu.Co	Kuusamo-type Cu-Co	4.68	7769		15 912			
Ruimu	NE		Ni.Cu	Magmatic Ni-Cu	3.5	1050	8400	11 550			
Hautalampi	NE	FinnCobalt	Ni.Cu.Co.Zn	Outokumpu-type VMS	3.16	3476	13 588	11 376	2212		
Kouvervaara	NE	Latitude 66 Cobalt	Au.Cu.Co	Kuusamo-type Au-Co	1.58	2371		4742		0.6	
Luikonlahti	CM	Boliden	Ni.Cu.Co.Zn	Outokumpu-type VMS	0.85	1020	765	10 200	5525		
Kylylahti	Closed	Boliden	Ni.Zn.Cu.Co	Outokumpu-type VMS	6.88	7774	19195	26969	15548	0.55	
Total					2545.62	443 543	5 306 008	5 030 305	8 096 925	101	323.6

*Estimated Co tonnage. NE = not exploited, CM = closed mine. Juomasuo deposit with maximum tonnage.

3.1 Significant Co-containing deposit types

Important Finnish Co-containing deposits can be classified into the following six types:

1. Orthomagmatic Ni-Cu-PGE-Co deposits (e.g., the Boliden Kevitsa mine and Suhanko Arctic Platinum deposits);
2. Black schist-hosted Ni-Cu-Co-Zn deposits (the Terrafame Sotkamo mine);
3. Outokumpu-type polymetallic Cu-Co-Ni-Zn deposits (e.g., the Boliden Kylylahti mine, FinnCobalt Hautalampi);
4. Supracrustal rock-hosted polymetallic Co-Au-Cu deposits (e.g., Kuusamo type: Juomasuo - Lat66 and Rompas-Rajapalot - Mawson Oy);
5. IOCG (iron oxide-copper-gold) polymetallic Fe-Cu-Au(-Co) deposits (e.g., the Hannukainen Mining Kolari area deposits, Vähäjoki, Tervola Norrbotten Exploration);
6. Other deposit types. Several Au deposits (orogenic gold deposit type) in central Lapland and some in Ostrobothnia contain elevated Co-concentrations. Some pyrite deposits could be a future source of Co (e.g., Pattasoja, Iso-Povivaara, Kannusjänkä, Kelujoki), as pyrite is often variably Co-enriched (global example: Thackaringa project, Australia, with 111 Mt at 0.07 wt% Co).
   - Black schist-hosted deposits hold by far the largest known Co-tonnage, with the Terrafame Sotkamo mine alone containing some 58% of known in situ cobalt resources, having an estimated annual production of 500 t of Co (not reported under Terrafame operations). Other known deposits are comparably small in size.
   - Orthomagmatic deposits contain the second largest known resources, representing 20%, although for some deposits, such as the Ahmavaara PGE-Ni-Cu deposit, the Co content has been estimated due to the lack of publicly reported data in more recent resource estimates. There is active production (495 t of Co in 2020) from the Boliden Kevitsa mine in Sodankylä. Three large deposits, Ahmavaara, Kevitsa and Sakatti, contain 75% of cobalt in orthomagmatic deposits (Fig. 8).
   - Outokumpu-type deposits have been significant producers in the past, especially the Outokumpu deposit itself (1919–1989), with a total reported production of 54 356 t of Co. Cobalt has been produced from Outokumpu mine products since the late 1930s, first from the sulphide concentrate roasting residues by Vuoksenniska Oy at Imatra. Outokumpu Oy continued cobalt production from the late 1950s, but initially it simply exported the roasting residues to Germany instead of further refining them, as conducted by Vuoksenniska Oy. Only after 1968 was produced cobalt further refined at the new Kokkola refinery, initially amounting to 500 tpa. For the next decade, mainly domestic raw materials were refined,also including streams from Luikonlahti and Vuonos mines. Since the late 1970s, imported raw materials have been increasingly used, especially since 1989 and the closure of the Outokumpu mine (Kuisma 1985).

The Kokkola plant has evolved during the years into the current Umicore/Freeport-owned state-of-the-art refinery, which is the largest single cobalt refinery in the world. This evolution has included a change of ownership, first with Mooney Chemicals 1991 (new company OMG Kokkola Chemicals Oy 1993) and later with a Freeport McMoran-led joint venture in 2013, and most recently with Umicore 2019.

The Boliden Kylylahti mine was closed at the end of 2020, although Co-Ni- concentrate was only produced as a by-product. However, a significant amount of low-grade Co-Ni- concentrate and Co-Ni-containing pyrite concentrate is stockpiled at the mill site, with the potential for further processing. There are a number of known (generally small) Outokumpu-type deposits in a geographically restricted area (Fig. 7B).

- Supracrustal rock-hosted polymetallic deposits contain some 5% of known cobalt resources. Typically, this deposit type contains a number of (generally small) deposits, especially in the Koillismaa–Rovaniemi area. Deposits of the Rompas–Rajapalot area represent a new type of deposit that is not yet fully understood geologically, but they resemble the Kuusamo deposits in many aspects.

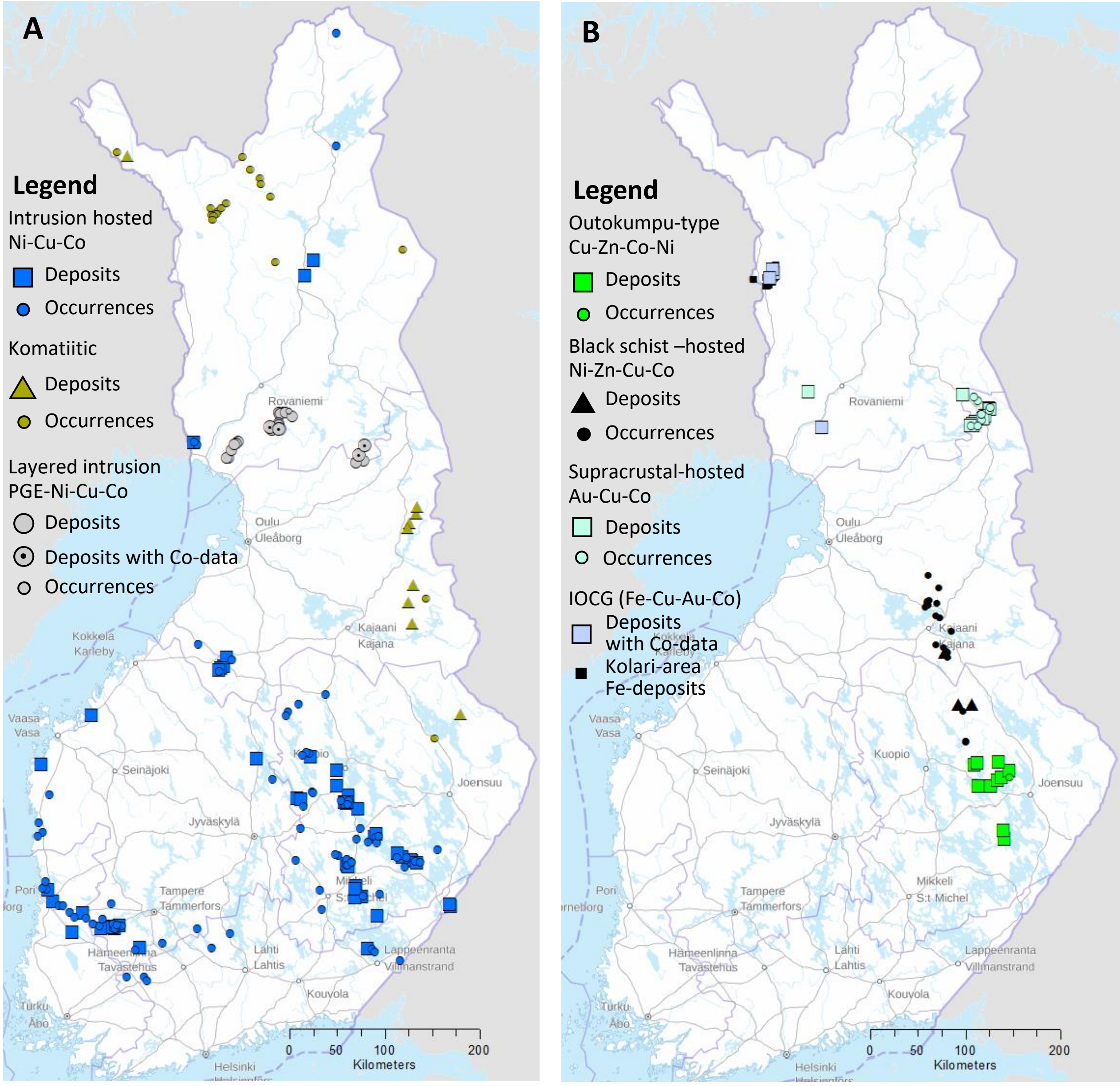

Fig. 7. Major Co-containing deposit types of Finland, including unexploited deposits, active mines and closed mines with remaining resources. Also indicated are some deposits without Co-data. A. Orthomagmatic Ni-Cu-Co-PGE deposits and occurrences. B. Outokumpu-type (VMS) Cu-Zn-Co-Ni deposits and occurrences, black schist (Talvivaara) hosted Ni-Zn-Cu-Co deposits and occurrences, supracrustal rock-hosted (Kuusamo type) Au-Cu-Co deposits and occurrences, and IOCG deposits and occurrences (background map © Maanmittauslaitos).

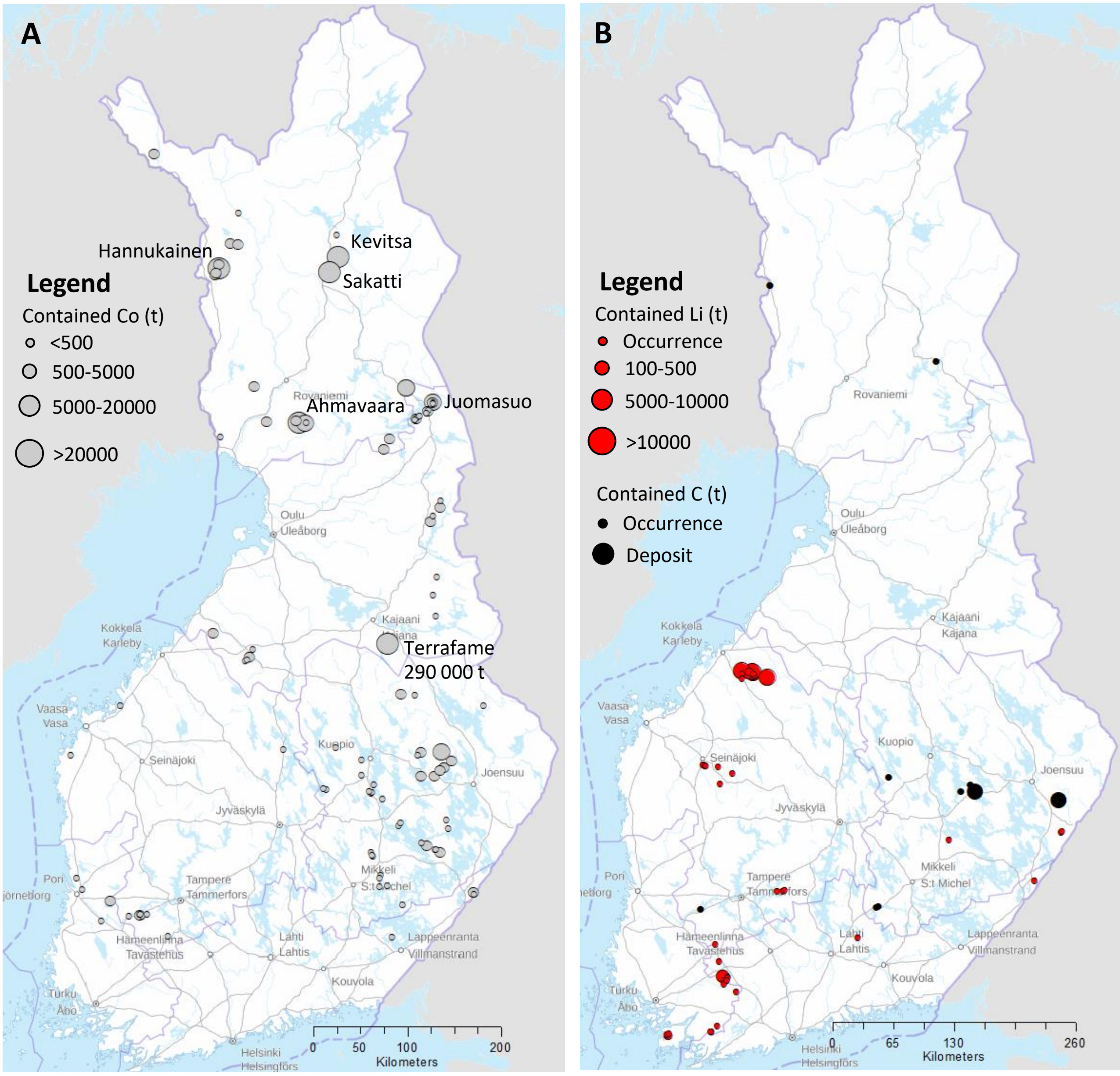

Fig. 8A. Contained Co (t) in Finnish deposits with available grade-tonnage data. For some deposits, grade-tonnage data are estimated. B. Lithium and graphite deposits and occurrences, with contained tonnage indicated for deposits (background map © Maanmittauslaitos).

Other battery minerals

- Lithium typically occurs in spodumene-bearing LCT-type pegmatites, which usually occur in certain pegmatite provinces in W–SW Finland.

Graphite occurs in graphite schist (black schist) deposits. Known Finnish graphite deposits are usually quite small and are divided into amorphous and flake graphite types.

3.2 Total reserves and resources in Finland

The total Finnish cobalt, lithium and graphite resources are presented in Table 4, broken down according to major deposit types. The data include actives mines, closed mines with resources remaining and unexploited deposits. In many cases, the resource estimates date from the 1980s and 1990s and do not comply with modern CRIRSCO-based reporting codes (hereinafter referred as non-compliant resources). However, for this compilation, any deposit with reported Co grade-tonnage data has been included. Deposits in active production or resource estimates from the 2000s comply with CRIRSCO codes and include most of the large-tonnage deposits (e.g., Kevitsa, Konttijärvi, Ahmavaara, Sakatti and Hannukainen). In some cases, the resource estimates lack cobalt and average concentrations are estimated based on past studies (e.g., reports, beneficiation tests and drill core analyses).

Altogether, Finnish deposits contain approximately 0.49 Mt of cobalt (Table 4), which represents 3% of global cobalt resources (Fig. 4). Most of the resources, i.e., about 80%, are hosted by orthomagmatic Ni-Cu-PGE-Co deposits and black schist-hosted deposits. The Hannukainen IOCG deposit and Juomasuo Au-Co deposit are the only other types of deposits containing significant Co (contained Co). The five largest deposits (Table 3), each containing >10 000 t Co, account for approximately 80% of all contained cobalt. The top 18 deposits presented in Table 3 account for over 90% of all contained cobalt.

It should be noted that the tonnages listed in Table 4 represent *in situ* resources. Furthermore, for other commodities than cobalt, the resource does not represent all known resources in Finland. This is because in this table, only the deposits also including cobalt have been taken into account. In many cases, when mineral resources are converted to mineral reserves, i.e., economically and technically mineable reserves, the deposit size and contained cobalt tonnage are likely to be smaller than the resources. In some large deposits, which can be bulk mined from an open pit, the resources and reserves can be nearly identical. Also, some resources in past-producing mines could be inaccessible in practical terms.

Table 4. Tonnage and contained metal data by deposit type (mineral resources).

Deposit type (polymetallic)	Main metals	Resources +reserves Mt	Co (t)	Ni (t)	Cu (t)	Zn (t)	Au (t)	Pt+Pd (t)
Magmatic Ni-Cu-Co-PGE	Ni,Cu,Co,PGE	748.7	95 965	1 734 185	2 528 616		71.2	472.7
Black shale	Ni,Zn,Cu,Co	1563	294 341	3 885 959	2 173 642	8 075 503		
Outokumpu-type Cu-Zn	Cu,Zn,Ni,Co,Au	18.1	20 139	41 955	155 956	109 828		
Supracrustal-hosted Au-Cu-Co	Au,Cu,Co	42.4	33 276		43 997		42.4	
IOCG	Fe,Cu,Au(Co)	286	39 358		525 940		25	
Other	Cu,Zn,Co,Au	34.65	4530	11 600	141 865	14 137	3.3	
Total		2692.85	487 609	5 673 699	5 570 016	8 199 468	142	472.7
Lithium and graphite			**LiO (t)**	**C (t)**				
Li-deposits	Li *	15.994	161 278					
Graphite deposits	C	31.2		2 477 994				

*Also small amounts of, for example, Be, Nb, Ta and Sn.

3.3 Major individual deposits

3.3.1 Sotkamo Ni-Zn-Cu-Co deposit (active mine)

The Terrafame Sotkamo mine is a large tonnage low-grade black schist deposit (Table 3). The main commodities are nickel and zinc, with copper and cobalt as by-products (Table 5). The mine uses bioheapleaching to extract the metals into solution. Ore is extracted from the open pit mine, crushed, agglomerated and stacked in leach heaps. Air is blown into the stacks of ore and the stacks are irrigated from the top with an acidic leaching solution. The stacked ore is first leached for approximately 15 months in a primary heap and is then reclaimed and conveyed onto a secondary heap for final leaching for several years. In the metal recovery process, the metals are sequentially precipitated from the pregnant leaching solution as sulphides using gaseous hydrogen sulphide. Based on early pilot tests, it is estimated that 90% of nickel and zinc and 60% of copper and cobalt can be recovered (Riekkola-Vanhanen 2013).

Following the restart of the mine in 2015, metal production has increased and approached the targets of 30 000 t of Ni and 60 000 t of Zn (cf. Table 5). Terrafame plans to start producing Ni and Co sulphates in 2021 as battery chemicals for rechargeable Li-ion batteries. The current estimated life of mine (LOM) extends to the 2040s, subject to exploitation of the Kolmisoppi deposit.

3.3.2 Kevitsa Ni-Cu-Co-PGE deposit (active mine)

The Boliden Kevitsa mine is a large tonnage low-grade orthomagmatic deposit (Table 3) hosted by the Kevitsa ultramafic intrusion, located some 40 km north of Sodankylä (Fig. 8A). The main commodities are nickel and copper, with gold, platinum, palladium and cobalt as by-products (Table 5). Annual ore extraction has been 7–8 Mt from an open-pit operation, with an expansion to 9.5–10 Mt executed in 2020 (SRK Consulting 2020). The mine produces Ni concentrate and Cu concentrate using a conventional sequential sulphide flotation process. The nickel concentrate contains most of the recovered Co, Pt and Pd, while the Cu concentrate contains most of the recovered Au and minor Co, Pt and Pd. In the final stage, the remaining sulphides, mostly Fe sulphides, are floated to clean the tailings of sulphides. The resultant sulphide-rich tailings are stored in a separate, membrane-lined storage pond. The nickel concentrate is shipped to the Boliden Harjavalta Ni smelter and the Cu concentrate to the Rönnskär smelter in Sweden. The current estimated life of mine (LOM) extends to the 2030s.

3.3.3 Kylylahti Cu-Au-Zn-Ni-Co deposit (closed in 2020)

The Boliden Kylylahti mine is an Outokumpu-type polymetallic VMS deposit located in the Outokumpu region (Fig. 8A). The Kylylahti mine was shut down at the end of 2020 due to the exhaustion of economic resources (Boliden 2020a). The main ore type consists of massive to semi-massive sulphides and the main commodities were Cu, Zn, Au and more recently also Ni and Co. Ore was extracted from an underground mine extending to a depth of 800 m and processed at the Luikonlahti concentrator. The mine produced a gravity Au concentrate, Cu sulphide concentrate and Zn sulphide concentrate. As the ore contained more Ni-Co –rich domains, the Zn refining circuit was periodically used to produce a Ni-Co concentrate. As in Kevitsa, the remaining sulphides were floated and stored in separate area. In Luikonlahti, this concentrate was co-stored together with sulphur concentrate. These sulphide-rich tailings contain low-grade Ni-Co concentrate that could be a future Co and Ni resource.

Table 5. Cumulative production and 2020 data for active mines producing cobalt.

	In production	Produced metals	Ore mined Mt	Co (t)	Ni (t)	Cu (t)	Zn (t)	Au (t)	Pt+Pd (t)
Kevitsa	2011-	Ni.Cu.Co.PGE. Au	64	2978	89 996	182 798		4.372	17.234
Past year	2020		9.5	495	11 074	27 402		0.854	2.134
Kylylahti	2011-	Cu.Zn.Ni.Co.Au	5.431	8207 *	3138	74 268	13 325	4.049	
Past year	2020		0.681	447	989	3609	326	0.623	
Sotkamo	2008-2013. 2015-	Ni.Zn.Cu.Co	136.9	3100**	173 217	***	371 554		
Past year	2020		16.87	550**	28 746		55 100		

*Kylylahti produced both low-grade Ni-Co concentrate and pyrite concentrate with 0.2–0.4% Co and Ni. Ni-Co concentrate was mostly stockpiled at the mine. **Estimated based on Ni production. ***Cu is produced but amounts have not been stated.

3.3.4 Sakatti Ni-Cu-Co-PGE deposit

The orthomagmatic Anglo American Sakatti Ni-Cu-PGE-Co deposit is a relatively recent world-class discovery, located some 15 km north of Sodankylä (Fig. 8A). The current mineral resource is 44.4 Mt with 0.96 wt% Ni, 1.9 wt% Cu, 0.046 wt% Co, 0.64 g/t Pt, 0.49 g/t Pd and 0.33 g/t Au (Anglo American plc 2016). The main deposit is hosted by a sub-vertical ultramafic body and consists of several massive sulphide sheets, vein sulphides and disseminated sulphides (Brownscombe et al. 2015). In addition to the main deposit, there are two smaller satellite ore bodies. The massive parts of the ore bodies can be extremely metal rich, with up to 28 wt% Cu, 9.5 wt% Ni and 25 g/t precious metals (Brownscombe et al. 2015). The project owner has been carrying out preliminary technical feasibility studies during the past few years. The project ESIA (environmental and social impact assessment) was recently published but has not yet been approved. Project permitting will be undertaken next. The mine could possibly ramp up production by the turn of decade, subject to successful permitting.

3.3.5 Suhanko PGE-(Cu-Ni-Co) deposits

The so-called Suhanko deposits comprise several mostly disseminated orthomagmatic PGE-dominant sulphide deposits with 1–2 g/t combined precious metals, low Cu and Ni contents generally ≤0.2 wt% and Co <0.01 wt%. The two largest deposits, Ahmavaara and Konttijärvi, have a combined resource of 260 Mt (Table 3) (Puritch et al. 2007). No more recent public resource estimates are available for individual deposits. The deposits are hosted by the Portimo layered intrusion complex located 45 km SSE of Rovaniemi. They have been under exploration since the 1980s and are currently held by CD Capital Asset Management Ltd. Project technical feasibility studies are ongoing, as well as associated ESIA/permitting procedures. Potential mine ramp-up could take place around the mid-2020s subject to successful studies, permitting and project financing.

3.3.6 Kuusamo Au-Cu-Co deposits

The Au-Cu-Co deposits of the Kuusamo area can be classified as supracrustal rock-hosted Au-Cu-Co type deposits, or as atypical orogenic gold deposits. They have quite variable metal contents and associations, ranging from dominantly Au deposits with low <0.05 wt% Cu and Co (e.g., Apajalahti) to Au-Cu-Co deposits with 0.1–0.3 wt% Cu and 0.05–0.2 wt% Co (e.g., Juomasuo, Meurastuksenaho) and Cu-Co deposits with low to nil Au (e.g., Haarakumpu and Lemmonlampi). Deposits of the Kuusamo area are currently held by Latitude 66 Cobalt. The Mawson Resources Palokas and Raja Au-Co deposits resemble, at least in part, the Kuusamo deposits. Typical grades are 1.5–5 g/t Au and 0.04–0.05 wt% Co (Mawson Resources 2020). In contrast to orthomagmatic Ni-Cu deposits, where cobalt is "automatically" recovered in the Ni concentrate, these types of deposits require the extraction of sulphide concentrate that would contain enough Co to be commercially viable, possibly >1 wt% Co. More detailed information on Co-hosting minerals is provided in the detailed deposit descriptions. Both projects are not yet very mature, as they lack technical feasibility studies, permitting and ESIA. Subject to successful implementation of these and project financing, these projects could be in production by the late 2020s at the earliest.

3.3.7 Hannukainen IOCG deposit

The Hannukainen Fe-Cu-Au(-Co) deposit is the largest iron deposit in the Kolari area, with a resource of 221 Mt. The deposit is held by Hannukainen Mining Oy. Currently, the planned start-up of the mine will be in 2025 due to delays in project permitting, the main products being Fe concentrate and a Cu-Au concentrate, as well as a sulphur concentrate. As the bulk of Co is hosted in Fe sulphides, part of it would report to sulphur concentrate and part to the separate pyrrhotite tailings (Hannukainen Mining 2017).

4 CHARACTERIZATION OF BATTERY MINERAL DEPOSITS

4.1 Orthomagmatic Ni-Cu-Co-PGE deposits

Orthomagmatic deposits are associated with mafic to ultramafic ("dark") rocks that either formed intrusions within the Earth's crust or extruded as lavas on the surface. As the host rocks crystallized from magmas generated in the mantle, they inherently contain more Ni, Cu, Co and platinum group elements (PGEs) compared to more felsic rock types, such as granitic rocks. In certain cases, these elements combine with sulphur to form a sulphide melt that can collect at the bottom of the hosting formation in sufficient quantity and density to form a mineral deposit, which, if it can be economically extracted, forms an ore deposit.

Depending on the amount of sulphide minerals present, these deposits can be classified as disseminated, matrix or semi-massive and massive sulphide deposits. In disseminated deposits, the rock/ore contains 0.5–17 wt% S, corresponding to 1–33% sulphides. In matrix deposits, the corresponding values are 17–28 wt% S and 33–66% sulphides, and in massive deposits, 28–38 wt% S and >66% sulphides. The rest is comprised of silicate minerals, in this case mostly Mg-Fe-Ca containing silicates and their alteration products. Most deposits are a combination of different ore types, also including sulphide breccias and veins. Economic deposits generally contain >0.5 wt% Ni and comparable amounts of Cu. They always contain some cobalt, especially those that are Ni-dominant, usually in the range of 0.01 to 0.05 wt%, and they can contain some PGEs, usually 0.5–2 g/t.

The sulphide mineralogy of orthomagmatic deposits is generally fairly simple, with pyrrhotite ($Fe_{(1-x)}S$) being the dominant sulphide mineral, followed by pentlandite ($(Ni,Fe)_9S_8$) and chalcopyrite ($CuFeS_2$). Of these, pentlandite and chalcopyrite contain valuable metals, whereas pyrrhotite is considered to be a waste or unwanted mineral (although it contains low amounts of Ni and Co). They also contain a number of minor or trace phases, such as pyrite, violarite, millerite, mackinawite, cubanite, bornite and gersdoffite (see Table 2), but these rarely have economic importance. Some deposits are mineralogically more complex and a few deposits have atypical sulphide paragenesis resulting from post-magmatic modifications by metamorphic or supergene alteration effects; for example, pyrrhotite can be replaced by pyrite and pentlandite by violarite and millerite.

Finnish orthomagmatic deposits can be classified into three different groups based on their age, host-rock type and metal association: 1. intrusion-hosted Ni-Cu deposits, 2. 2.44 Ga (billion year) layered intrusion-hosted PGE-Ni-Cu deposits and 3. komatiite-hosted Ni+Cu+PGE deposits (Fig. 7A).

4.1.1 Finnish intrusion-hosted Ni-Cu deposits

Most of the intrusion-hosted deposits and past-producing Ni-Cu mines belong to the so-called 1.88 Ga aged Svecofennian intrusions, which occur along two distinct belts, one extending from Raahe towards the SE along the so-called Raahe–Ladoga zone, known as the Kotalahti belt, and the second occurring along an E–W zone from Vammala to Pori, known as the Vammala belt (see Fig. 9). These types of deposits were in production from the 1950s until the mid-1990s, with the Hitura mine closing in 2013. The four largest deposits and also past-producing mines (Hitura, Kotalahti, Vammala and Enonkoski) range in size from 8 to 20 Mt, with fairly typical Ni, Cu and Co grades (0.5–0.66 wt% Ni, 0.16–0.26 wt% Cu and 0.02–0.04 wt% Co), and produced 50 000–92 000 t of Ni and 14 000–35 000 t of Cu during their life time. However, there is very little data on historic Co production; Enonkoski mine is reported to have produced 2 500 t of Co in concentrate (includes ore processed from the small Hälvälä and Telkkälä mines) (Pöyry & Isomäki 1996). Hitura has a reported Co production of just 544 t, but this has been reported from a few years (Puustinen 2003). In actuality, all of the mines produced cobalt, which is mostly contained in pentlandite and would have been included in the Ni concentrates (or bulk Ni-Cu concentrates). The Kevitsa mine is the only

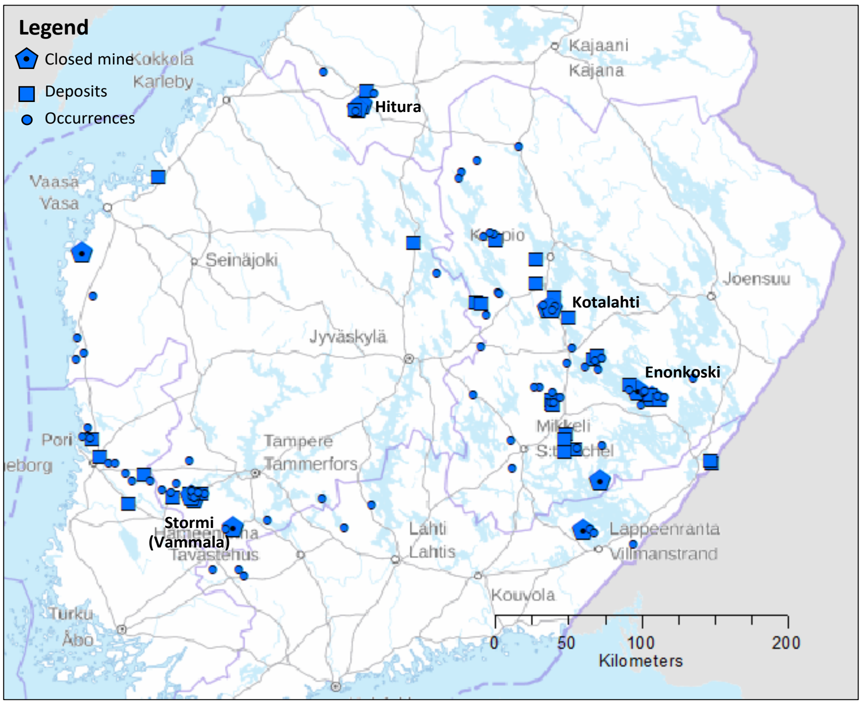

Fig. 9. Mostly Svecofennian 1.88 Ga-age intrusion-hosted Ni-Cu deposits, occurrences and closed mines, with the most important indicated (background map © Maanmittauslaitos).

currently producing orthomagmatic Ni-Cu deposit in Finland with an annual production of 400–500 t of Co (Table 5). The Kotalahti mine (1959–1987) was one of the main reasons for the development of the Harjavalta nickel smelter, with commercial production starting in 1960, initially producing nickel cathodes (Kuisma 1985). Since 2002, nickel chemicals have also been produced. By then, the smelter and associated refinery was operating under OMG Harjavalta Nickel Oy (the plant was sold to OM Group in 2000). The smelter was bought by Boliden in 2004 and the refinery by Norilsk Nickel in 2007. The same companies are currently operating the facilities, but there have been significant changes in the raw material sourcing. Furthermore, the plants are not currently integrated but operate on an individual basis.

4.1.2 2.44 Ga layered intrusion-hosted PGE-Ni-Cu deposits

These types of deposits are associated with a belt of distinctive intrusions, forming an E–W belt extending from the Swedish border to Russia and also occurring in central Lapland and in the Käsivarsi area. They host several types of PGE-Ni-Cu deposits, the most significant being the so-called reef-type deposits and contact-type deposits (e.g., Alapieti 2005). Reef-type deposits are relatively thin strata-bound continuous layers enriched in platinum and palladium but containing only low or negligible Ni, Cu and Co. Contact-type deposits are thicker sulphidic zones at the contacts of the intrusions. PGEs are also the main commodity in these deposits, but they additionally contain minor Ni, Cu and low Co. The map of Figure 10 presents the locations of known deposits and occurrences: the Penikat intrusion in the west only hosts reef-type deposits, the Suhanko–Konttijärvi area is composed of several intrusion blocks (the so-called Portimo Complex) that host several contact-type deposits and one major-reef type deposit, while intrusions in the Posio–Taivalkoski area (the so-called Western Koillismaa Intrusion Complex) host two smaller contact-type deposits (Fig. 10). These deposits have not been in commercial production, but test mining for beneficiation tests has been conducted at Ahmavaara and Konttijärvi. In addition to PGE-Ni-Cu deposits, these types of intrusions also host chromium deposits (e.g., the Kemi mine) and vanadium deposits (e.g., the former Mustavaara mine).

4.1.3 Komatiite-hosted Ni+Cu+PGE deposits

Komatiites are high-magnesium volcanic rocks typically found in Archean and also Proterozoic cratons such as Western Australia, Southern Africa, Canada and Fennoscandia. They are known to host generally small but high grade (up to 8 wt%) Ni deposits, especially in Western Australia. Similar deposits but usually at much lower grades also occur in Zimbabwe, Canada and Finland. Most of the Finnish deposits occur in eastern Finland associated with the Archean Kuhmo–Suomussalmi greenstone belt and one in the Käsivarsi area, also associated with Archean komatiites (e.g., Makkonen et al. 2017). There are also a number of showings and two small deposits associated with Paleoproterozoic

Fig. 10. 2.44 Ga layered intrusion-hosted PGE-Ni-Cu deposits (background map © Maanmittauslaitos).

komatiites in the Central Lapland Greenstone Belt (Fig. 7A). Finnish deposits are generally small, ranging from 0.4 to 4 Mt (Ruossakero has a non-compliant resource of 35.6 Mt using a lower Ni cut-off grade), with about 0.5 wt% Ni, generally low but variable Cu grades from <0.01 to 0.4 wt% and 0.01–0.056 wt% Co. Sulphides mostly occur as disseminated sulphides, and some deposits also contain massive to semi-massive parts. Small-scale mining (20 000 t) was carried out at Tainiovaara in 1989 by Outokumpu Oy.

4.1.4 Sulphide mineralogy, Co distribution and beneficiation

As stated before, the sulphide mineralogy of magmatic Ni-Cu sulphide deposits is fairly simple, with pyrrhotite, chalcopyrite and pentlandite being the main sulphide minerals, of which pyrrhotite is the most abundant (Table 6). The amount of pyrrhotite in relation to other sulphides often increases from disseminated to massive sulphides. In disseminated sulphides, where the overall amount of sulphides is low, the ratio of pyrrhotite and chalcopyrite+pentlandite can be close to 1:1, increasing to 10:1 in more massive sulphides, except for some very high-grade deposits. Pyrite is a common minor phase, but it can be a major phase in some deposits. Other Ni sulphides such as millerite and violarite, which typically represent alteration products of pentlandite, are common trace phases, but can be major phases in some deposits (or in some parts of deposits). Other common trace phases include cubanite, mackinawite (low Co) and gersdoffite (5–15 wt% Co).

The Finnish orthomagmatic Ni-Cu deposits usually lack any Co-rich minerals or they occur only as trace phases, such as Co-bearing sulpharsenides. The typical Co carrier in these deposits is pentlandite, which is nearly always Co bearing. Average Co contents are typically 1–1.5 wt%, with similar concentrations also occurring in pentlandite alteration products (i.e., millerite and violarite). Typically, there is considerable variation within the deposit, but Co contents rarely exceed 3 wt%. Pyrrhotite is also often Co bearing, but contents are very low, usually 0.01–0.03 wt%. Pyrite is also commonly Co bearing, but the contents can vary even from grain to grain, from low contents of 0.01 wt% up to 2–3 wt%, averaging 1–1.5 wt%. As pentlandite has a much higher Co content compared to pyrrhotite, it carries 80–95% of the contained cobalt in most deposits (Table 6), the rest residing in pyrrhotite. In deposits in which pyrite is a major phase, it can account for up to 1/3 of the contained cobalt. The co-occurrence of Ni and Co is also reflected in the binary Ni-Co diagrams of Figure 11, which show Ni and Co concentrations in some intrusion-hosted and komatiite-hosted deposits and occurrences. The data extend to very low Ni and Co values, as they include analyses from both non-mineralized and mineralized samples. The data display some spread in Co values at a given Ni concentration and also some variation in the Ni:Co ratio, but overall, they show a very good correlation between Ni and Co.

Traditional flotation technology is usually used to treat sulphidic Ni-Cu ores. The ore is blasted, crushed and ground, and then fed to the flotation process, in which the ore is upgraded by floating the Ni and Cu-containing sulphide minerals while at the same supressing gangue minerals (silicates) and unwanted sulphides such as pyrrhotite and pyrite (Fe sulphides). This is done in a series of flotation tanks to upgrade and "clean" the concentrate, with the aim being to achieve a maximum level of metal concentration at an acceptable recovery percentage. For Ni-Cu ores, the suppression of pyrrhotite, which is often necessary in order to upgrade the Ni and Cu content, can be problematic, as it can result in the loss of Ni to the tailings. Furthermore, some Mg-rich alteration minerals, such as serpentine and especially talc, can cause problems in the efficient working of the flotation cells or by floating with sulphides, increasing the MgO content of the concentrate (talc) above the desired level, which can cause problems in the downstream processing of the concentrate at smelters.

The end product of the flotation process can be a bulk sulphide concentrate, usually containing a minimum of 8–9 wt% of combined Ni and Cu along with minor quantities of Co, typically 0.3–0.5 wt%, and precious metals (if present in the deposit). Bulk sulphide concentrates are still the norm today, as they are less complicated to produce and tend to have a relatively high recovery recovery percentage for metals. However, they are not accepted by all smelters and are less valuable than separate concentrates. As a consequence, many mines further process the bulk concentrate by flotation to produce separate Ni and Cu concentrates. An alternative to this is to do sequential flotation, whereby chalcopyrite is separated first to produce a copper concentrate, followed by pentlandite flotation to generate Ni(-Co) concentrate, as is done in Kevitsa mine.

Table 6. Sulphide mineralogy, average Co content of sulphides and Co comportment between sulphide phases for orthomagmatic Ni-Cu deposits. For data sources, see the references for mineralogical and beneficiation data.

	Sulphide mineralogy																
Intrusion-hosted	**Po**	**Pent**	**Cpy**	**Py**	**Mil**	**Viol**	**Haez**	**Cob**	**Gers**	**Asp**	**Cub**	**Bor**	**Vall**	**Sp**	**Gl**	**Mack**	
Eko	***	**	**	tr		*			tr		tr						
Ekojoensuu	***	**	**	*					tr		*			tr		tr	
Enonkoski	***	**	*	tr	tr	tr			tr								
Hanhisalo	***	**	**	*		tr					tr					tr	
Hitura	***	**	*-tr	tr							*		tr-**			*-**	
Kevitsa	**	**	**	*	tr		tr		tr		*			tr		*	
Rytky	***	**	*	(*)		tr		tr			tr			tr		tr	
Särkiniemi	***	**	**			tr (**)			tr								
Telkkälä	***	**	**	*		*			tr								
Vammala	***	**	*	*					tr		tr		tr	tr		tr	
Layered intrusions																	
Ahmavaara	***	**	**	**										tr	tr		
Konttijärvi	***	**	***	*-**	tr						tr	tr		tr			
Komatiitic																	
Vaara		*	*	**	***	*											
Peura-aho	***	tr	*	*		**											
Kauniinlampi	tr-***	**					**										
Hietaharju	***	**	**		*			tr	tr		tr					tr	

*** - ** = Major phases, * = Minor phase, tr = Trace amounts.

	Co content (wt. %)									Co distribution between phases (%)							
Intrusion-hosted	**Po**	**Pent**	**Cpy**	**Py**	**Mill**	**Viol**	**Gers**	**Haez**	**Mack**	**Po**	**Pent**	**Cpy**	**Py**	**Mill**	**Viol**	**Gers**	**Oth**
Eko	<0.01	1.22								4.2	95.8						
Ekojoensuu	0.03	1.16							0.67	11	89						
Enonkoski	0.03	1.46		0.27						13	87						
Hanhisalo	0.07	1.6	0.04	0.07						20.4	79	0.6					
Hitura	0.05	1.13															
Kevitsa	0.06	1.41	0.03	1.13					0.27	11	82	3	3				1
Rytky	<0.01	1.15								4	96						
Särkiniemi	0.046	2.84								17	82	0.5					
Telkkälä	<0.01	1.65								4	96						
Vammala	0.02	1.2							0.25	5	95						
Layered intrusions																	
Ahmavaara	0.01	2.23		1.21						3.5	65		31.5				
Konttijärvi	0.02	1.65		1.27	1.71					3	61		36				
Komatiitic																	
Vaara		0.42	<0.01	1.2	0.2	0.34					5		71	19	5		
Peura-aho	0.01	1				1.92				10					90		
Kauniinlampi	0.9							<0.01									
Hietaharju	0.085	1.52					5.77			26	64					10	

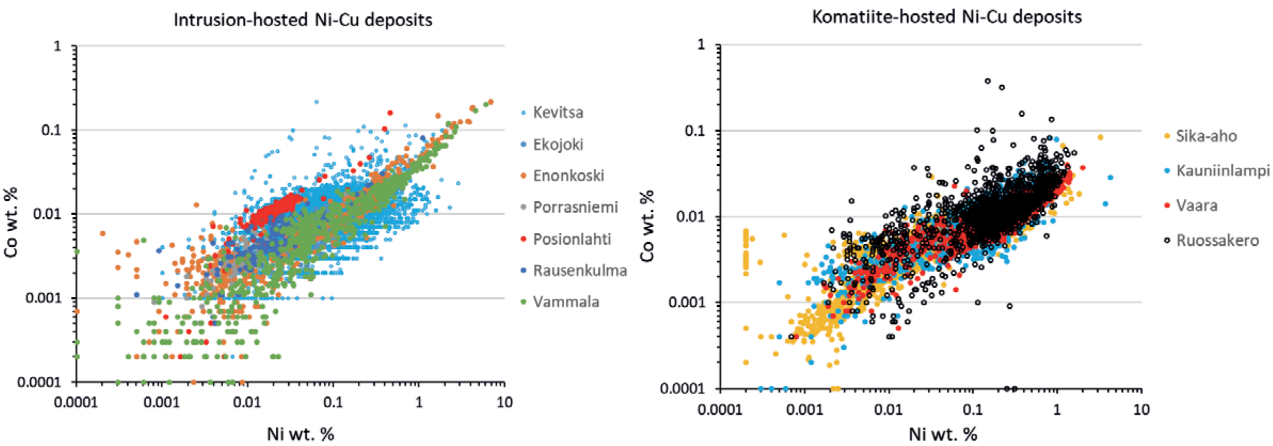

Fig. 11. Ni-Co correlation in some Finnish intrusion-hosted and komatiite-hosted Ni-Cu deposits and occurrences.

Generally, the aim for Ni concentrates is to have a concentrate containing at least 8% Ni and preferentially low Cu, as well as low amounts of deleterious elements such as As, Sb, Bi, Hg and Cr. Magnesium contents are often an issue, as they can be very high when dealing with low-grade Ni-Cu deposits (up to 20 wt% MgO, e.g., Pikinini 2016). Usually, it is desirable to have below 10% MgO in the concentrate (some smelters impose a penalty for >5% MgO in concentrate), and also to have a high Fe:MgO ratio (preferentially 5 and higher) and sufficient sulphidic iron.

Table 7 presents Ni-Cu concentrate data for past-producing Finnish Ni-Cu mines, the Kevitsa mine and also some test results for non-exploited deposits. Cobalt data are in some cases missing or incomplete, but what is evident is that despite pentlandite hosting over 80% of contained Co, cobalt recovery into concentrate(s) is generally around 50% and distinctly lower compared to Ni. An exception is the Kotalahti mine, where recoveries for all metals were very good due to the properties of the ore (coarse-grained sulphides). In addition, at some mines, e.g., Kotalahti and Enonkoski, a separate low-grade Ni concentrate was produced from pyrrhotite tailings and added to the Ni concentrate, resulting in some dilution of the concentrate grade but resulting in higher recoveries for Ni and Co (Lukkarinen 1960, Alopaeus et al. 1986). It is difficult to ascertain the reasons for the low Co recovery (compared to what mineralogical data suggest). It could be due to inadequate mineralogical data to carry out more precise calculations on ore mineral amounts and metal distributions, especially for a by-product such as Co, which could be carried in a high-Co-containing minor to trace phase possibly lost to tailings. In addition, the suppression of pyrrhotite and pyrite will have a stronger impact on Co compared to Ni. Finally, small amounts of cobalt also occur in both primary and secondary silicates (e.g., olivine, pyroxenes, serpentine minerals and chlorite), typically 50–200 ppm (0.005–0.02 %) (e.g., Herzberg et al. 2016, Marescotti et al. 2019), some of which can be incorporated in base metal analyses using the aqua regia digestion method. However, the cobalt recovery percentage from Finnish deposits is comparable to that from other Ni-Cu mines worldwide (Table 8).

A more thorough description of the flotation process and variables affecting it, as well as downstream processing technologies, is presented in chapter 5 of this report.

Table 7. Flotation concentrate grades and metal recoveries for some Finnish Ni-Cu(-PGE) mines and deposits.

Kevitsa	Cu %	Ni %	Co %	Pt+Pd+Au g/t	Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	2PGE+AuRec %
Cu-concentrate	22-24	018-1	<0105	15-18	25-30	25-35	3-9	74-86	4-6	2*	29-44
Ni-concentrate	1.2-3.2	715-10	013-016	7-8	30-40	25-35	3-9	6-13	64-70	42-55*	9-28
Total rec. %								89-93	68-74	45-60*	50-70
Kotalahti	Cu %	Ni %	Co		Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	
Cu-concentrate	22-25	113-116	107		30	29		75	1-2		
Ni-concentrate	015-1	6-615	125		39	27		20	91-92		
Total rec. %					95	98		95	>90	High**	
Enonkoski	Cu %	Ni %	Co		Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	
Bulk Ni-Cu conc.	215	912	14					~85	~80		
Vammala (Stormi)	Cu %	Ni %	Co		Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	
Bulk Ni-Cu conc.	5-6	8-9	134			21	9	75-80	75	65	
Hitura	Cu %	Ni %	Co		Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	
Bulk Ni-Cu conc.	1-3	4-7				20-27	6-12	37-77	59-84		
Non-exploied deposits, concentration test results											
Vaara, bulk Ni-Cu	Cu %	Ni %	Co		Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	
Best rec. %	1108	9154	1172		11.11	10.79	26.75	67.7	87.5	65.6	
Best grade	2172	2414	1448		17	29.5	10.8	53.6	75	53.4	
Ruossakero	Cu %	Ni %	Co		Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	
Bulk Ni-Cu	<015**	6-8	12		5-6	9-10	12		70	?	
Kaukua	Cu %	Ni %	Co	Pt+Pd+Au g/t	Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	Rec %
Bulk Ni-Cu	11	4-5	011**	~60			<4	90	40-50		43-77
Haukiaho	Cu %	Ni %	Co	Pt+Pd+Au g/t	Fe %	S %	MgO %	Cu rec %	Ni rec %	Co rec %	Rec %
Bulk Ni-Cu	917	5		25				89	64		65-80

*Calculated, **Estimated, Rec = Recovery.

Table 8. Cobalt recovery percentage from magmatic sulphide Ni-Cu mines and projects.

Mine/Project	Annual ore extraction (Mt)	Ni %	Cu %	Co %	Annual Co production (t)	Co recovery %
Fortaleza. Brazil	0.893	1.75	nd	0.026	219.1	94.6
Sudbury (Xstrata). Canada	1.884	1.46	3.23	0.07	473	36
Sudbury (Vale inco). Canada	5.612	1.45	1.61	0.04	593	26
Voisey's Bay. Canada	2.366	3.38	2.39	0.12	1585	56
Thompson. Canada	1.903	1.61	0.1	nd	158	nd
Raglan. Canada	1.206	2.39	0.69	0.07	561	66
Redstone. Canada	0.017	0.45	0.05	0.03	2.1	40
Shakespeare Canada	0.152	0.314	0.368	0.019	15	50
Jinchuan. china	8.3	1.3	2.4	0.01	450	55
Cosmos-Sinclair. Australia	0.769	2.69	nd	nd	396	nd
Savannah. Australia	0.637	1.52	0.74	0.08	439	88.3
Kambalda Group. Australia	1.04	2.88	0.23	0.06	137	22
Nkomari. South Africa	6.442	0.3	0.11	0.02	553	43
Santa Rira. Brazil	5.373	0.5	0.14	0.02	273	28.9
Munali. Zambia	0.625	0.75	0.14	0.06	100	25
Mimosa. Zimbabw	2.32	0.14	0.12	nd	86	nd

Data source: Mudd et al. 2011.

4.2 Black schist-hosted deposits

Black schists are a fairly common rock type in Finland, generally occurring in areas of volcano-sedimentary belts (Fig. 12). They represent subaqueous accumulations of fine-grained sediments (muds) containing >0.5 wt% carbon (graphite), sulphur (typically 5–10 wt%) and minor amounts of metals, typically Zn and Ni, lesser amounts of Cu and trace Co. Typically, concentrations are below 0.1 wt%, but can in some locations reach 0.1–0.4 wt% for Zn, Ni and Cu, and 0.01 wt% for Co (e.g. Västi 2008, Loukola-Ruskeeniemi 2011, Törmänen et al. 2011). More metal-enriched black schists and associated Sotkamo (Talvivaara)-type deposits and occurrences occur along a belt of metasedimentary rocks extending from Rautavaara to north of Lake Oulujärvi (Fig. 12). Typically, they contain 0.3–0.5 wt% Zn (up to 0.8 wt%), 0.2–0.3 wt% Ni, 0.1–0.15 wt% Cu, 0.01–0.02 wt% Co and 10 wt% S. Mineral resource estimates only exist for three deposits (Talvivaara, Pappilanmäki and Lintumäki, Appendix 1), and the most detailed information is only available from the Talvivaara deposit. However, even the Talvivaara deposit has not been reported for all commodities in place.

Black schists typically form laterally extensive but relatively thin (1–10 m thick) horizons. At Sotkamo, the metal-enriched black schist has been tectonically upgraded so that the current Kuusilampi ore body is 2.5 km long, 330 m thick and extents down to a depth of 600 m. The nearby Kolmisoppi ore body, which is currently under environmental assessment, is approximately similar in dimensions. The main sulphide minerals are pyrite and pyrrhotite, with relatively minor amounts of sphalerite, pentlandite, chalcopyrite, alabandite (MnS) and violarite. There is considerable variation in the pyrite-pyrrhotite ratio within the ore and also in the estimation of Co contents in the important Co-containing sulphides (Table 9). According to several studies, the main Co carriers are pyrite (63%) followed by pyrrhotite (26%) and pentlandite (11%), which is the most important Ni mineral, accounting for about 66–75% of Ni (Loukola-Ruskeeniemi & Heino 1996, Langwaldt & Kalapudas 2007, Riekkola-Vanhanen 2007, 2013, Kontinen & Hanski 2015).

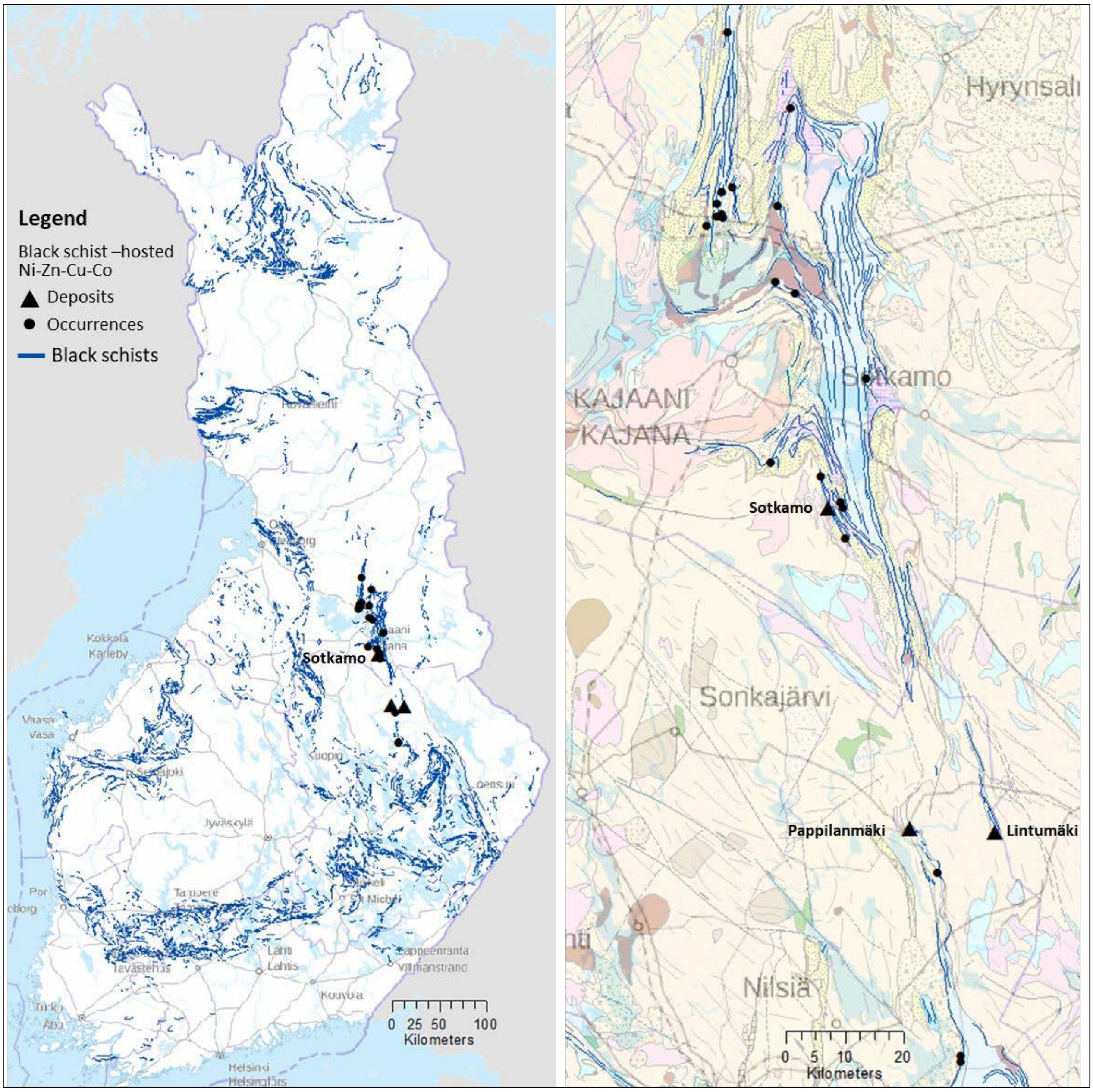

Fig. 12. Sotkamo-type black schist-hosted deposits and occurrences and the occurrence of black schists in Finland (background map © Maanmittauslaitos). The map on the right shows black schist-containing schist belts (blue) and associated black schist-hosted deposits and occurrences.

Table 9. Sotkamo sulphide mineralogy and Co comportment.

	Pyrrhotite	Pyrite	Sphalerite	Pentlandite	Chalcopyrite	Violarite	Alabandite
Amount (%)	9.3-20	0.57-36.9	0.3-1	0.03-1	0.36-0.56	0-0.6	0-0.25
Co content (wt. %)	<0.01-0.15	0.08-1.43	<0.01	0.36-1.9	<0.01-0.03	nd	<0.01
Average Co (wt. %)	0.05	0.39	<0.01	1/1/2021			
Co distribution (%)	26	63		11			

nd = Not determined.

Conventional flotation tests on the ore demonstrated that although metal recoveries into bulk sulphide concentrate were fairly good (74% Ni, 91% Cu and Zn and 89% Co), the Ni grade of the concentrate was low (<1 wt%) due to large proportions of Fe sulphides, and the concentrate also had a relatively high carbon content (e.g., Langwaldt & Kalapudas 2007, Riekkola-Vanhanen 2007). As a result, a bioheapleach process was developed to extract metals: Ore is extracted from an open-pit mine, crushed, agglomerated (to consolidate fine particles with coarser particles, creating sufficient pore spaces in the heaps for the circulation and aeration of leach solution), stacked as 8 × 400 × 1200 m heaps and leached with acid leach solution and with the aid of bacteria for 18 months. Ten percent of the pregnant leach solution (PLS) goes to metal extraction, where metals are sequentially precipitated (Cu -> Zn -> Ni-Co) as sulphides (Fig. 13). Pilot tests also demonstrated early recovery of Ni and Zn, whereas Cu and especially Co displayed much lower leaching rates (Riekkola-Vanhanen 2007). This has been attributed to the electrochemical properties of sulphide minerals, resulting in different oxidation–reduction properties of oxidation and dissolving into solution, while chalcopyrite (Cu host) and pyrite (major Co host) only start to oxidise after most of the other sulphides have been exhausted (Riekkola-Vanhanen 2013, Tuovinen et al. 2018). Leaching continues in secondary heaps for 5–7 years to recover as much of the remaining metals as possible.

Terrafame plans to start producing Ni and Co sulphates in 2021 as battery chemicals for rechargeable Li-ion batteries. This will be carried out by pressure leach of Ni-Co sulphides produced from the heapleach process in autoclaves at 15–20 bar and 150–200 °C. In the process, sulphidic sulphur is oxidised to sulphate sulphur, releasing metals into solution and producing solid Fe-rich residue (Fig. 14). The solution is purified and directed to Co extraction using Co-specific kerosene-based organophosphorus acid reagent. The resulting cobalt sulphate solution is filtered and the final Co sulphate is crystallized by steam evaporation at 50–60 °C. Nickel is extracted from the raffinate solution using a Ni-specific kerosene-based carboxylic acid reagent, and the resultant solution is filtered and the final Ni sulphate is crystallized. The Fe residue from the autoclave, which also contains some Ni, Co and Zn (2%), can be deposited in the secondary heaps for metal extraction (Ramboll 2018). The autoclave pH will be controlled with ammonium, which will be precipitated as ammonium sulphate (fertiliser) as a by-product.

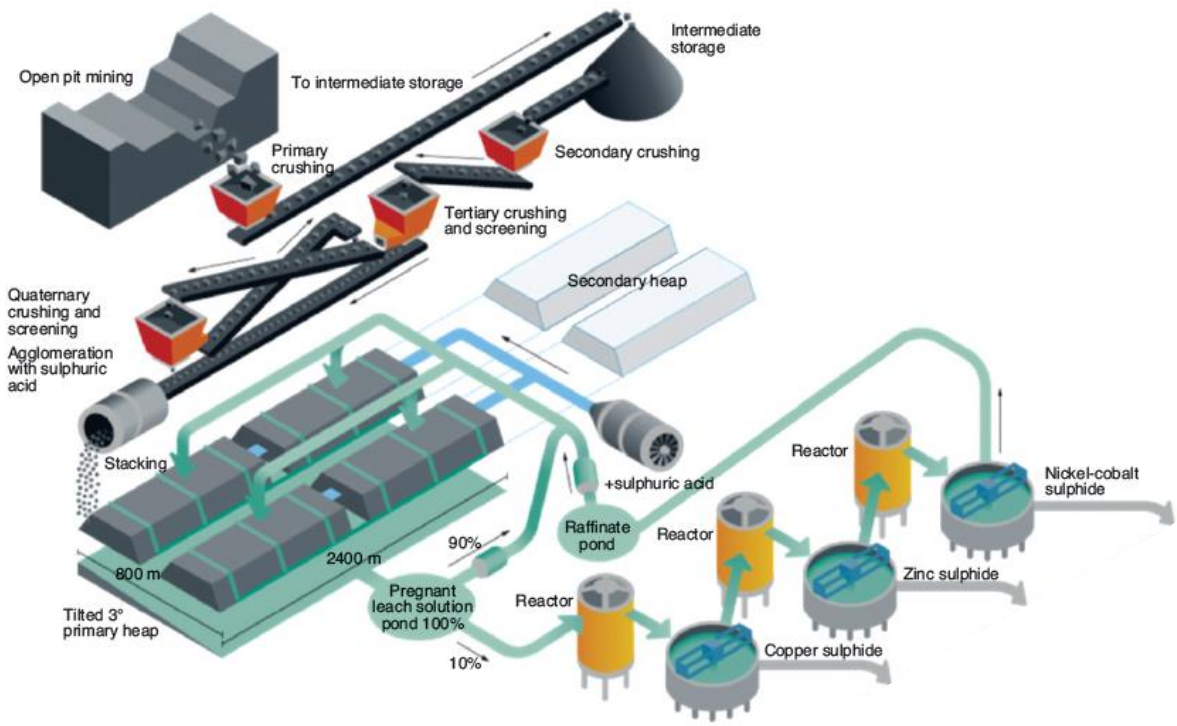

Fig. 13. Schematic diagram of the Terrafame Sotkamo bioheapleach process (modified after Saari and Riekkola-Vanhanen 2012).

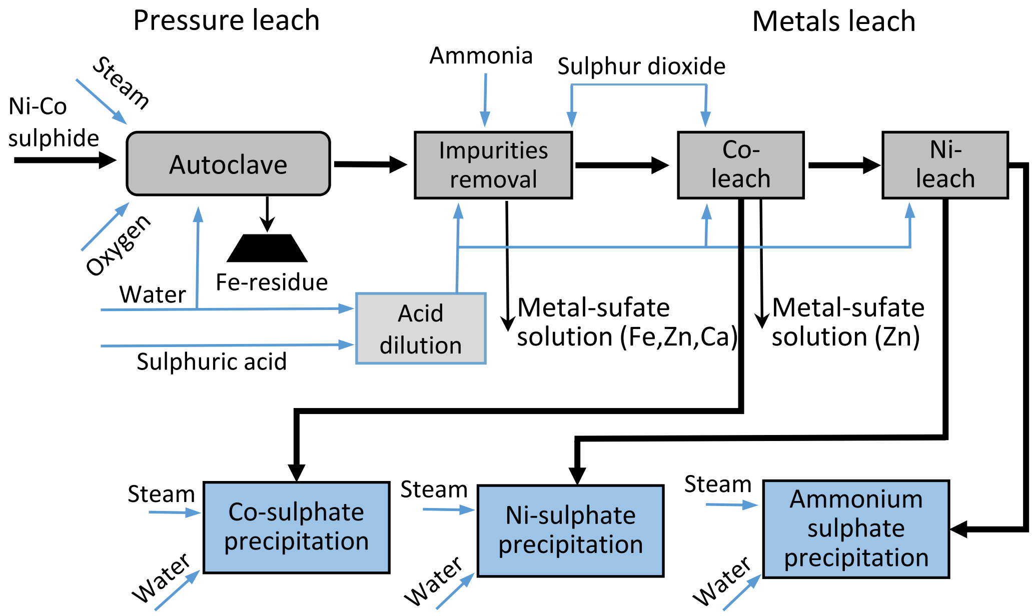

Fig. 14. Flow sheet of the Terrafame Sotkamo sulphate production process.

4.3 Outokumpu-type Cu-Zn-Co-Ni VMS deposits

The Outokumpu-type Cu-Zn-Co-Ni ores represent a distinct type of volcanogenic massive sulphide (VMS) deposits, typified by their relatively high Ni-Co contents. VMS-type Cu-Zn deposits are formed in volcanically active areas at or below the sea floor, typified by mid-ocean spreading centres, such as the Mid-Atlantic Ridge, or collisional subduction zones – volcanic arcs present in the Western Pacific ("ring of fire"). In these areas, magmatic activity drives the sea water circulation system, resulting in hot fluids discharging on the sea floor and precipitating metals as sulphides. Cobalt-enriched VMS deposits are rare, with some similar, ophiolite-associated (tectonically displaced fragments of ocean floor) deposits occurring in Canada and China and sediment-hosted deposits in Canada and Japan.

In the Outokumpu district, the ore deposits are associated with the so-called Outokumpu assemblage, which consists of a package of serpentinites, carbonate rocks, skarn, quartzites and associated black schists, tectonically emplaced with the surrounding metasedimentary rocks (Fig. 15) (Kontinen et al. 2006, Peltonen et al. 2008). There have been four past-producing mines in the Outokumpu region, of which the Kylylahti mine was closed in late 2020. Of these mines, the Outokumpu (Keretti) Cu-Zn mine was by far the most important, with 29 Mt of ore, producing 956 000 t of Cu, 226 000 t of Zn and 54 000 t of Co. Altogether, the mines produced 1.21 Mt Cu, 333 000 t Zn, 75 000 t Co, 9 800 t Ni and significant amounts of Au and Ag.

There are eight known small unmined deposits in the Outokumpu area, ranging from 0.1 to 3.4 Mt in size, with Saramäki, Hautalampi and Perttilahti being >1 Mt deposits (Fig. 15). Of these, Hautalampi represents what is called a parallel Ni-Co ore, low in Cu and Zn, which also occurs at Vuonos (mined) and Kylylahti. These contain some 15 000 t of Co, representing 3% of the known total Co tonnage in Finnish deposits.

Outokumpu-type ores typically occur as fairly sharply bounded massive to semi-massive sulphide ores, sometimes with associated disseminated parts. Pyrrhotite is the dominant sulphide mineral, except at the Outokumpu and Kylylahti mines, where there are also pyrite-dominant parts. In addition to pyrrhotite, chalcopyrite and sphalerite are other main sulphide minerals, while cobaltpentlandite is an important minor phase in Outokumpu-type deposits. Trace minerals include cobaltite, cubanite, mackinawite and stannite. Compared with orthomagmatic Ni-Cu deposits, cobalt contents are higher in many sulphide minerals. Distinct features are the occurrence of cobaltpentlandite, in which most of the Ni is replaced by Co, an approximately ten times higher Co content in pyrrhotite (0.1 wt% vs. 0.01 wt%) and relatively high Co also occurring in sphalerite (0.25–0.6 wt%). Pyrite has comparable Co contents, but can locally be more Co-enriched (up to 8 wt%) (Table 10). Cobaltpentlandite is the most important Co carrier in the Outokumpu deposits, although the amounts are fairly low, generally 0.5–1% of the ore (note that these are absolute amounts and not sulphide fraction compositions, i.e., massive to semi-massive ores would have more Co pentlandite compared to disseminated sulphides). Cobaltpentlandite typically accounts for more than 50% of contained Co, with pyrrhotite accounting for the rest. Some deposits contain pyrite-rich parts, and in these, pyrite can account for up to 90% of contained Co. In more mineralogically heterogeneous deposits such as Kylylahti, the distribution of Co varies greatly between different ore types (Table 10). Siegenite or linnaeite–polydymite ($(Ni,Co)_3S_4$) occurs in the Hautalampi deposits and in the Ni-Co concentrate, in addition to Co-bearing pentlandite (Table 10) (Meriläinen et al. 2009).

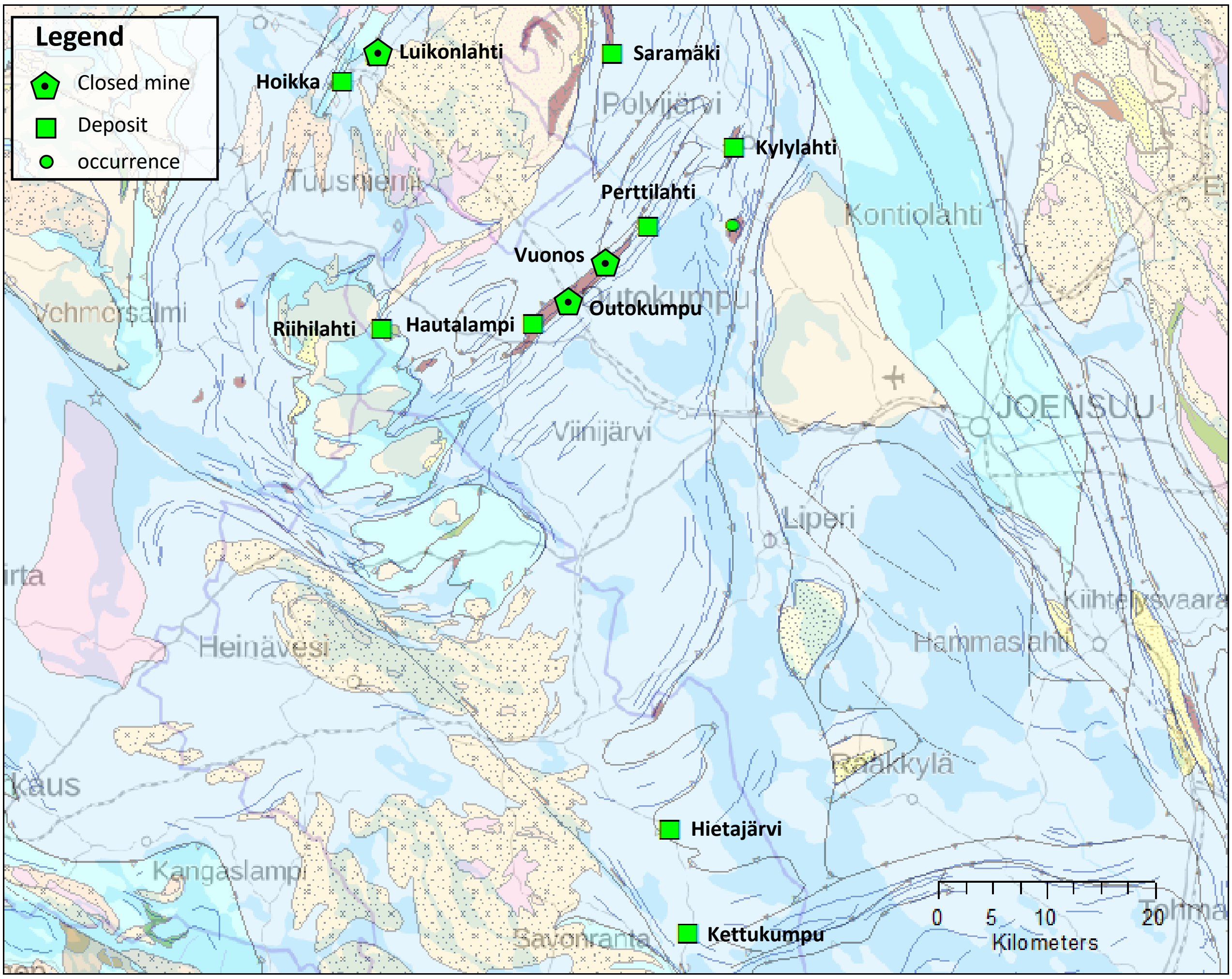

Fig. 15. Outokumpu-type past-producing mines, deposits and occurrences. The background geological map (Bedrock of Finland – DigiKP) displays associated serpentinites (dark brown) and black schists (thin blue lines) and surrounding metasediments (blue colours) (background map © Maanmittauslaitos).

Table 10. Sulphide mineralogy for Outokumpu-type VMS deposits. See the references for mineralogical data sources.

	Sulphide amounts									
Deposit	**Po**	**Py**	**Cpy**	**Sp**	**Co-Pent**	**Cob**	**Cub**	**Mack**	**Sta**	**Sieg**
Outokumpu	23	21	11	1.7	0.5		tr	tr	tr	
Vuonos	40	tr-*	7.3	3.2	0.3		tr	tr	tr	
Kylylahti	major	major	major	minor	tr-minor	tr-minor	tr	tr	tr	
Kylylahti*	4-35	2-52	1.7-17	0.2-4.8	0.1-1.3					
Saramäki**	18-50	tr	1.2-3	0.1-2.7	0.3-0.5	tr				
Hautalampi	major	minor	major	tr-minor	minor	tr	tr-minor	tr	tr	minor

*Kylylahti has considerable variation in the amounts of sulphide minerals and in the cobalt distribution. **Amount of cobaltpentlandite estimated. Sta = Stannite (Cu2FeSnS4).

	Co content (wt. %)						Co distribution (%)					
Deposit	**Po**	**Py**	**Sp**	**Co-pent**	**Cob**	**Sieg**	**Po**	**Py**	**Sp**	**Co-Pent**	**Cob**	**Sieg**
Outokumpu	0.1	0.7	0.25	33-45			6-7	37-45	1	46-56		
Vuonos	0.11	3.25	0.3	20-45			13-30		5-7	64-82		
Kylylahti	0.09	1.24	0.63				2.2	75	0.9	13.1	8.1	
Kylylahti*	<0.01-0.13	<0.01-8.68	0.03-0.72	10.8-52.7	30		0.1-8	13-90	0.2-18	6-77	0-47	
Saramäki**	0.16			33			14-45			55-86		
Hautalampi	<0.02			5.14		24.9				62		38

Production data, for example concentrate grades and metal recovery percentages, are patchy for Outokumpu-type deposits. In most cases, the metal production data in the GTK database are based on a report by Puustinen (2003), in which the metal production is determined from the amount of feed to the flotation plant and the metal content of the feed, representing the in situ metal content (t), and the amount of metal produced (t) assumes 100% recovery, at least from some deposits. Table 11 summarises the available data from some mines and flotation test results from unmined deposits. The past-producing Outokumpu, Vuonos and Luikonlahti mines all produced separate Cu, Zn and Co concentrates. Data for the Outokumpu mine include data from concentrate studies (Hänninen 1977, 1985), in which recoveries were reported as the mineral recovery from a relatively limited number of concentrate samples, and metal recovery was calculated from the reported metal production, i.e., from data in the report by Puustinen. Comparing these, the mineral recovery would indicate higher recoveries, especially for Cu, but the calculated metal recovery is very similar for all three past-producing mines and indicates fairly good recovery for Co (80–85%) and Cu (80–88%), but lower for Zn (55–72%). Concentrate grades are also rarely reported, especially for Co, but available data indicate fairly low grades from 0.5 to 1.5 wt%. The Boliden Kylylahti mine produces Au concentrate, a Cu-Au concentrate and a Zn concentrate from the more Zn-rich part of the ore. At the start of mine production, a low-grade Ni-Co concentrate was produced with 0.8 wt% Co and 0.5 wt% Ni, which was stored at the mill site. Some Ni (~0.3 wt%) and Co (~0.4 wt%) has also been reported in high sulphur tailings stored in a separate tailings pond. The combined recovery percentage for these two concentrates is indicated by the higher recovery values (77–88%) in Table 11. These could prove to be significant in the future, as they contain a significant Co tonnage (10 000 t). In recent years, the mine has produced a saleable, higher grade Ni-Co concentrate, although at much lower calculated Ni-Co recoveries (as indicated by the low-end percentages in Table 11) (Boliden 2020a). The zinc circuit is used to produce Ni-Co concentrate, and any zinc present will report to the sulphur flotation, being deposited with the high sulphur tailings (Fig. 16). FinnCobalt flotation tests on the Hautalampi Ni-Co-Cu deposit indicate that commercial Cu and Ni-Co concentrates can be generated at ~80% recoveries (FinnCobalt 2019). Even higher recoveries of up to 90% were reported in earlier tests by Belvedere (Meriläinen et al. 2009) The Ni-Co concentrate can be sold to smelters or treated by leaching-solvent extraction–precipitation to produce battery chemicals.

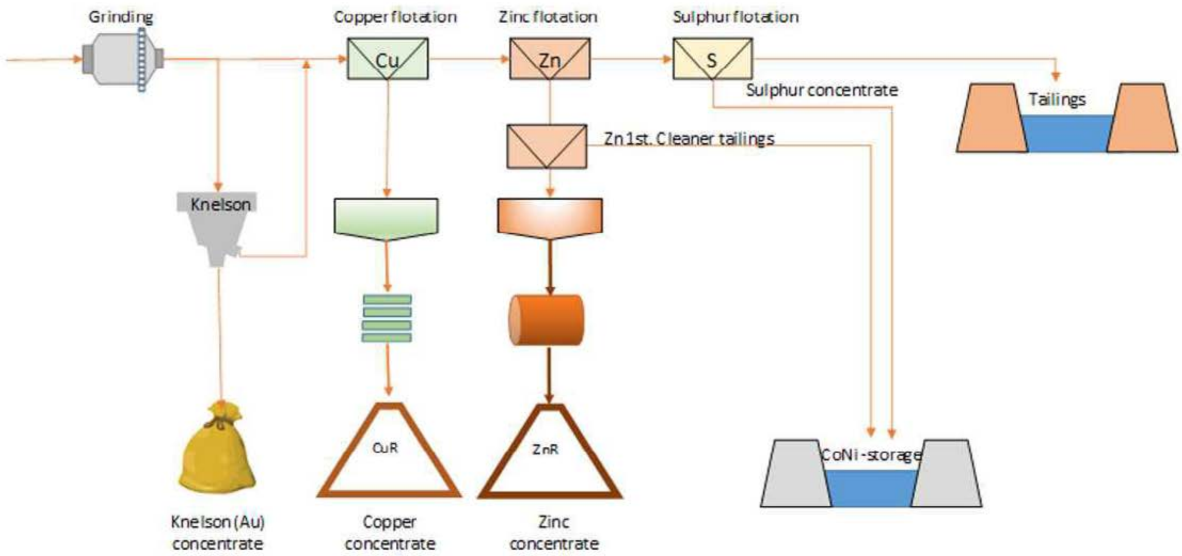

Fig. 16. Simplified process flow sheet for the Kylylahti mine (from Boliden 2019).

Table 11. Concentrate data for Outokumpu-type past-producing mines, the Kylylahti mine and test results from unmined deposits.

	Concentrate grade						Mineral recovery %				
Outokumpu	Cu %	Zn %	Co %	Ni %	Fe %	S %	Cpy	Sp	Co-pent	Po	Py
Cu concentrate	20-26	0.9-1.3	0.17-0.21	0.1	30-40	33-36	92-94	20-24	7-8.5	5.5-9	10-12
Zn-concentrate	0.5-0.7	29-42	0.18-0.2	0.1	21-34	34-35	0.1	15-32	0.1-0.3	0.5-1	0-0.2
Co-concentrate	0.3	0.5-1	0.5	0.3	45-49	36-37	3.5	37-62	78-80	74-85	67-90
							Metals recovery %				
Outokumpu							Cu rec %	Zn rec %	Co rec %	Ni rec %	
Recovery % based on production data							88	72	79		
Luikonlahti							79	55	85	10	
Vuonos*							82	73	82	100	
Cu concentrate	17-25	2	0.1-0.2								
Zn-concentrate	0.2-1	34-45	0.2								
Co-concentrate	0.1-0.2	0.2	1-1.4								
Kylylahti											
Cu concentrate	17-19						92-96				
Zn-concentrate		42-46						31-49			
Co-concentrate			?	?					18-87**	31-77**	
Non-exploted deposits. concentration test results											
Hautalampi											
Cu-concentate	26.2			0.5			79				
Ni-Co concentrate			1.5	6.2					78	80	
Saramäki											
Cu-concentate	15-25	0.6-3.5	0.07-1.3				73-82	0.5-5	1.5-14.5		
Zn-concentrate	0.1-0.3	10-41	0.3				1-3	92-64	4-64		
Hietajärvi											
Cu-concentate	25						80				
Ni-Co concentrate	1		~10	5			5		60-70	30-40	

*Production data for Vuonos are highly variable. depending on the source. and the calculated 100% recovery for Ni is unlikely. ** See text for explanation.

4.4 Supracrustal-rock-hosted Au-Cu-Co, e.g., Kuusamo type

The Kuusamo-type Au-Co-Co deposits are usually classified as metasedimentary rock hosted Co-Cu-Au deposits or Blackbird-type (Slack 2013, Slack et al. 2017), or as orogenic gold deposits with an atypical metal association (e.g., Eilu 2015). In order to separate these deposits from sediment-hosted Cu-Co deposits, we use the term supracrustal-rock-hosted Au-Co-Cu deposit or Kuusamo-type for short. In contrast to the previous deposit types, which are syngenetic, i.e., deposits formed via the same geological process that formed their host rocks, the Kuusamo-type deposits are epigenetic, i.e., they formed some time after the formation of their host rocks, generally related to tectonic–metamorphic events mobilizing metamorphic hydrothermal fluids that formed the deposits at favourable structural sites.

As the name implies, Kuusamo-type deposits mainly occur in the Kuusamo area, although the deposits of the Mawson Resources Rajapalot area have many similar features and are included here as belonging to Kuusamo-type deposits. The Kuusamo occurrences are hosted by a clastic sedimentary-dominated (quartzites) sequence deposited between 2.35 and 2.21 Ga, which also contains basaltic lavas, in the Kuusamo schist belt. The deposits in the Kuusamo belt occur at locations where faults intersect with regional anticlines (favourable sites). Au-Cu-Co deposits occur as sheets and pipes of mainly disseminated sulphides and sulphide veins, locally grading into 1–2-m intervals of massive to semi-massive sulphides (Vanhanen 2001). The main ore minerals are pyrite, pyrrhotite and chalcopyrite (in more Cu-rich deposits), common minor phases

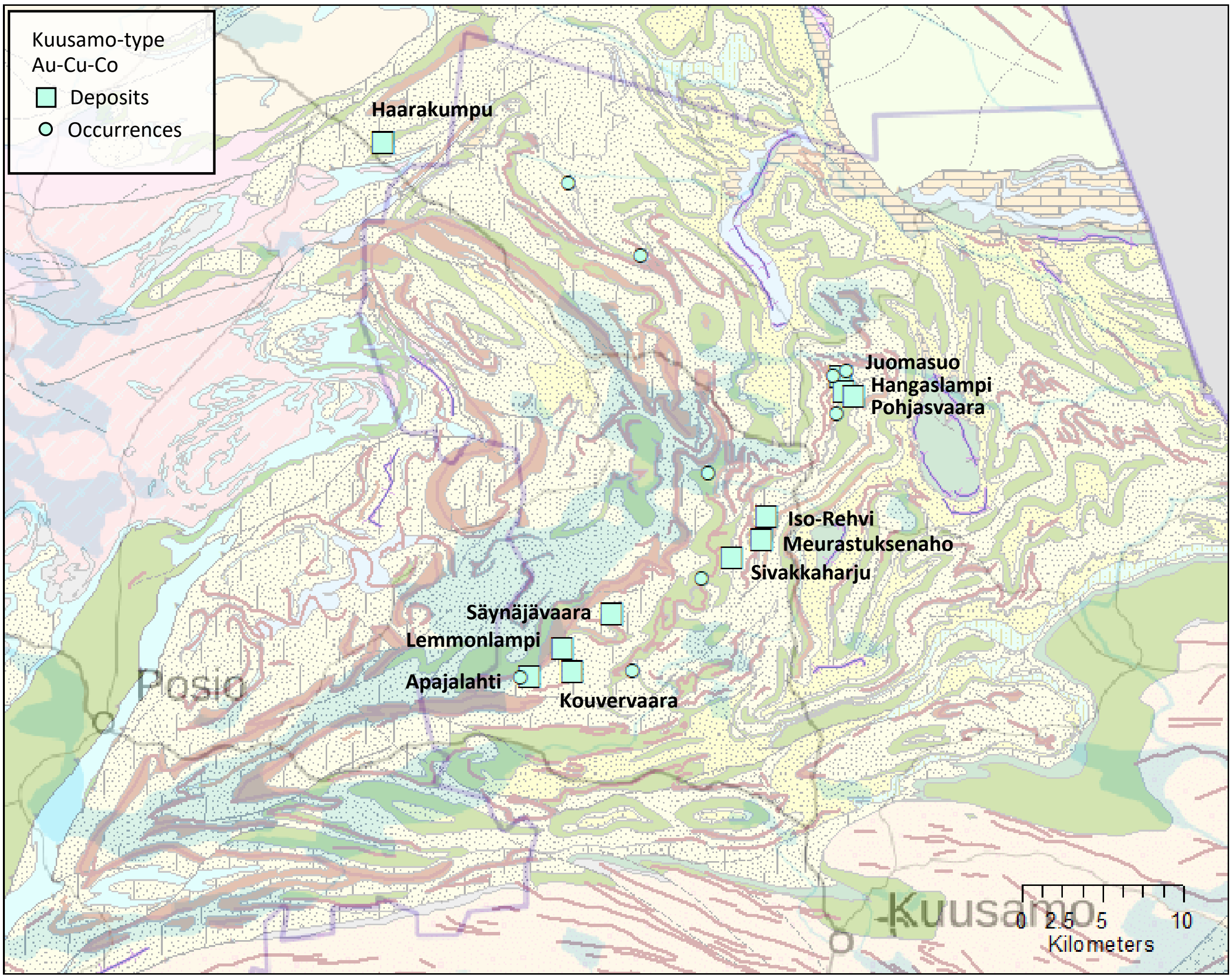

Fig. 17. Location of Kuusamo-type deposits and occurrences. The background geological map displays Kuusamo schist belt quartzites (various yellow colours), basaltic lavas (green) and mafic dykes (brown). (Background map © Maanmittauslaitos)

are cobaltite and cobaltpentlandite, and common trace phases include molybdenite, gold and various Bi and Te minerals.

Kuusamo-type deposits have quite variable metal contents and associations, ranging from dominantly Au deposits with low <0.05 wt% Cu and Co (e.g., Apajalahti) to Au-Cu-Co deposits with 0.1–0.3 wt% Cu and 0.05–0.2 wt% Co (e.g., Juomasuo, Meurastuksenaho) and Cu-Co deposits with low to nil Au (e.g., Haarakumpu and Lemmonlampi). They are often also zoned in relation to the occurrence of metals, with Co occurring in the outer parts of the deposits or even forming separate mineralized zones adjacent to Au-Cu(-Co) zones (e.g., Juomasuo). The deposits are relatively small, with ore tonnage ranging from 0.04 to ~5 Mt.

Cobalt pentlandite and cobaltite are the main Co phases (Table 12). Cobaltpentlandite is Co-rich in all deposits with available data, containing 45–60 wt% Co. It is a minor to trace phase, occurring mostly as "flames" in pyrrhotite and sometimes as a granular type. Cobaltite is also a minor to trace phase, occurring as grains and grain clusters, typically in the more Co-rich parts of deposits (Vanhanen 2001). Pyrite is also Co-bearing, with a variable Co content of 1–3 wt%, but in some deposits it is very Co-poor (Hangaslampi and Sivakkaharju). Pyrrhotite is also relatively Co-enriched, typically containing ~0.2 wt% Co, i.e., higher than in orthomagmatic Ni-Cu deposits and comparable with Outokumpu-type deposits, except for the Hangaslampi deposits, where it is Co-poor. Quantitative data on the Co distribution are only available from the Juomasuo deposits. The data indicate a highly variable comportment of Co between different sulphide and sulpharsenide minerals. Cobaltite is generally the most important Co carrier, accounting for 36–55% of Co. The fraction of Co in cobaltpentlandite, pyrrhotite and pyrite is highly variable, as seen in Table 12. Based on the data from Juomasuo and compositional data from other deposits, it can be surmised that in addition to Co-rich phases such as cobaltite and cobaltpentlandite, both pyrite and pyrrhotite contain a significant proportion of Co. The Au-Co deposits in the Rajapalot area are dominated by pyrrhotite, with subordinate pyrite and minor to trace amounts of cobaltite, cobalt pentlandite, pentlandite, linneaite and chalcopyrite, and with cobaltite being the main Co-bearing mineral (Mawson Resources 2020, Taipale 2018).

Preliminary beneficiation tests have been conducted on a few Kuusamo deposits (Table 13). These included the generation of both bulk Au-Co-Cu concentrates and separate Co and Cu concentrates. These resulted in relatively low Co and Cu grades of 0.5–3% and highly variable Au grades, generally 70–80 g/t for more Au-rich deposit types (e.g., Juomasuo, Hangaslampi) and a few grams per tonne

Table 12. Sulphide mineralogy, Co contents of sulphides and Co comportment between sulphide phases for Kuusamo-type Au-Cu-Co deposits. See the references for mineralogical data sources.

	Sulphide amounts										
Deposit	**Po**	**Co-Pent**	**Cpy**	**Py**	**Cob**	**Linn**	**Asp**	**Bor**	**Gl**	**Mol**	**Bi-Te**
Juomasuo	***	*	**	*-***	*					tr	tr
Meurastuksenaho	***	*	**	***	**			tr		tr	tr
Kouvervaara	***	*	**	*	*		tr				tr
Hangaslampi	*	tr	*	***	*-tr				tr	tr	tr
Sivakkaharju	tr	tr	*	***				tr			tr
Konttiaho	***	*	*	***	*				*	*	tr
Haarakumpu	***	*	*	***							
Rajapalot	***	*-tr	*	*	*	*-tr					
	Co content (wt. %)					**Co distribution (%)**					
Deposit	**Po**	**Co-Pent**	**Cpy**	**Py**	**Cob**	**Po**	**Co-Pent**	**Py**	**Cob**		
Juomasuo	0.19	49.9	0.002	1.51	32.7	8-20	8-39	11-48	36-55		
Meurastuksenaho	0.29	60.7	0.2	1.3	34.5						
Kouvervaara	0.2	58	0.02	0.95	33.5						
Hangaslampi	<0.01	55.1		<0.01	33.6						
Sivakkaharju		45		0.03							
Konttiaho	0.09	52.3		1.85							
Haarakumpu	0.3			0.3-3							
Rajapalot	0.25	45	0.05	<0.01-3	17						

for lower Au-grade deposits. It should be noted that the Meurastuksenaho tests were conducted on low-grade material (0.15 g/t Au, 0.09 wt% Co and 0.04 wt% Cu). Recovery percentages also vary, ranging from 50% to over 90% for Co and Cu and 75–85% for gold. A bulk sulphide concentrate would catch a high proportion of Co, which is also hosted by Fe sulphides, as mineralogical data show, but whether this low-grade As-containing Co concentrate would be commercially viable or attractive for pyrometallurgical treatment (i.e., smelters) is unknown. However, it could be amenable to hydrometallurgical treatment (Vartiainen 1984, Vanhanen 1989, Dragon Mining 2013).

Table 13. Flotation test results for Kuusamo-type deposits.

	Concentrate grade							Metals recovery %			
	Co %	Cu %	Ni %	Au g/t	As %	S %	Fe %	Co rec %	Cu rec %	Au rec %	As rec %
Juomasuo											
Bulk conc	0.94-2.84	0-2.92	0.10	55-77	0.34-1.55	40	45	62-85	0-84	78-84	60
Meurastuksenaho											
Co-concentrate	1.4	0.44		1.2	0.14	43	43.5	77	44	50	
Cu-concentrate	1.1	1.7		7	0.15	31	29.5	16	48	35	
Co-Cu bulk conc.	1.3	0.7			0.14	40.5	40.5	94	91-92		
Haarakumpu											
Co-concentrate	0.87	0.14		0.04		46		66.2	4.5		
Cu-concentrate	0.53	23.1		1.44		39		4.85	87.9		
Pyrrhotite conc.	0.42	0.12				37		11.6	1.4		
Hangaslampi											
Bulk conc.	0.55			80	0.08			50		75	50

4.5 IOCG deposits

Iron oxide-copper-gold deposits mostly occur in northern Finland, most notably in the Kolari area, where there are approximately 30 Fe deposits and occurrences, of which the Hannukainen and Kuervitikko deposits are the most significant (Niiranen et al. 2007, Moilanen & Peltonen 2015). At least some the deposits contain Cu (~0.2 wt%) and Au (0.07–0.2 g/t), and also 0.01–0.053 wt% Co. The small Rautuoja deposit also contains minor Cu-Au-Co contents, but Co is not included in resource estimations and its content was estimated from drill core analytical data (Korvuo 1982a), being only indicative. The Misi region contains some 10 Fe deposits and occurrences, also classified as IOCG type, four of which have been mined. Some of the deposits have sulphur-bearing parts that contain low amounts of Cu and Co (≤0.01 wt%), but no resource data are available (Niiranen et al. 2005) and they will not be discussed further. The Vähäjoki deposit is located near Tervola, in the southern part of the Peräpohja schist belt. The deposit consists of more than 30 (14 larger) Fe ore lenses along two N–S-trending zones (Korvuo 1982b, Liipo & Laajoki 1991). Copper, gold and cobalt contents are comparable with the Kolari deposits.

The Finnish IOCG deposits are metamorphic–hydrothermal replacement deposits where the original host rocks have been replaced by ironstone (Fe ores) and skarn rocks (amphibole–pyroxene-rich rocks). The deposits are associated with shear zones (Kolari area) and carbonate rocks (Vähäjoki). Disseminated sulphides are mostly pyrite and pyrrhotite, with lower amounts of chalcopyrite. The Vähäjoki deposit also contains cobaltite, arsenopyrite and linnaeite (Kiviniitty 2016, Turunen 2007). Sulphides occur as disseminations, thin veins and small massive lenses.

Available mineralogical data (Risto et al. 2010, SRK Consulting 2014) indicate that both pyrite and pyrrhotite contain elevated Co contents at Hannukainen, and chalcopyrite also contains minor Co (Table 14). As there are few indications of discrete Co minerals being present in any of the Kolari area deposits, it is probable that Fe sulphides also host most of the Co in other deposits in the area.

For the Hannukainen deposit, pyrite contains 57% cobalt, 41% pyrrhotite and under 2% chalcopyrite. No quantitative data exist for sulphide mineral amounts in the Vähäjoki deposits, but the common occurrence of cobaltite and the presence of linneaite could indicate that these Co-rich minerals probably host a significant proportion of contained cobalt. Beneficiation tests have only been conducted for Hannukainen, and in that case for Fe concentrate and Cu-Au concentrate. Cleaning of the Fe and Cu-Au concentrates produces pyrite- and pyrrhotite-rich concentrates, i.e., sulphur-rich tailings that would be stored in a separate tailings pond.

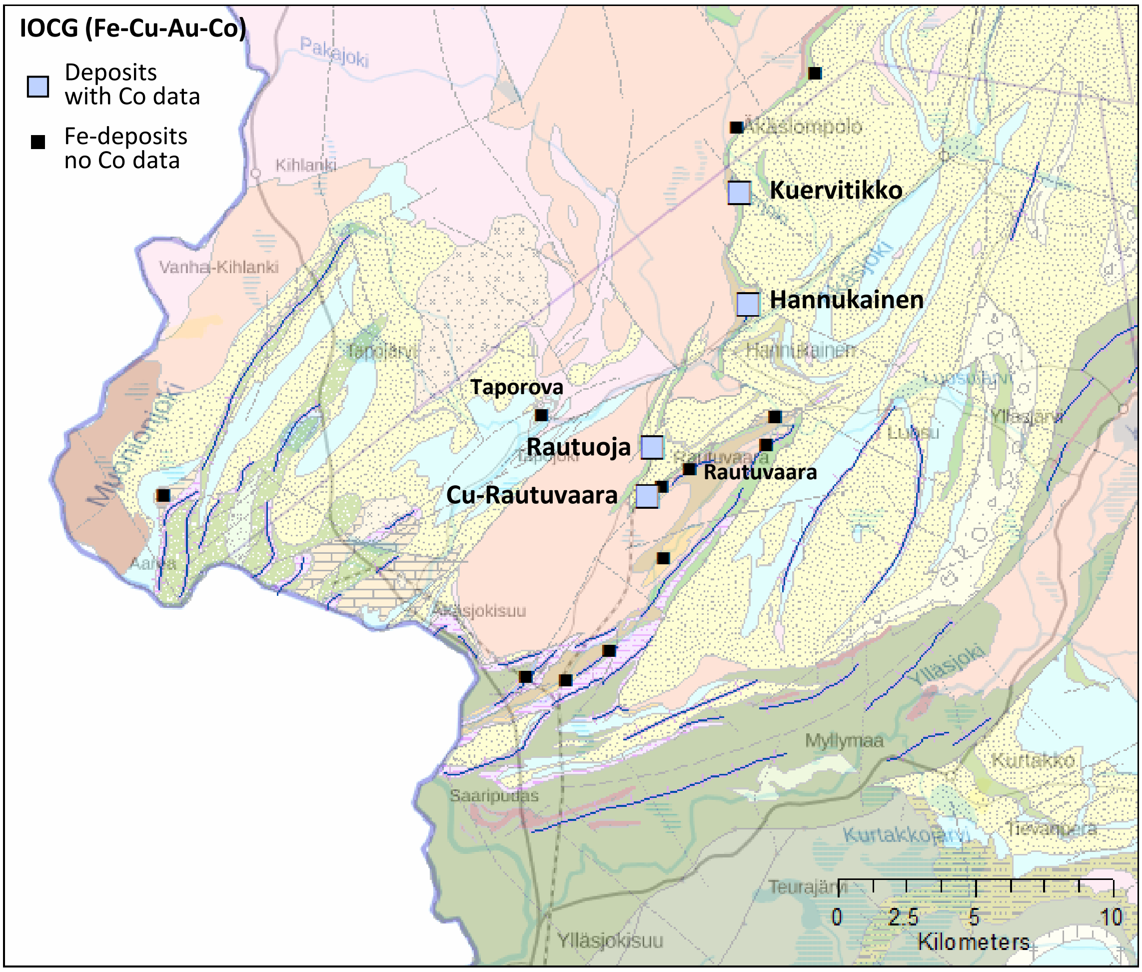

Fig. 18. Location of the Kolari area IOCG deposits. Most of the deposits are hosted by the Rautuvaara formation, located between quartzites in the east (yellow colours) and granitic intrusions in the west (pink-orange colours) (background map © Maanmittauslaitos)

Table 14. Sulphide mineralogy, Co contents of sulphides and Co comportment between sulphide phases for IOCG deposits. See the references for mineralogical data sources.

Deposit	Po	Py	Cpy	Cob	Asp	Linn	Mol	Mack	Pent
Hannukainen	***	**	*				tr		
Kuervitikko	*	**	*						
Cu-Rautuvaara	**	*	**				tr		tr
Rautuoja	*	*	*						
Vähäjoki	*	***	*	*	*-tr	*-tr		tr	
	Co-content (wt. %)						Co-distribution (%)		
Deposit	Po	Py	Cpy	Cob	Asp	Linn	Po	Py	Cpy
Hannukainen	0.1-0.2	0.1-0.6	0.056				41	57.2	1.8
Vähäjoki		0.1	<0.01	31.1		35.9			

Pyrite concentrate could possibly be sold on a commercial basis or at least the company could investigate such an option. Based on the SRK mine production model, the total amount of high-sulphur tailings would be 11 Mt. Based on the data of SRK Consulting (2014) and Risto et al. (2010), the high-S tailings have calculated grades of 0.2 wt% Co, 0.36 wt% Cu and 0.7 g/t Au, assuming that the tailings only contain pyrite and pyrrhotite. These figures should be considered as only indicative, as little data exist on the actual metal contents of the py-po tailings. However, as 98% of the cobalt is contained in pyrite and pyrrhotite, it can be surmised that most of the contained Co would end up in the high-S tailings and the contained Co tonnage would be in the range of 25 000–29 000 t over the LOM. Even if the tonnage is overestimated, it is significant, and further studies could be undertaken to evaluate the exploitation options for this stream. Pilot plant tests at the GTK pilot plant in 2018 indicated cobalt grades between 0.2–0.3% in pyrite concentrate (Knuutinen 2018).

4.6 Other deposit types

There are a number of other deposits/occurrences that, based on mostly historic drilling data by GTK and Outokumpu Oy, contain at least some cobalt, but Co was not included in any resource estimates. Available data are mostly limited to drill core analytical data, which can be incomplete (not all analyses are available), or Co was analysed from only part of the whole sample population or not analysed at all. Data on sulphide mineralogy are generally limited to a list of minerals present and possibly a notation of, for instance, pyrite being the main sulphide mineral present. Below, we list some examples of these deposits/occurrences. The data are mainly from GTK's drill core database(s), which also contains some analytical data from Outokumpu Oy.

Some orogenic Au deposits/occurrences, especially in central Lapland, contain elevated Co concentrations up to ca. 0.1–0.5 wt% in a limited number of drill core intersections, but concentrations are mostly much lower, in the range of <0.01–0.05 wt% (e.g., Soretiavuoma, Lammasvuoma, Kutuvuoma, Mustajärvi Tuongankuusikko, Palovaara and Levijärvi–Loukinen–Tienpää). There are also some indications of Au-Co occurrences in the Pohjanmaa area, namely Kurula near Alavieska, where quartz–tourmaline breccia veins contain 0.01–0.5 wt% Co and up to 5.1 ppm Au (e.g., Sipilä 1988), and Sudenkylä (Haudankylä) near Seinäjoki, where up to 0.1 wt% has been reported (Nurmi et al. 1991, Huopaniemi 1993). The Jouhineva porphyry/orogenic Au-style deposit is located on the western side of Ylivieska. Based on studies by Outokumpu Oy, it contains ca. 0.45 Mt ore with 0.8 wt% Cu, 0.2 wt% Co and 0.9 ppm Au. Cobalt is hosted in sulpharsenides (cobaltite–arsenopyrite) and pyrite (<0.01–1 wt% Co) (Saari & Hintikka 1983). Preliminary beneficiation tests conducted in 1983 (Saari & Hintikka op. cit.) indicated that it was possible to produce a bulk concentrate with ~20% Cu, ~2% Co, 160 g/t Ag, ~8,5 g/t Au, ~25% S and 4–6% As, at 90–95% recoveries for Cu and Co and 80–90% for Au and Ag.

There are several Co-enriched, massive Fe sulphide (+Cu+Ni) occurrences in central Lapland: Iso-Povivaara, Kannusjänkä, Kelujoki and Pattasoja. The first three occurrences are associated with gabbroic rocks and contain variable amounts of Cu (0.2–2 wt%) and Co (0.01–0.3 wt%). Pattasoja is a purely pyritic occurrence with 0.01–1 wt% Co (weighted average 26.68 m with 0.375 wt% Co) in one drill hole (Hiltunen 1973). For Kelujoki, there is a historical resource estimate of 1.5 Mt with 0.2 wt% Cu and 0.03% Co (Karvinen 1982) based on fairly limited drill data, while for the other occurrences, the data are even more limited. The Hietakero occurrence is also associated with gabbroic rocks with relatively high Co compared to Cu and Ni grades: ~0.1 wt% Co, 0.3–0.35 wt% Cu and 0.2 wt% Ni (Karinen et al. 2018). Some of these relatively high-grade Co occurrences could be interesting exploration targets, especially if the Co price was to increase. A global example of pyritic Co deposits is Cobalt Blue's Broken Hill project: 111 Mt @ 0.0715% Co, 8.9% Fe and 7.8% S with pyrite concentrate containing 0.4 wt% Co (Cobalt Blue Holdings 2020).

Cobalt and nickel are also produced from Finnish talc mines as a by-product. Concentrate production by Elementis (formerly Mondo Minerals) has been in the range of 5 000 t/y, containing 10% Ni and 0.5% Co (Wakeman et al. 2011). Expansion of talc production would double the concentrate production.

4.7 Lithium deposits

The known Finnish Li deposits and most of the occurrences are located in western and southern Finland (Fig. 8B). Typically, they occur as swarms of granite pegmatite dykes forming Li provinces, the most notable being the Kaustinen province 35 km SE of Kokkola. This hosts six deposits, of which five are held by Keliber Oy. Another known Li province is the Somero area, 10 km SW of Forssa. The Eräjärvi area, 45 km E of Tampere, also contains a number of Li pegmatite showings. Some of the occurrences are low grade or Li is contained in some other mineral than spodumene, which is the preferred mineral for Li extraction. Li pegmatites belong to the so-called LCT-type (lithium-cesium-tantalum) complex pegmatites. "Normal" granitic pegmatites that resemble complex pegmatites in their main mineral content but lack more "exotic" minerals and elements are quite common in Finland. However, complex pegmatites are rarer and only a handful of occurrences are known in addition to the ones mentioned above, especially from the northern half of Finland, although no systematic exploration has been undertaken since the 1980s.

The known deposits comprise a total resource of 16 Mt of ore containing ca. 161 000 t of lithium oxide (Li2O) (45 500 t Li) and reserves of 9.3 Mt containing 92 000 t of lithium oxide. The contained Li in the ore reserves is enough for 7.9 million fully electric cars with 60 kW battery packs. GTK also carried out an estimation of undiscovered Li in 2018 (Rasilainen et al. 2018), with an estimated median of 1.1 Mt of lithium oxide in undiscovered deposits.

Lithium extraction follows the same general stages as most hard-rock mining operations, with blasting, crushing, grinding and flotation of spodumene. Gravity and dense media separation can also be used as pre-treatments before flotation, and pre-flotation and magnetic separation can be used to enhance the concentrate quality, as in the planned treatment flow sheet of Keliber Oy in Figure 19. Spodumene concentrate is calcinated, i.e., heated to 1050–1000 oC to convert the insoluble a-spodumene to soluble b-spodumene. For lithium hydroxide production, the converted spodumene is soda leached in an autoclave at 220 oC, producing solid lithium carbonate (slurry) and analcime. Lithium carbonate is made into a soluble form (Li ions) by reacting with calcium hydroxide. The Li solution is purified by ion exchange and Li hydroxide is precipitated by evaporation (Keliber 2019b, 2020).

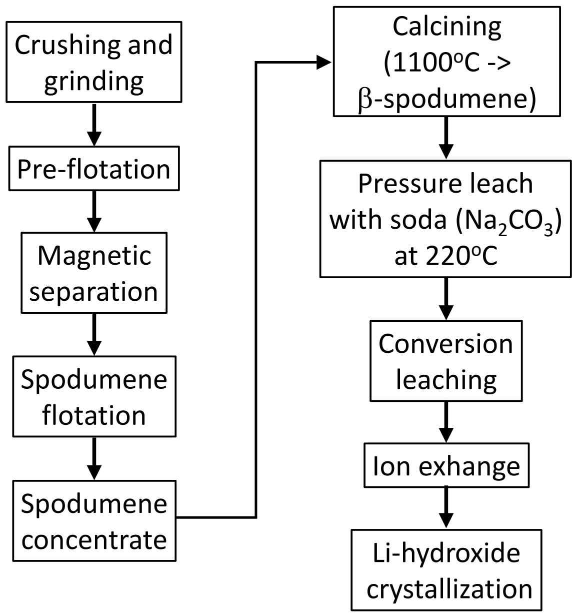

Fig. 19. Simplified Keliber process flow sheet for spodumene concentration and Li hydroxide production (modified after Keliber Oy 2019b).

Table 15. Mineral resources and reserves of Finnish Li deposits.

	Mineral Resources			Ore Reserves		
Deposit	**Tonnage**	**Li_2O%**	**Li_2O (T)**	**Tonnage**	**Li_2O%**	**Li_2O (T)**
Rapasaari	8.214	1.02	83 782	5.28	0.94	49 632
Syväjärvi	2.827	1.2	33 924	1.924	1.13	21 741
Länttä	1.328	1.04	13 811	1.09	0.89	9701
Emmes	1.076	1.22	13 127	0.856	1.01	8645
Kietyönmäki	0.4	1.5	6000			
Leviäkangas	0.468	1.0	4680			
Outovesi	0.281	1.43	4018	0.222	1.06	2353
Rosendal	1.3	0.012	156			

Data: Keliber 2019a, and GTK data.

4.8 Graphite deposits

There are only two Finnish graphite deposits with grade-tonnage data: Aitolampi near Heinävesi (Beowulf Mining) and Viistola near Outokumpu. There are a number of small deposits/occurrences that were in production for flake graphite until 1947 (Sarapää et al. 2016). More recently, GTK has identified several potential flake graphite occurrences in northern and southern Finland (Al-Ani et al. 2016, 2018). Graphite generally occurs either as a fine-grained amorphous form or as flake graphite, which is more desirable for a number of industrial uses, including electrodes in rechargeable Li-ion batteries. Crystalline flake graphite can be classified into coarse flakes with a diameter of >150 mm and fine flakes >45–150 mm in size, with coarse-flake graphite having a higher price (Al-Ani et al. 2020).

Graphite is formed from dead organic matter present in fine-grained subaqueous sediments (muds). During burial and diagenesis, organic carbon is transformed into hydrocarbons (oil, gas) and a solid residue that can be transformed into graphite with increasing temperatures associated with high-grade metamorphism (Buseck & Beyssac 2014). Graphite occurs in so-called black schists and graphite-bearing gneisses, which are quite common in Finland. The formation of flake graphite requires medium to high-grade metamorphism and such a metamorphic grade covers most of Finland. Thus, it can be considered that Finland has good potential for additional discoveries of flake graphite deposits (e.g., Sarapää et al. 2016).

The beneficiation of natural graphite involves the same initial stages as sulphide or lithium ore, i.e., flotation to produce graphite concentrate. This is then purified by alkaline (NaOH) roasting at 200–250 °C, in which common impurities are converted to a soluble form. The resultant concentrate is then leached with sulphuric acid to remove more insoluble impurities and then filtered and washed. For rechargeable battery material, an ultra-high purity of >99.95% is required (e.g., Al-Ani et al. 2020).

5 PRODUCT APPLICABILITY/RECOVERY IN CONCENTRATES

In Finnish deposits, cobalt is hosted by sulphides and sulpharsenides, either as a minor component in Ni minerals such as pentlandite in magmatic Ni-Cu deposits or as a major component or discrete Co phases such as cobalt pentlandite or cobaltite typically found in Outokumpu-type Cu-Zn-Co-Ni deposits and Kuusamo-type Au-Cu-Co deposits. It is also a common minor to trace component in Fe sulphides (pyrite, pyrrhotite), which are ubiquitous minerals in any sulphide ore deposit.

In sulphide deposits, the economic commodities such as base metals (Ni, Cu, Zn, Co) are concentrated by a flotation process in which the desired sulphide minerals are separated from the so-called gangue phases (common rock-forming silicate minerals) and also unwanted sulphides such as pyrite and pyrrhotite, and/or sulpharsenides. The exception is the Sotkamo mine, where the whole-ore heap leach method is used due to the nature of the ore, making it difficult to treat by conventional flotation. The process starts from the blasting of the ore, where ore is freed but also fragmented. The aim is to reach a desired size range suitable for the crushing stage and avoid too large blocks, which would require additional breaking. The ore is then further crushed (e.g., jaw, gyratory and/or cone crushers) and then ground to the desired particle size by milling in autogenous, semi-autogenous, pebble and/or rod mills, depending on the ore characteristics. Typically, ore is ground to 70–80% -75 µm, i.e., 70–80% of the material is smaller than 75 µm. At the Kevitsa mine, this is 76–78% -75 µm, at the former producing Hitura Ni mine it was 80% -74 µm (200 mesh size) and at the former Kotalahti Ni-Cu mine it was 55% -74 µm. The desired grain size is related to the size of sulphide minerals: the finer the grain size, the finer the ore has to be ground. However, overgrinding also has to be avoided, as very small sulphide particles (<-10–25 µm) are generally difficult to float and generate metal losses to tailings (e.g., Senior & Thomas 2005, Musuku et al. 2016). Generally, maximizing the amount of material in the size range between 10–100 µm is desired for any targeted sulphide mineral (Senior & Thomas 2005, Greet 2009, Lawson et al. 2014).

In the flotation process (Fig. 20), the valuable sulphide minerals are separated from gangue minerals and unwanted sulphide phases. In addition to the aforementioned grain-size distribution, a large number of variables affect the flotation process. The grinding media used can have an effect, as micron-sized iron particles from the mills can attach to the surface of sulphide minerals and have an adverse effect on the floatability of sulphides (e.g., Greet 2009). Process water quality can also have an effect on flotation; metal ions such as Ni^{2+}, Cu^{2+} and Ag^{2+} can hinder pyrrhotite suppression, whereas the presence of Cl^- and Ca^+ can promote, for instance, pentlandite flotation (Rao 2000). The presence of hydrophobic minerals such as talc, chlorite and serpentine, which often occur as alteration phases of primary magmatic minerals in mafic–ultramafic-hosted Ni-Cu deposits, are easily ground to a fine grain size and can cause problems due to sliming (coating sulphide minerals) or by being floated into, for example, the Ni-Co concentrate. This results in a high magnesium content in the concentrate, which causes problems in smelting (Rao 2000, Senior & Thomas 2005, Musuku et al. 2016). Finally, conditions such as the pH, pulp and froth densities, and various chemicals (collectors, modifiers, depressants, frothers) can be adjusted to optimize the flotation conditions.

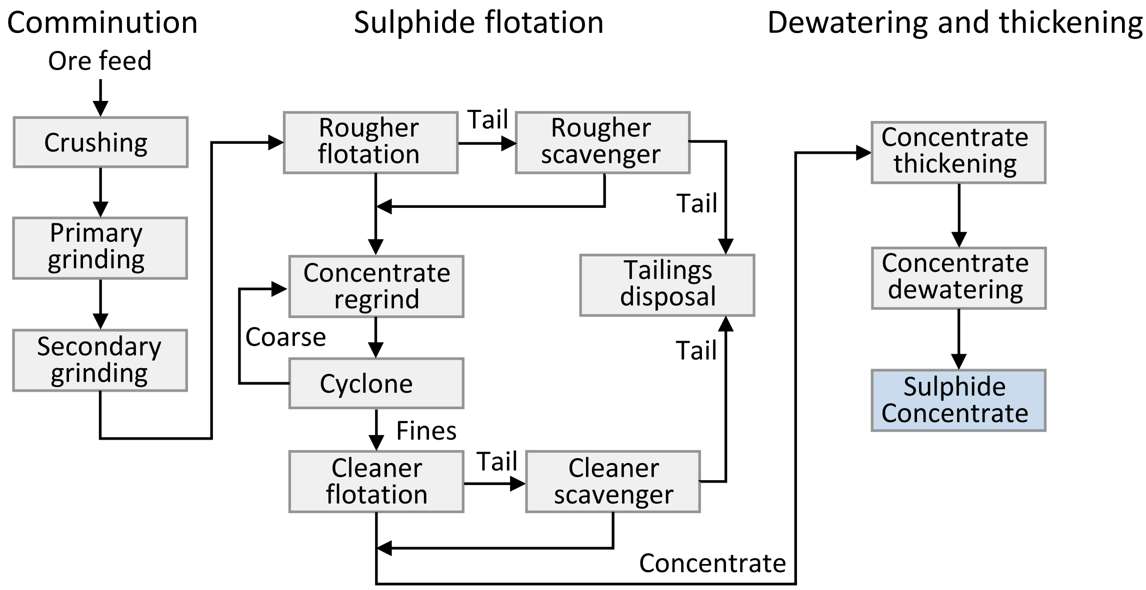

Fig. 20. Simplified flow sheet for the sulphide flotation process (modified after Zanin et al. 2019).

5.1 Flotation of orthomagmatic Ni-Cu-Co ores and produced concentrates

In the past, most of the Finnish Ni-Cu-Co production came from the so-called Svecofennian intrusion-hosted deposits (e.g. Hitura, Kotalahti, Vammala, Enonkoski) mined by Outokumpu Oy, providing concentrates for the Outokumpu Ni-Co smelters and metal refineries, which started in the 1950s (see the website of Outokumpu Oy). In most cases, a bulk Ni-Cu-Co concentrate was produced at a low pH, which promotes the flotation of all sulphide minerals and ensures a high recovery of Ni (+Co) and Cu into the bulk concentrate (Lukkarinen 1984). Separate Cu and Ni-Co concentrates were then produced at a higher pH with a basically similar procedure to that used today (Lukkarinen 1984, Kirjavainen & Heiskanen 2007). At the Kevitsa mine, which is the only currently operating Ni-Cu mine (orthomagmatic Ni-Cu deposit type), a sequential flotation process is used, which directly produces separate Cu and Ni-Co concentrates and also separate high-sulphur tailings. In contrast, most Ni-Cu mining operations elsewhere still produce a bulk Ni-Cu-Co concentrate, and in some cases, this is further processed to separate Cu and Ni-Co concentrates (Rao 2000), but in many cases a bulk concentrate is shipped to downstream processing (e.g., Lawson et al. 2014).

As stated in the previous chapter, there are several steps in the pre-flotation and flotation process, starting with the liberation of sulphide minerals by grinding the ore to a small enough grain size. Liberation, i.e., freeing sulphides from gangue minerals and preferentially also from other sulphide phases, is relatively easy for more coarse-grained sulphide deposits (e.g., Kotalahti), but is more difficult with more fine-grained deposits (see Fig. 21) and when alteration phases such as talc, chlorite and serpentine minerals are present. This is often the case with orthomagmatic Ni-Cu deposits, especially when hosted by more ultramafic rock types. These phases are relatively soft and easily ground to fine particles (slimes), which can cause problems by floating with pentlandite flotation, increasing the MgO content of the concentrate. They can coat unwanted phases such as pyrrhotite, causing it to float, and downgrade the Ni content of the concentrate, suppress pentlandite flotation and adversely affect the flotation slurry properties (Rao 2000, Kirjavainen & Heiskanen 2007). Pentlandite has a tendency to produce fine particles (<10–20 µm), which are difficult to float and can cause a significant loss of Ni to tailings of up to 20–30% of the feed nickel (Senior & Thomas 2005, Musuku et al. 2016). There are several techniques to improve the recovery of the fine fraction, e.g., by decreasing the pulp density, pre-conditioning before flotation and using activators (Rao; Senior and Thomas, op. cit.). One of the major problems in pentlandite flotation is pyrrhotite suppression. Pyrrhotite has a tendency to float together with pentlandite, thus increasing the sulphur content of the concentrate and diluting its Ni content. On the other hand, pyrrhotite contains some Ni (0.3–0.5 wt%), and also fine-grained pentlandite flames and trace cobalt (also occurring in the pentlandite flames). In general, there is a trade-off between the Ni grade of the concentrate and Ni recovery: Higher recovery results in increased pyrrhotite recovery, diluting the concentrate, and a higher concentrate grade results in lower recovery and the loss of Ni (and Co) to tailings.

In sequential flotation such as used at the Kevitsa mine, chalcopyrite is first floated at a high pH using a selective collector and depressant for silicate gangue (carboxy methyl cellulose, CMC). This occurs in four stages. The tails from the first two Cu flotation stages are fed to the Ni flotation circuit. Pentlandite is floated at pH 10 to enhance pentlandite flotation and pyrrhotite suppression. Again, a selective collector (xanthate) is used with a silicate gangue suppressant (CMC) (Musuku et al. 2016). Chalcopyrite flotation and separation from pentlandite is generally relatively easy at acceptable concentrate grades and recoveries and at a low Ni content (Kevitsa: 23% Cu, ~83% recovery, ~0.8% Ni). Producing an acceptable Ni concentrate is more difficult and a balancing act between grade and recovery and achieving other prerequisites for an acceptable concentrate. In recent years, the Kevitsa Ni concentrate has had a Ni grade of ~9% and recovery between 63–71%, with a fairly significant improvement in recovery from the start of the mine operations (56–63%) (Musku et al. 2016, SRK

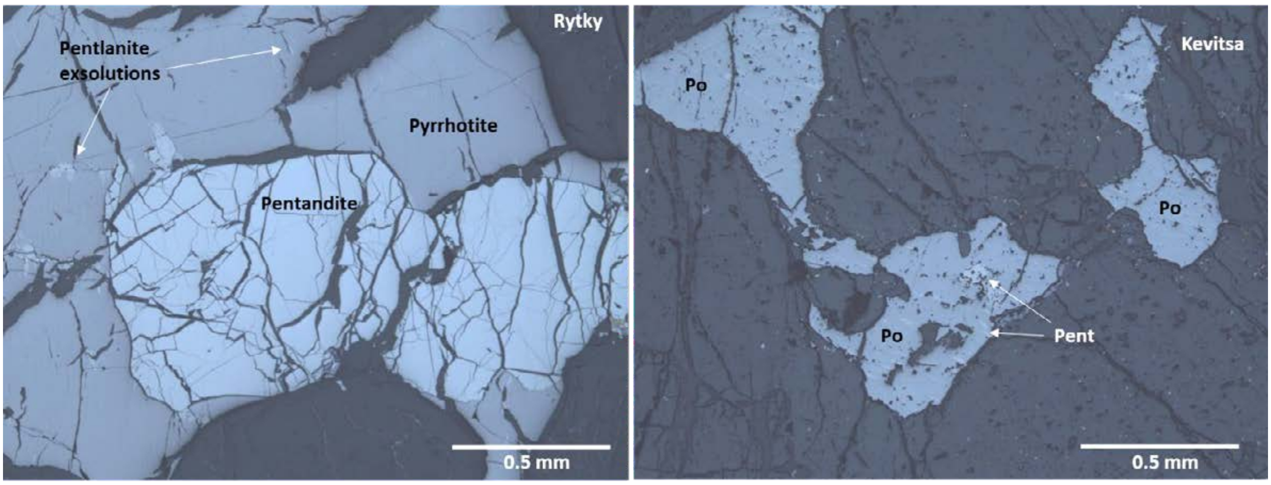

Fig. 21. Same-scale microscope images of two different types of Ni-Cu ore with relatively coarse-grained but fractured pentlandite from the Svecofennian Rytky deposit on the left, and more fine-grained pyrrhotite-dominant low-grade ore with small pentlandite inclusions and “flames” in pyrrhotite from Kevitsa on the right.

Consulting 2020), as well as a Co content of 0.3–0.6% with calculated recovery between 60–79%, and a MgO content between 3–9% and a calculated Fe:MgO ratio of 5–6. The Ni-Co concentrate from Kevitsa is transported to the Boliden Harjavalta Ni smelter for further processing.

For cobalt recovery, high pentlandite recovery is essential, as on average 75% of Co is carried by pentlandite in orthomagmatic Ni-Cu-Co-PGE deposits, with the balance in Fe sulphides that mostly end up in tailings. Generally, over 90% of Ni is carried by pentlandite or in a few cases some other Ni-rich sulphide phase, whereas there is more variation in the percentage of Co carried by pentlandite and other sulphides between different deposits. This implies that even at a 100% pentlandite recovery, a smaller proportion of Co is recovered, and as Ni (pentlandite) recovery is in practice 70–85%, Co recovery is further diminished to reported levels of 50–65%. In order to maximize Co recovery, Fe sulphides should be floated with Ni, which would dilute Ni grades, increase the S content and increase the overall mass of the concentrate, thus rendering it less desirable for smelters. However, it could be treated by hydrometallurgical or biohydrometallurgical processes. In cases like Kevitsa, where Fe sulphides are also floated in order to clean the silicate tailings and are stored in a separate tailings pond, these could provide a future, albeit low-grade resource for Co and also Ni and Cu. According to mine environmental monitoring results, the nickel content of high sulphur tailings typically varies between 1% and 2% (Boliden 2020b). The cobalt content has not been regularly monitored, but probably has a rather similar Ni:Co ratio to that in the actual Ni concentrate. Processing options for this material should definitely be studied in the future.

Finnish layered intrusions host several PGE-Ni-Cu-Co deposits, such as Ahmavaara and Konttijärvi in the Portimo Complex and Kaukua and Haukiaho in the Western Koillismaa Complex. In these deposits, palladium and platinum are the main commodities, but they do contain low concentrations of Cu and Ni (0.1–0.2% Cu and 0.05–0.14% Ni) and trace amounts of Co (0.005%). Even at these low concentrations, they contain a potentially significant Co resource, as they are potentially large tonnage deposits, especially the Portimo Complex deposits (cf. Table 3). Both bulk sulphide (Haukiaho–Kaukua) and separate Cu-PGE and Ni-PGE(-Co) concentrate flotation tests have been conducted for these deposits (Puritch et al. 2007, Mroczek & Butler 2013, Sokolov & Iljina 2019). No data are available on Co recovery, but as these deposits have similarities with the Kevitsa deposit, a 50% recovery estimate can be assumed. In the report

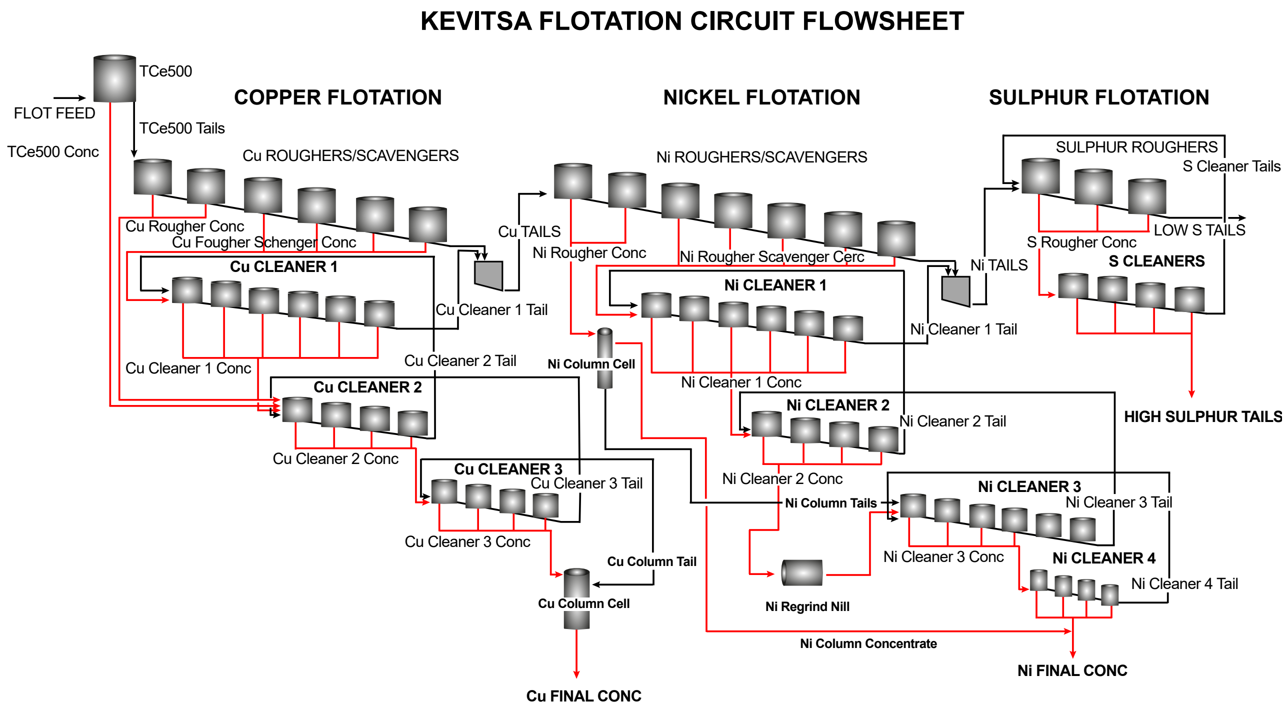

Fig. 22. Flotation flow sheet for the Boliden Kevitsa mine (modified after Musuku et al. 2016) showing sequential flotation of Cu and Ni.

of Sokolov & Iljina (2019), it was noted that the Cu-rich nature of the bulk concentrate would limit smelter opportunities that would enable a high return on concentrate sales. A bulk concentrate sample was also treated with the Platsol pressure-leach method with 90–99.8% extraction of Ni, Cu, Co, Pt, Pd and Au. There have been several feasibility studies for the Suhanko deposits, but most of them have not been publicly disclosed. Both bulk concentrates and separate concentrates have been studied. Early in the 2010s, the production of bulk concentrate further processed with Platsol pressure leaching was investigated. The final products were copper cathode, Ni-Co precipitate and precious metal concentrate. Ni-Co precipitate was reported to contain 40% nickel and 4% cobalt, with the annual tonnage ranging from 7 000 to 14 400 t, depending on the ore feed. The planned mill feed was 10 Mtpa at that time. However, such a process was seen as unfeasible due to the extremely high investment costs and potentially associated technical risks. Studies undertaken since then have no longer included pressure leaching. From a technical point of view, decent products could be produced with such a process, but project economics was apparently the challenge (GFAP 2013).

Summary for cobalt in concentrates from orthomagmatic deposits:

- Traditional flotation treatment to produce Ni-Co concentrate with 0.5% Co, emphasis on optimizing the Ni content;
- Cobalt recovery is strongly dependent on Ni recovery but variable from deposit to deposit;
- Higher recovery in high-grade Ni deposits;
- In some deposits, a higher proportion of Co occurs in Fe sulphides, especially in pyrite;
- Ni-Co concentrate further processed in smelters (pyrometallurgical treatment), in some cases by hydrometallurgy, which is generally more effective in recovering metals from the concentrate;
- Maximizing Co recovery, and also Ni recovery, would result in a lower grade Ni concentrate, which might not be desirable for smelters but would be treatable by hydrometallurgical or biohydrometallurgical methods.

5.2 Flotation of Outokumpu-type Cu-Zn-Co-Ni ores

In past-producing mines, the Co concentrate grades were relatively low, generally 0.5 to 1.5 wt% Co. Concentrate data from the Outokumpu mine indicate that the concentrate is mainly composed of Fe and S, which is supported by concentrate mineralogical data indicating that most of the pyrite and pyrrhotite report to the Co concentrate, with Co coming from cobalt pentlandite and also from Fe sulphides. The low-grade Co-Ni concentrate from the Kylylahti mine is of a similar grade (<1% Co and 0.2–0.5% Ni). A concentrate test conducted on the Hautalampi deposit, which represents a "parallel Ni-Co" ore zone, produced a Co-Ni concentrate with 1.5 wt% Co and 6.2 wt% Ni after first floating a Cu concentrate at a high pH (FinnCobalt press release 3/2019). A beneficiation test on the Hietajärvi deposit (Isomäki 1994) indicated that it was possible to produce a separate Cu concentrate (at 25% Cu and ~80% recovery) and a Co-Ni concentrate, which actually is the highest grade Co concentrate reported anywhere in Finland, with 5–15% Co at 60–70% recovery and 5% Ni at 30–40% recovery. Historically, the Co concentrates from Outokumpu-type deposits were processed at the Kokkola cobalt refinery to produce various final Co products.

5.3 Flotation of Au-Cu-Co (Kuusamo-type) ores

In Kuusamo-type deposits, Co is hosted in various sulphide phases and sulpharsenides at varying proportions. Cobaltite, when present, usually in the more Co-rich parts of the deposits, is often the main Co carrier. Cobaltpentlandite is another important Co carrier, but it mostly occurs as "flames" in pyrrhotite and very seldom as its own grains. Pyrite in most cases also contains 1–3% Co, and in a few deposits the Co content is very low. Pyrrhotite also has a relatively high Co content, with up to 0.3% Co (Table 12). A beneficiation test indicated that a bulk Co-Cu-Au concentrate can be produced, containing moderate Co (0.5–2.8%) and low Cu contents, with a variable Au content (Table 13). In addition, in the Haarakumpu deposit, a commercial-grade Cu concentrate was produced with 23% Cu, a Co concentrate with 0.87% Co and also a low Co-grade pyrrhotite concentrate with 0.42% Co. Based on available concentrate data, in some cases the As content is likely to be higher than 0.1%, which would induce smelter penalties in downstream processing, as the limit for As, for example in Cu concentrates, is generally 0.1% and similar if not lower in Ni-Co concentrates (Lane et al. 2016).

Summary for Co concentrates from hydrothermal (Outokumpu–Kuusamo–IOCG) deposits:

- Dedicated Co concentrates have been produced from mined Outokumpu-type deposits, but they tend to be fairly low grade, typically with 0.5–1.5% Co. Co-Ni concentrate from the Hautalampi deposit has a similar Co grade and significant Ni grade. Currently, the company developing the Hautalampi deposit (Finncobalt/Eurobattery Minerals) is studying options for hydrometallurgical downstream refining for the concentrates.
- Similar concentrates can be produced from Kuusamo-type deposits, but they often contain elevated arsenic, which is a penalty element in smelting and requires safe disposal in hydrometallurgical processes. Haarakumpu Co and pyrrhotite concentrates have lower As contents (<0.1%).
- Pyritic concentrates (tailings) from IOCG deposits such as Hannukainen could be a potential source of cobalt, as well as the Co-Ni tailings and stored low-grade concentrates from the Kylylahti mine. Another interesting side stream could be Kevitsa high-sulphur tailings, especially in terms of nickel.
- There is also potential in massive pyrite deposits such as Pattasoja, which contain up to 26 metres of massive pyrite with 0.37% Co, similar to the grade in the pyrite concentrate from the Cobalt Blue Holdings Broken Hill deposits in Australia (0.45% Co in concentrate).
- Although some of the Co concentrates contain more than 1% Co, which is of a similar grade to Co concentrates produced in the DRC (BGR 2017), they would probably require either pyrometallurgical or hydrometallurgical pre-treatment to produce an intermediate product and to get rid of deleterious elements such as arsenic to make it more attractive for refined cobalt production and to lower shipping costs (e.g., Alves Dias et al. 2018). In addition, 75% of global cobalt trade is represented by intermediate Co products (e.g., Co hydroxide with 20–40% Co) (e.g., Matthews 2020).

6 DOWNSTREAM TREATMENT

The Co-containing concentrate or Co concentrate can be treated using two different process routes to extract the metals contained in the concentrate. Typically, sulphide concentrates are treated by pyrometallurgy, where the concentrate is smelted and converted to produce “matte” containing valuable metals, iron and sulphur. Metals are then extracted from the matte by various leaching processes. Typically, Ni(-Co) and Cu concentrates are treated in a dedicated smelter, but a mixed Ni-Cu concentrate can also be treated. Ni-Cu-Co sulphide concentrates can also be treated by various hydrometallurgical processes, with Cu-Co concentrates in particular generally being treated by hydrometallurgy in the DRC, and Ni-Cu-Co sulphide concentrates more rarely (Crundwell et al. 2011, Dehaine et al. 2020).

6.1 Pyrometallurgy for Ni-Cu-Co sulphide concentrates

Pyrometallurgical treatment of Ni-Cu-Co concentrates can be carried out by flash smelting or by electric furnace smelting. Flash smelting accounts for about 70% of metal production from nickel sulphides, with electric furnace smelting accounting for the rest (Warner et al. 2007). Both methods have their advantages and disadvantages. For example, flash smelting requires less energy but results in the loss of metals to the slag, whereas as electric furnace smelting is more energy intensive but results in better retention of metals in the matte and can handle more complex concentrates, such as platinum-group elements, as well as high chromium and magnesium contents.

In electric furnace (EF) smelting, the concentrate must first be roasted by heating it in oxygen-enriched air at 600-700°C to reduce the sulphur content and partially oxidise metals before the smelting phase. In the electric furnace, the roasted concentrate, called calcine, is melted with silica flux and in some cases also coke to keep conditions more reducing, at ~1300°C. Liquid sulphide matte containing Ni, Cu and Co is separated from molten slag, mostly composed of silica, iron and small amounts of magnesium. The slag, which is relatively free of Ni-Cu-Co, is discarded and the sulphide matte goes to a conversion process (Fig. 23).

So-called Peirce-Smith (PS) converters are then used to transform the furnace matte into low-Fe matte (Bessemer matte) by blowing oxygen-enriched air into the molten matte at ~1300°C, which reduces the Fe and S content of the matte (Crundwell et al. 2011). Matte and slag are separated, and the slag is either recycled to the electric furnace or goes to a slag cleaning electric furnace, while the matte is cooled and granulated/milled and goes to the metal extraction process. The converter slag contains some Ni-Cu and Co due to the oxidation of metals, which then report to the slag, and by physical entrainment of matte droplets (Yu & Chattopadhyay 2018). In the slag-cleaning electric furnace, the slag is melted, often together with a carbonaceous reducing agent (coke), which enhances partitioning of metals to the matte, and small amounts of converter matte or sulphide concentrate or ore to provide sulphur for the liquid matte formation. The cleaned slag can be discarded and the matte goes to the metal extraction process.

Flash smelting is the preferred technology used for Cu sulphide concentrates and is also commonly used for the smelting of Ni-Cu-Co-sulphide concentrates, accounting for nearly 70% of primary metal production from Ni sulphide sources (Warner et al. 2007). In flash smelting, developed by Outokumpu, the concentrate and flux (silica) are fed to the flash furnace together with oxygen-enriched air and fuel (coal, oil or natural gas). As the oxidation (roasting) and smelting both occur in the furnace, flash smelting removes the separate roasting stage of EF smelting with the further advantage of the oxidation providing a significant amount of heat (energy) for the smelting, making it less energy intensive compared to EF smelting. A further advantage of flash smelting is that it produces relatively low volumes of SO_2-rich gas, which is more suitable for SO_2 scrubbing and the production of sulphuric acid and/or liquid SO_2 (Riekkola-Vanhanen 1999, Crundwell et al. 2011). Conventional flash smelting requires a matte-converting stage, as in EF smelting (Fig. 23), whereas in the direct Outokumpu nickel (DON) process, used for instance at Harjavalta, the concentrate is directly flash smelted to low-Fe matte, eliminating the separate converting stage (Mäkinen & Taskinen 2006, Johto et al. 2018).

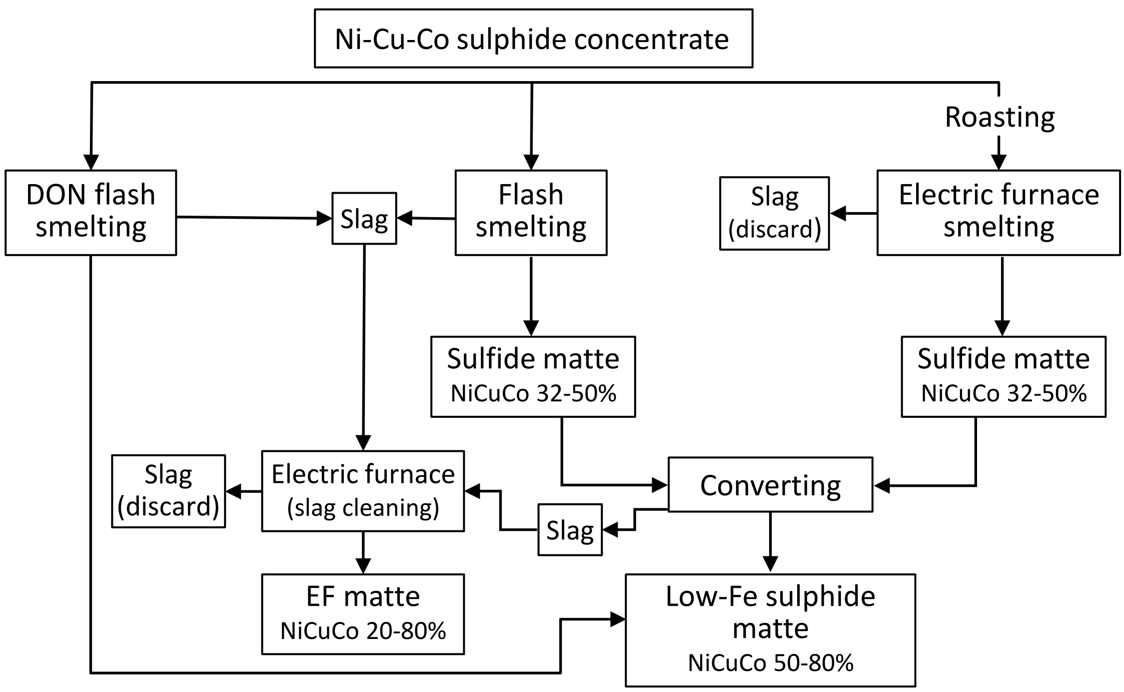

Fig. 23. Flow sheet for pyrometallurgical treatment of Ni-Cu-Co sulphide concentrates.

Due to the more oxidative nature of flash smelting compared to EF smelting, substantial amounts of Ni, Cu and especially Co are also oxidized and end up in slag (up to 54% of Co in the concentrate). The DON process eliminates some of the metal loss by eliminating the converting stage, but metal losses to the slag are still several percent for nickel and approximately 0.5 percent for Cu and Co (representing 77% of Co in the concentrate) (e.g., Mäkinen & Taskinen 2006, Avarmaa et al. 2020). The metal-containing slag from flash smelting is cleaned in an electric furnace, much in the same way as when converting slag in EF smelting. This is done with the aid of a reducing agent and sulphur addition, which reduces the quantity of metals in the final discarded slag to a level closer to that of EF smelting, although some 30% of Co is still lost to the slag (Table 16).

Table 16. Recovery percentage of Ni, Cu and Co in different smelter types (after Warner et al. 2007) and slag composition (after Riekkola-Vanhanen 1999, Wagner et al. 2007).

	Flash smelters			Electric furnace smelters		Discard slag composition (%)		
	Traditional	DON*	Inco	Ni-Cu	PGM	Flash	DON	EF
Ni	90–96		97	97–98	90–99	0.07–0.36	0.1–0.3	0.06–0.17
Cu	80–93		97	97	89–96	0.19–0.4	0.05–0.25	0.01–0.2
Co	26–69		46–48	51-75	30–35	0.09–0.15	0.1–0.25	0.06–0.08

*No exact data are available for the DON process, but the estimated recovery for Co is possibly 50–70%.

Metal-rich matte(s) produced by smelting and slag cleaning are ground for final metal extraction and purification, which is performed using a variety of leaching processes. These generally proceed with atmospheric and/or pressure leaching in an autoclave, followed by sequential removal/precipitation of Cu, Fe (as an impurity), and Co-Ni separation and extraction.

In ammonia pressure leaching, ground matte is leached in an ammoniacal sulphate solution under pressure and moderate temperature in autoclaves, where Cu, Ni and Co are dissolved as ammonia complexes. Copper is precipitated as sulphides with the addition of SO_2 or sulphur. The Ni and Co-containing sulphate solution is pressure oxidized and Ni can be precipitated as a metal powder by hydrogen reduction or precipitated with Co as sulphides with H2S addition (Riekkola-Vanhanen 1999)

Another matte treatment method is chloride leaching, where hydrochloric acid or chlorine is added at elevated temperatures (90–140°C) in reactors or autoclaves. Cobalt is extracted from the Ni-Co solution by solvent extraction and can then be precipitated or recovered as Co cathodes by electrowinning. Ni is usually extracted by electrowinning. Different variations of the chloride leach are used/provided, for example, by Eramet, Falconbridge and Outotec (Riekkola-Vanhanen 1999, Aspola et al. 2012).

Finnish Ni smelters (Nornickel) use Outotec three-stage leaching, where the first two phases are atmospheric leaching with the aid of sulphuric acid, with Ni and Co leached while Cu is cemented (Cu product) and iron is precipitated. The solid residue is then pressure leached in an autoclave. The Ni-Co leach solution is filtered and cleaned of impurities and then Ni and Co are separated by solvent extraction. The Ni-bearing solution can then be used to produce metallic Ni powder or briquettes by hydrogen reduction, Ni cathodes by electrowinning, or different Ni chemicals (e.g., sulphates, hydroxides). Cobalt can be extracted in a similar way from the Co-bearing solution as Co powder by hydrogen reduction or by precipitating Co sulphate (Riekkola-Vanhanen 1999, Aspola et al. 2012).

Pyrometallurgy can be used to treat a variety of Co-containing sulphide concentrates of varying grades, including Fe sulphide-rich tailings. Recent global projects include the Cobalt Blue Holdings Broken Hill Cobalt project, which would treat pyritic concentrate containing 0.45% Co by thermal decomposition (roasting), resulting in calcine containing 0.5% Co, 50% Fe and 30% S. The calcine would then be leached by pressure oxidation or atmospheric leach to produce Co sulphate. Elemental sulphur would be a by-product (Cobalt Blue Holdings 2020). The Santo Domingo Fe-Cu-Co project in Chile is a manto-type (or IOCG) deposit with 0.02–0.025% cobalt (mostly in pyrite) resembling Finnish IOCG deposits such as Hannukainen. Pyrite flotation concentrate has an average Co grade of 0.268% Co. One option to treat this concentrate would be to "dead roast" the concentrate to remove all sulphur, captured from the off-gas for sulphuric acid production, to produce calcine and then use pressure oxidation to leach Co from the calcine for Co sulphate production by solvent extraction (Maycock et al. 2020).

Arsenic-bearing concentrates can also be treated by pyrometallurgy, but it is preferable to remove arsenic before smelting, as it degrades the quality and usability of the end product (e.g., Lane et al. 2016, Cheng et al. 2019, Rijin et al. 2019). Arsenic can be removed by partial roasting of concentrate to volatilize As or partial leaching of the concentrate, such as alkaline leach (Toowong Process, Core Group 2020). As arsenic is highly toxic and harmful, it is essential to capture any arsenic in off-gas, dust and effluents and precipitate it as a stable form, such as scorodite or crystalline ferric arsenate (e.g., Monhemius & Swash 1999, Bligh & Mollehuara 2012).

6.2 Hydrometallurgy for Ni-Cu-Co sulphide concentrates

Hydrometallurgy, i.e., direct leaching of concentrates, is a relatively common method to treat various sulphide concentrates such as Cu, Zn, and refractory Au, but is rarely used for Ni-Cu-Co sulphide concentrates. However, several processes are available that could treat such concentrates, and several have been developed or are in development to treat PGE-rich concentrates. Currently, only the Voice's Bay Ni-Cu mine concentrate of Vale SA is treated by hydrometallurgy for metal extraction, producing 1592 t of Co in 2020 (Vale 2020).

Hydrometallurgical processing of sulphide concentrates has several advantages compared to smelting: A bulk sulphide concentrate can be used, and also low-grade concentrates, enhancing metal recovery in the concentrate stage, and high recovery of metals can be achieved, generally >90% (often ≥95%). Capital costs are also lower than building a dedicated smelter, but can be high for a large-scale operation. Disadvantages are the availability of relatively few "mature" technologies for Ni concentrates (compared to Cu) (e.g., Mpinga et al. 2015). Also, the processes tend to be complex, and variability in the concentrate metal content and mineralogy (e.g., pyrrhotite vs. pyrite) can cause problems.

Hydrometallurgical processes can be classified into pressure oxidation (POX) processes and atmospheric leach processes. In POX processes, sulphide minerals are broken down to soluble forms in autoclaves at elevated pressures and temperatures with the aid of oxygen and sulphuric acid or by the addition of chloride in the form of hydrochloric acid, NaCl or chlorine gas. In atmospheric leach, leaching is performed in reactors at atmospheric pressures and temperatures in the range of 80–100°C, sometimes with O_2 addition. Some processes use a combination of roasting and pressure oxidation. Another classification method is based on the solution chemistry (lixiviant) of the leaching process, i.e., whether sulphuric acid (sulphate process) or chlorine (chloride process) is used. Some processes use sulphuric acid with small amounts of chlorine, or chlorine and bromide, or cyanide.

6.2.1 General features of concentrate pre-treatment, leaching process and metal extraction

In many cases, the concentrate is reground to a fine grain size (generally 80% at 5–50 μm size) before leaching in order to enhance leaching and shorten the leaching time. A pre-leaching stage is sometimes used before the actual leach (e.g., Vale hydromet) (Kerfoot et al. 2002). As stated above, leaching can be performed at atmospheric pressures and temperatures typically between 80–100°C. In some cases, oxygen is added to enhance sulphide oxidation. The low pH required for the leaching is achieved by the addition of sulphuric acid (sulphate process), although some processes use chlorine instead of sulphuric acid (e.g., Outotec). Additional acidity is typically generated by the oxidation reactions of sulphur to sulphuric acid. Spent electrolyte from Cu electrowinning can also be recycled to the leaching stage to generate acidity (Fig. 24). Atmospheric leaching of the concentrate slurry is generally performed in a series of agitated tanks. Alternatively, the leaching can be carried out by pressure oxidation (POX) in autoclaves at elevated pressures and temperatures. In low-temperature POX, the temperature is typically between 100–150°C, whereas in high-temperature POX, the temperature is 200–230°C. Oxygen, sulphuric acid or chlorine is added to the autoclave to promote leaching and oxidation. Some processes combine sulphuric acid with small amounts of chlorine to enhance precious metal dissolution. The leaching process transforms sulphides into soluble sulphates. The metal-containing solution is separated from the solid residue, which can be directed to precious metal recovery or to tailings storage. If precious metals such as platinum group metals are leached, these are generally precipitated in the first stage by the addition of limestone (Albion Process) or NaHS (Platsol Process) (Ferron et al. 2001, Glencore Technology 2020). The base metals are sequentially extracted, usually with copper solvent extraction (SX) followed by electrowinning (EW) to produce copper cathodes. In most processes, this is followed by the removal of impurities, mostly Fe, by neutralization in several stages. Some metals in the leach solution can be precipitated or stripped to waste solution in these stages, in which case the solid precipitate can be directed back to the leaching process and/or metals are recovered from the waste solution. After purification, nickel and cobalt can be precipitated as a mixed hydroxide product or they can be sequentially recovered by solvent extraction. Cobalt is often extracted first and is either precipitated (e.g., as a sulphide or carbonate) or electrowon (Vale, Co "rounds"). The Ni-containing solution goes to electrowinning to produce Ni cathodes or is precipitated. In many cases, acidic solutions coming out of various stages, such as electrowinning, are redirected to leaching. Vale's Voicey's Bay process is presented as an example of a hydrometallurgical process in Figure 24.

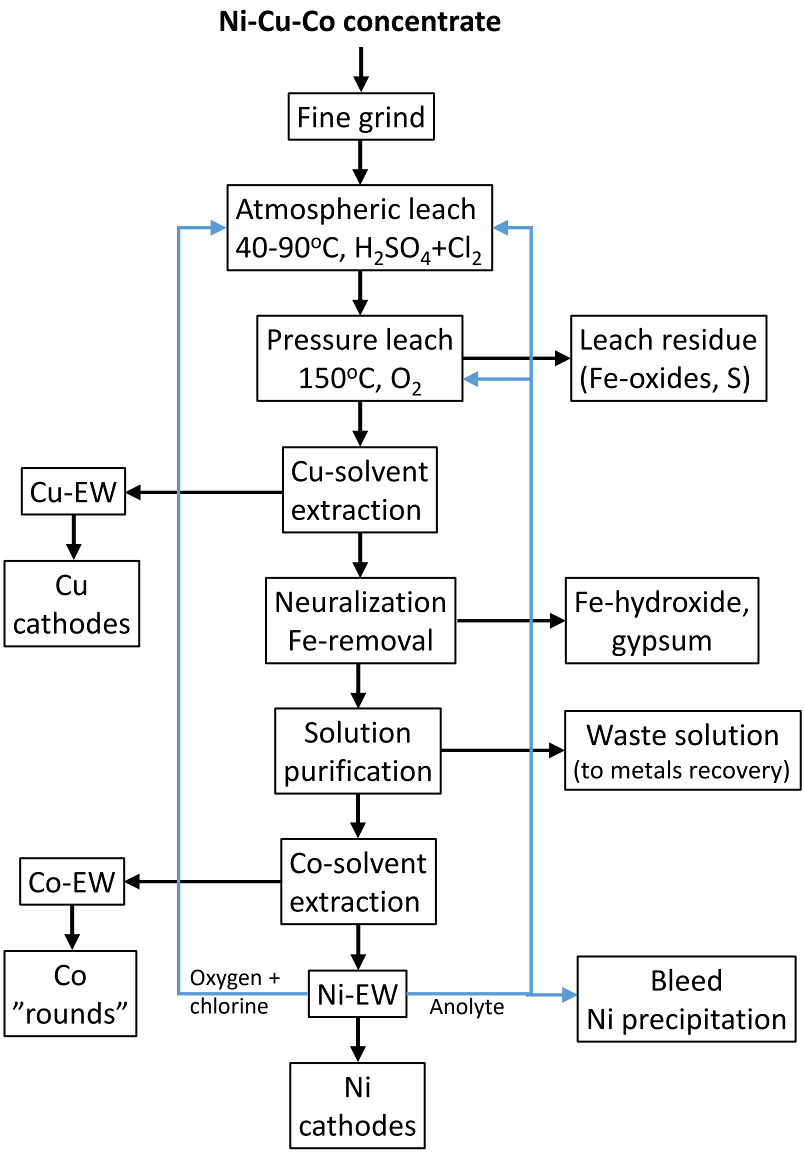

Fig. 24. A flow sheet of the hydrometallurgical process used for Vale's Voicey's Bay Ni-Cu-Co concentrate (modified after Kerfoot et al. 2002).

In addition to Ni-Cu-Co concentrates coming from orthomagmatic deposits, hydrometallurgy has been piloted for a few other deposit types, such as the NICO Co-Au-Bi-Cu IOCG-type deposit in Canada (Mezei et al. 2009), and Idaho Co-Cu-Au deposits (Sletten et al. 2020), which have strong similarities to Kuusamo-type deposits. More detailed descriptions of the various processes can be found, for example, in Mpinga et al. (2015) and Sinisalo & Lundström (2018).

6.3 Biohydrometallurgy for Ni-Cu-Co sulphide concentrates

In biohydrometallurgy or bioleaching, iron and sulphur-oxidizing microorganisms (bacteria and archaea) are utilized in leaching sulphide minerals. Although bioleaching has been around since the mid-1960s, it accounts only for ca. 10–15% of Cu recovery, ~5% of gold recovery and smaller percentages for other metals (zinc, nickel, cobalt and uranium) (e.g., Johnson 2018, Kaksonen et al. 2020). Leaching takes place at a low pH (generally 1–2) with sulphuric acid and at a typical temperature of 40–50°C, although higher temperatures of ~70°C can be needed for efficient and rapid oxidation of some more refractory Cu minerals. Different temperatures require different bacterial cultures, as they are temperature sensitive. In most cases, aeration (air/oxygen addition) is required, although reducing environments can also be used (Johnson 2018).

The scale and length of bioleaching varies greatly depending on the leached material. Large-scale heap, dump or pad leaching is generally used for long-term leaching of low-grade ore, such as at the Terrafame (Talvivaara) operation. The overall leaching time can be several years (or even decades). Smaller scale stirred tank or bioreactor leaching can be utilized for concentrates or tailings. These are used in a series of several tanks. The advantage of tanks and reactors is the faster leaching rate of 4-6 days, but they can treat much lower volumes, as the amount of solid concentrate is typically 10–20%, although up to 30% solid loading has been also used (Kaksonen et al. 2020). Bioleaching is not as effective in extracting metals as POX processes and is more variable for different metals, with ~50% extraction of Cu and 60–90% extraction of Ni and Co. Higher temperatures result in higher extraction rates (Norris 2017, Kaksonen et al. 2020, Mäkinen et al. 2020), with results varying from case to case. After sufficient leaching of metals to the solution, they can be precipitated as in traditional hydrometallurgy, i.e., solvent extraction and electrowinning for Cu and, for example, mixed hydroxide precipitation with MgO addition for Ni and Co.

Bioleaching with stirred tanks at 42°C and 20% solid concentration was successfully used between 1998–2013 to treat 900 000 t of pyritic tailings in Kasese, Uganda, achieving 90% extraction of Co after 6 days of leaching and producing ca. 1100 t of Co per year (D'Hugues et al. 2019). In Finland, a commercial plant was construct at the Mondo Minerals (now Elementis) Vuonos talc concentrator to treat by-product Ni-Co-As sulphide concentrate (12 000 t per year) using Mintek's (South Africa) BacTech stirred tank technology. The concentrate was leached for 7 days at 45°C at a 15% solid concentration, achieving >90% extraction of Ni and Co. A mixed Ni-Co hydroxide product (~1000 t per year) is precipitated with the aid of MgO (Wakeman et al. 2011, Kaksonen et al. 2020). The Elementis leaching plant has only been periodically operational. At other times, the concentrate is presumably sold on the market without treatment.

Stirred tank bioleaching has also been tested for a Finnish mine tailings case with 4.46% Zn, 1.17% Co, 0.41% Cu and 0.37% Ni. Ten days of leaching at 30°C resulted in high leaching rates for Zn (100%) and Co (87%), but significantly lower rates for Ni (67%) and Cu (43%) (Mäkinen et al. 2020). Another commercial application of bioleaching is the Western Areas Cosmic Boy concentrator, where high-grade tailings (15% Ni, 2.4% As) from the concentrator plant are leached in tanks, producing Ni sulphide (4000 t per year with 45–50% Ni) via sodium sulphide precipitation. Arsenic is precipitated as a stable Fe compound (Taylor 2017). Bioleaching has also been tested as a pre-treatment method to aid atmospheric cupric chloride leaching (Outotec) at 95°C of Kylylahti mine tailings (Altinkaya et al. 2018).

Bioleaching can treat As-containing concentrates and tailings. In order to generate stable As compounds (ferric arsenate) for stable storage, the leach solution should have a minimum Fe:As ratio of 3:1 or 4:1 (e.g., Wakeman et al. 2011). At lower ratios, additional Fe needs to be added, potentially increasing costs. As an example, the Canadian Company

BacTech Environmental planned to treat 300 000 t (potentially 16–18 Mt) of Au-As-Co containing stockpile from a past-producing Au mine to extract metals from the stockpile and stabilize arsenic. While the bioleaching was found to be suitable for the treatment of the stockpile material, the Fe:As ratio was too low (1.8:1) to stabilize arsenic, requiring the addition of Fe to the system. Also, there was a lack of nearby sources of limestone for pH control, and a decline in the Au price finally made the project unviable (BacTech Environmental 2020).

7 MINERAL POTENTIAL FOR BATTERY MINERAL DEPOSITS

Finland has been a cobalt producing country for several decades, with annual production of 1000–1500 t, and finished Co production (Co powder and chemicals) has been ongoing from the late 1960s with the commencement of production at the Kokkola plant. In the past, the primary production has come from Outokumpu-type Cu-Zn-Co-Ni deposits and orthomagmatic Ni-Cu deposits in southern and central Finland (i.e., Svecofennian-type intrusions). In more recent years, there have only been three mines producing cobalt: Kevitsa (2012–), the Terrafame Sotkamo mine (2011–) and the Kylylahti mine (2012–2020).

Future potential for Co-production can be broadly classified into three categories: 1) Active advanced exploration projects with already delineated resources such as the Sakatti Ni-Cu-PGE-Co project in Sodankylä (Anglo American), Rajapalot area Au-Co deposits at Ylitornio (Mawson Resources), Juomasuo at Kuusamo (Latitude 66 Cobalt), Portimo Complex PGE-Ni-Cu deposits at Rovaniemi–Ranua (Suhanko Arctic Platinum/CD Capital Natural Resources Fund III L.P.), Kaukua and Haukiaho in southern Posio (Palladium One), and Hautalampi Ni-Cu-Co at Outokumpu (Finn Cobalt Oy/Euro Battery Minerals). 2) Deposits where resources have been delineated in the past ("historic" estimates), but are not under active exploration, and some past-producing mines, e.g., Vaara Ni-PGE deposit at Suomussalmi and Rytky Ni-Cu deposit near Kuopio. 3) "Green fields" exploration, i.e., exploration for totally new deposits.

The last category mentioned above is the most difficult to assess: what is the potential for discovering totally new cobalt deposits? The great majority of the known deposits occur in a specific area, such as the Kuusamo deposits, or are associated with a distinct geological unit, such as the Outokumpu deposits, which are hosted within a former sea floor of distinct age that is only known to occur in the Outokumpu region. The so-called Svecofennian Ni-Cu deposits occur in small mafic–ultramafic intrusions in two major areas: the east–west-stretching Vammala belt in southern Finland and along a broader belt extending from Parikkala towards Raahe (the Raahe–Ladoga zone) (see Fig. 7). They represent a distinct age group of intrusions related to a major geological event. Similarly, layered intrusion-hosted PGE-Ni-Cu deposits occur in intrusions of distinct age, while komatiite-hosted Ni-Cu deposits only occur in MgO-rich volcanic rocks in eastern Finland and central Lapland. Most of these areas have been under exploration for decades and are at least thought to be well known. However, most if not all of these deposits occur at or very close to the surface of bedrock and are thus more easily detectable by traditional exploration methods such as till geochemistry (anomalous metal concentrations in till), ore boulders excavated and transported by glaciers that can be traced back to the source, and magnetic and electromagnetic signatures that can be measured by aero- and ground geophysical measurements. As a result, exploration drilling generally only extends to relatively shallow depths of 100–200 m. However, there are a few good examples of more recent discoveries, e.g., the Sakatti Ni-Cu-PGE-Co deposit at Sodankylä and the Rajapalot Au-Co deposit(s) at Ylitornio. The Sakatti discovery was the result of decade-long systematic exploration by Anglo American. Although the high-grade ore occurs at a fairly deep level (500–700m), low-grade mineralization extends to the surface and the host rock is detectable by geophysics. The Rajapalot Au-Co deposit represents a new discovery in a new area not known to be potential for Au deposits. Recent advances in exploration methods have made it possible to detect deep ore bodies, for example by geophysics, and also to drill deeper exploration holes, and exploration trends indicate fewer discoveries of exposed or shallow ore bodies.

Despite the recent low Co prices, after the price spike in 2017–2018, exploration for cobalt has remained active in Finland. This is indicated by the map in Figure 25, which shows the current situation regarding (exploration) reservations and exploration permits, with cases where cobalt has been indicated as one of the target commodities marked in green (reservations and reservation applications) and red (exploration permits and applications for exploration permits).

Prior to the current drive to lower CO_2 emissions by, for example, switching to hybrid and FEVs, and hence an expected increase in the demand for rechargeable Li-ion batteries and the metals and minerals needed for them, interest in cobalt was relatively low. As a result, cobalt might not have even been analysed or it might have been ignored at concentration levels now deemed significant or at least interesting. Therefore, looking more carefully at analytical data from past exploration could also reveal some new potential Co-containing deposits. The expected or potential increase in demand for cobalt could result in higher cobalt prices, which could make currently uneconomic deposits more viable.

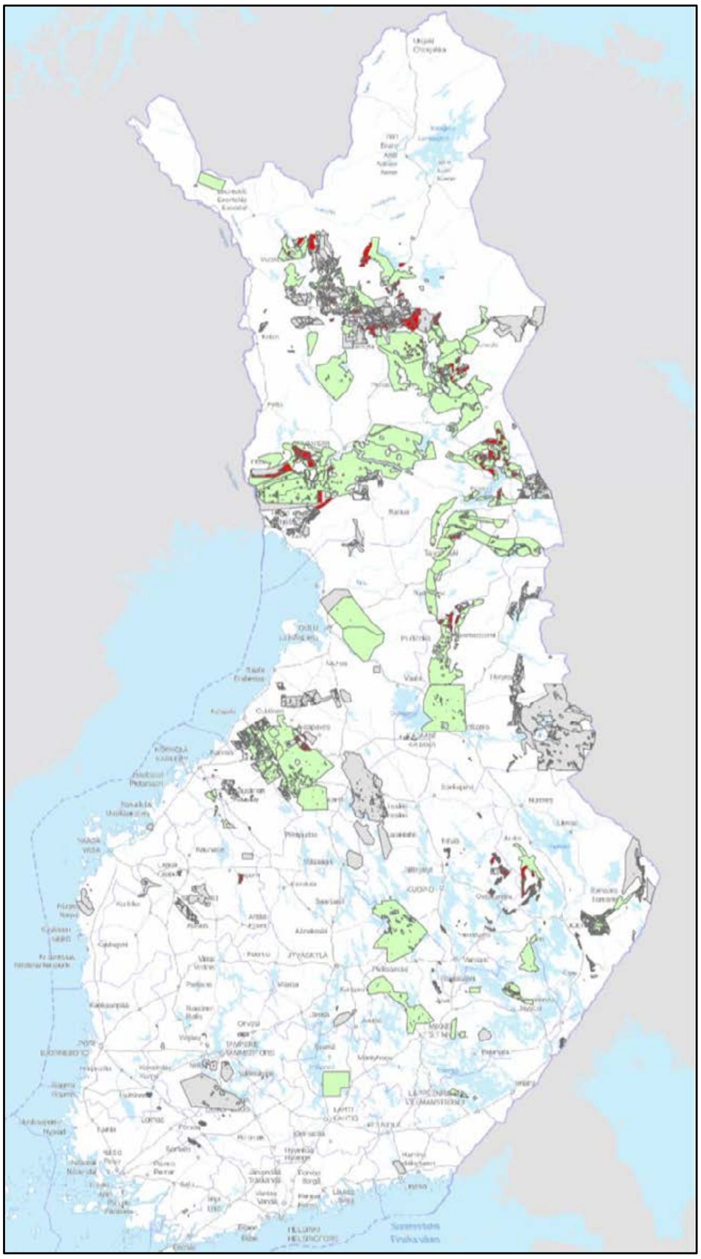

Fig. 25. The current situation (February 2021) regarding reservations and exploration permits. Reservations with cobalt indicated as a possible commodity are marked in green and exploration permits are marked in red.

Evaluating the exploration potential for cobalt at the scale of Finland is difficult and only broad features can be shown. Figures 26 and 27 display typical datasets used in exploration (excluding aerogeophysical data). Figure 26 (left) shows the rastered (averaged) Co content in regional till samples and various types of ore deposits. Low till Co contents are indicated in blue, while elevated values are shown in green to red colours. At the regional scale, some Co anomalies correspond with known metallogenic zones, such as the Vammala Ni belt in southern Finland, and partially with the Kotalahti Ni belt, Outokumpu area and Talvivaara areas in central-eastern Finland. It should be noted that the large anomalous area in northern Finland is mostly due to the presence of abundant mafic and especially ultramafic rock formations, which effectively mask Co anomalies due to actual mineralisations. Based on evaluation of the till data, contents of about 20 ppm can be considered anomalous, while in the anomalous areas in Lapland, the regional background value is already between 20–30 ppm, simply due to the prevalent rock types. The map on the right in Figure 26 shows drill core analyses, with intersections >500 ppm Co marked in green and those with 100–500 ppm Co marked in black (GTK and Outokumpu Oy data). Comparing this data set with the deposit map on the left, it is fairly obvious that nearly all higher grade intersections correspond to a known drilled deposit or occurrence. Some of the lower grade intersections, however, occur outside of known deposits in the GTK deposit database and could merit further scrutiny.

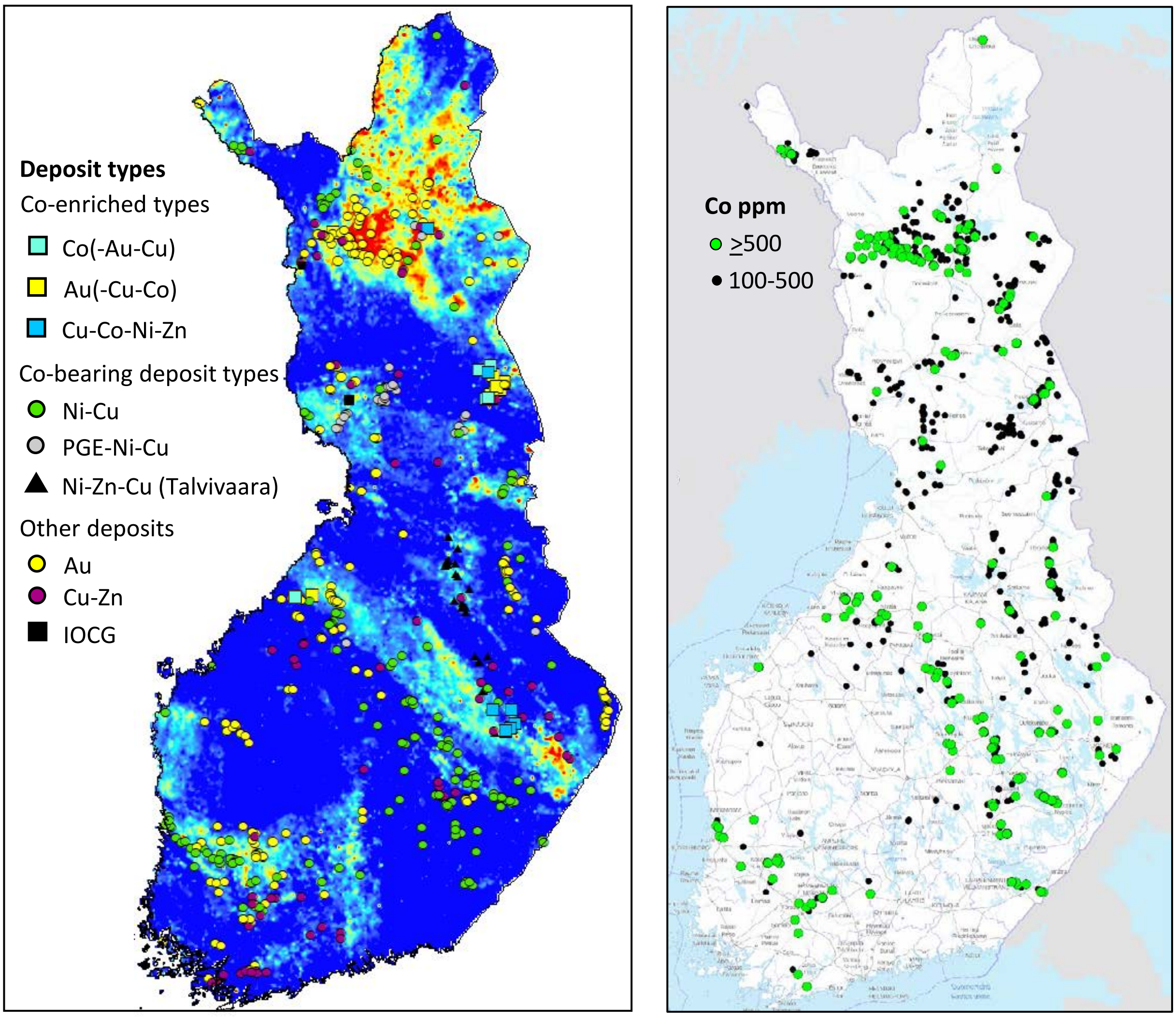

Fig. 26. Left: Till Co content (background) and Co-containing deposits. Blue colours indicate low till Co contents (<10 ppm), greenish colours indicate moderate contents (10–15 ppm), and yellow (15–20 ppm) to red (>20 ppm) colours indicate high Co contents. Right: GTK and Outokumpu Oy drill core data, with green dots indicating drill intersections with a minimum of 500 ppm Co and black dots indicating intersections with 100–500 ppm Co.

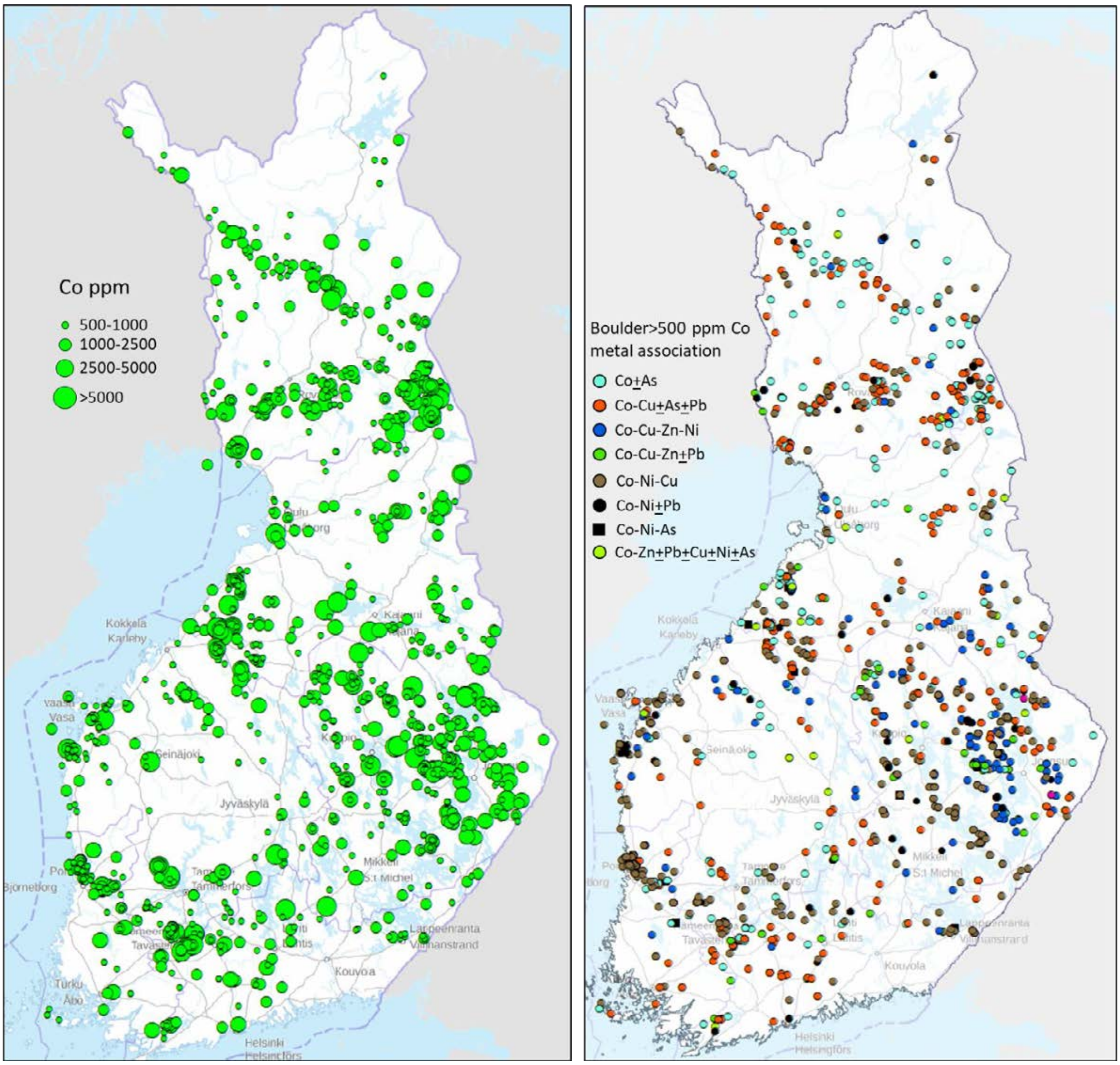

Fig. 27. Boulder and outcrop data with analyses revealing >500 ppm Co presented on the left and cobalt metal associations presented on the right. See text for discussion.

Another example of exploration is depicted in Figure 27, which shows analysed GTK and Outokumpu Oy boulder and outcrop (bedrock) samples (>2000 samples) with >500 ppm Co (left) and a "metal association", i.e., metals (or elements) occurring with Co at anomalous levels (right). Metal association is useful together with the sample rock type (not shown) in trying to evaluate the type of deposit from which a boulder originated, which affects the exploration strategy. For example, there is a cluster of Co-Cu-Zn-Ni boulders (shown in blue) in the Outokumpu region, which also corresponds to the spectrum of metals typical for Outokumpu-type deposits. Similarly, Co-Ni-Cu boulders are common along the Vammala and Kotalahti Ni belts in southern and central Finland (brown dots). In can be then postulated that these could have been extracted by glaciers from known deposits. On the other hand, there are a number of Co-As boulders scattered across northern Finland, some of which might originate from Kuusamo–Rajapalot-type Au deposits or orogenic Au deposits, common in central Lapland. Sifting through all the boulder data would require a loser scrutiny of boulder rock types, ice transport directions and distances for each boulder.

8 DEPOSITS IN NATURE CONSERVATION AREAS

Geological mineral resources only provide information on what is known to be available *in situ* for each commodity. Many technical and economic factors define what percentage (if any) of each deposit can possibly be commercially exploited. These aspects have been discussed earlier in this report. However, many other factors may limit or even completely prevent measures to exploit a deposit. Of these factors, the most important are other conflicting needs for the land use, either in the deposit area itself or in its vicinity. An exact distance cannot be unambiguously defined, as it is strongly dependent on the competing land use type. This may include residential or vacation home areas, tourism centres, reindeer herding, nature conservation and Sami rights, to name a few.

This report concentrates on geological resources, but it is worthwhile briefly considering one conflicting land use interest that can easily be spatially defined, i.e., nature conservation. There are numerous nature conservation areas in Finland that have been spatially outlined. In the following assessment, these outlines have been compared with the known battery mineral deposits in Finland. The outcome is presented in three categories with respect to existing nature conservation areas:

- Deposits located inside conservation areas;
- Deposits located in the immediate vicinity of conservation areas. In practice this means that at least part of the conservation area is located <1 km from the centre of the known deposit. In the case of operating mines or advanced projects, where the site infra layout is known, a 2-km buffer from the centre of the deposit has been used, or alternatively, if some associated infrastructure (e.g., a tailings storage facility) is located <1 km from the nature conservation area;
- Deposits located elsewhere.

In many cases, the location of a deposit in a nature conservation area may completely prevent project permitting and hence deposit exploitation. In other cases, the permitting and exploitation may be possible, but are much more challenging than for similar deposits located elsewhere. Similarly, the location of a deposit near a nature conservation area may be rather challenging from the permitting point of view, obviously to a large extent depending on factors such as the actual locations, conservation basis, site layout and environmental consequences. The purpose of the following assessment is not to provide a comprehensive overview of the permitting challenges or discuss the exploitation justification for these deposits. Rather, the purpose is simply to present how the known deposits are located in relation to the current nature conservation area network.

All conservation area types have been included in the assessment, of which the closest border has been selected to determine the distance to the deposit in question. Therefore, the actual conservation basis can vary widely from deposit to deposit. The most typical overlapping/bordering conservation areas appear to be Natura 2000 conservation areas (SAC and SPA), which form over 50% of the areas overlapping or with borders near to the deposits. If the Tornionjoki–Muonionjoki watershed Natura area is included, overlapping/bordering a Natura 2000 area applies to nearly 60% of the deposits in question.

The outcome for the assessment is that 8–11% of the known nickel and cobalt resources are located in nature conservation areas (Table 17). The percentage increases to 18–25% if deposits located near conservation areas are counted, as described above. These numbers are somewhat modest, but when the resource tonnage contained in Terrafame Sotkamo (Talvivaara) is excluded, the figures are clearly higher. In this case, 27–31% of nickel and cobalt resources are located in conservation areas, and when including those near conservation areas, 62–71% of the resource tonnage is constrained. In the case of copper, the figures are even higher in all cases. Lithium appears to be the "easiest" commodity in this sense. Basically, the whole lithium tonnage is located in areas not constrained by nature conservation areas. The assessment for graphite deposits is somewhat skewed, as there is only one graphite deposit with a resource estimate in place. The Aitolampi deposit happens to be located near a local scenery protection area (the Heinävesi route), with other types of conservation areas further away (at least 3.5 km).

Table 17. Finnish known resources for nickel, cobalt, copper, lithium and graphite and the distribution of the deposits in relation to nature conservation areas. The percentage distributions for deposits located in nature conservation areas as well as those with a conservation area in the vicinity have been colour coded for three classes (see coding at the bottom of the table). The distribution is also shown for tonnage excluding Terrafame Sotkamo, which is the biggest resource for nickel, cobalt and copper.

	Ni	Co	Cu	LiO2	Graphite
Number of deposits with a resource estimate	98	76	156	9	1
All deposits, Total (t)	5 804 988	410 564	5 977 211	161 033	1 276 794
In or close to a nature conservation area, Total (t)	1 453 818	74 978	2 820 420	1 780	1 276 794
In a nature conservation area, Total (t)	**625 772**	**32 283**	**1 386 047**	**1 780**	**0**
Proportion of resources in or close to a nature conservation area (%)	25	18	47	1	100
Proportion of resources in a nature conservation area (%)	11	8	23	1	0
Terrafame Sotkamo (Talvivaara) % of total resources	66	71	36		
Proportion of tonnage in or close to a nature conservation area (%, excluding Terrafame)	73	62	73		
Proportion of tonnage in a nature conservation area (%, excluding Terrafame)	31	27	36		

> 50% of the tonnage at nature conservation area or vicinity
20–50% of the tonnage at nature conservation area or vicinity
0–20% of the tonnage at nature conservation area or vicinity

In principle, it can be stated that for nickel, cobalt and copper, the constraints set by nature conservation areas are significant regarding the resource tonnage in general. Individual deposits are not further discussed here. It is imperative to remember these conditions when discussing Finnish battery mineral resources or primary resources in general. Including all other conflicting land-use needs, the exploitable resources are likely to be even smaller than this limited assessment discloses. As such, the Finnish battery metal resources (and mineral resources in general) are impressive, especially in the European context. However, it must be remembered that only a specific portion of the total resources can eventually be exploited when all the land-use constraints are included and assuming technical-economic feasibility can be proved.

A resource breakdown for Ni, Co, Cu and Li is presented in Figure 28. When comparing the resource data with the other sections of this report, please note that the total tonnage may vary due to two reasons: 1) due to the Co estimates given for some deposits and 2) in other resource estimates in this report, only those including cobalt have been included. Resource tonnages for Co in this nature conservation assessment are generally smaller, as only the official figures are used for this purpose. Furthermore, it is noted that the tonnage depicted in Table 17 and Figure 26 also includes data from deposits that do not contain any (known) cobalt, e.g., Cu-Zn deposits, and a number of 2.44 Ga layered intrusion-hosted Ni-Cu deposits without Co data. Nevertheless, the comparison generally presents the effect of nature conservation areas rather well.

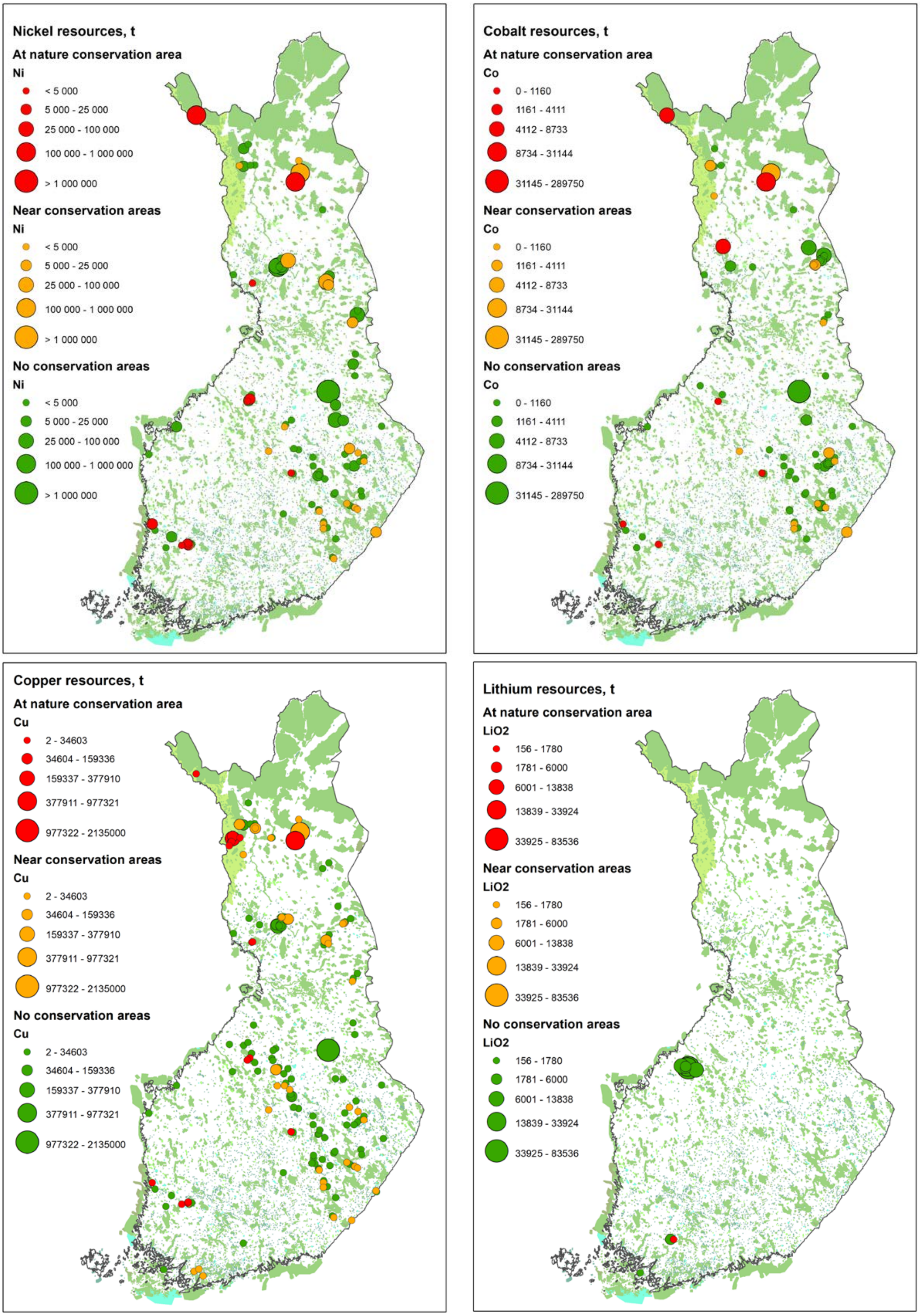

Fig. 28. The size and location of Finnish nickel, cobalt, copper and lithium deposits with respect to nature conservation areas. Green background colours indicate various nature conservation areas.

9 UNDISCOVERED DEPOSITS

The Geological Survey of Finland has been conducting evaluations of the so-called undiscovered deposits since 2008. These are based on the USGS (United States Geological Survey) three-part quantitative assessment method developed since the mid-1970s (Singer 1993). The method does not provide mineral resource or reserve estimates, but rather produces probabilistic estimates of the total *in situ* tonnage of metals in undiscovered deposits to a depth of 1 km (Rasilainen et al. 2020). The assessment method used by GTK does not take into account any economic, technical, social or environmental factors that might affect the utilization of any deposit.

As the name implies, the three-part assessment method consists of three parts: 1. Selection of a descriptive model and grade-tonnage model for each deposit type under assessment. The descriptive model gives geological information on the deposit type (e.g., its host rocks, geological and tectonic environment and possible associated structures) needed in the second part of the assessment method. The grade-tonnage model contains data on the commodity grade and deposit tonnage data for known deposits of the type under assessment. Ideally, the model should include a sufficient number of deposits with a similar range of grades and tonnages as is known or assumed to occur in Finland. The model can be based on Finnish deposits alone, on Fennoscandian deposits or on a global model if deemed suitable for Finnish deposits. 2. Delineation of areas where the geology is regarded to be permissive (suitable) for the occurrence of the deposit type. For example, VMS-type deposits (e.g., Outokumpu-type) can only form in an oceanic environment, and only areas that are known to represent such geological formations would be considered to be permissive. These permissive tracts can vary in size from a few to hundreds of square kilometres (Fig. 29), depending on factors such as the deposit type, local–regional geology and level of exploration activity. Finally, a group of experts makes an independent estimate of the number of deposits occurring within the each of the permissive areas. Well-delineated deposits with published grade-tonnage data within the permissive areas are considered to be discovered deposits, whereas deposits that are thought be "open", i.e., those that have not been completely delineated by drilling, are considered to be undiscovered deposits and are included in the estimate. Generally, the estimations are divided into three confidence levels (90%, 50% and 10%). For example, a permissive area can be estimated to contain one undiscovered deposit at the 90% level of confidence, 2 deposits at the 50% confidence level and 4 deposits at the 10% confidence level. In the final step, the estimates are combined using statistical methods such Monte Carlo simulations to achieve the distribution of tonnage for the contained metals in undiscovered deposits. For a more detailed description of the method, see GTK reports (e.g., Rasilainen et al. 2020). Since the initiation of the GTK assessment project in 2008, a number of different deposit types has been assessed: platinum-group element deposits in mafic–ultramafic layered intrusions (e.g., Suhanko–Konttijärvi) (Rasilainen et al. 2010), orthomagmatic Ni-Cu deposits related mafic–ultramafic intrusions (e.g., Svecofennian Ni-Cu deposits such as Hitura) and komatiitic rocks (e.g., Ruossakero) (Rasilainen et al. 2012), volcanogenic massive sulphide (VMS, e.g., Pyhäsalmi Cu-Zn-deposit), porphyry copper and Outokumpu-type deposits (Rasilainen et al. 2014), orogenic gold deposits (e.g. Kittilä mine) (Eilu et al. 2015), chromite deposits (e.g. Kemi mine) (Rasilainen et al. 2016), pegmatite-hosted lithium deposits (e.g. Keliber Oy deposits) (Rasilainen et al. 2018), orthomagmatic mafic intrusion-related iron-titanium-vanadium deposits (Rasilainen et al., in preparation) and Kuusamo-type Co-Au deposits (Rasilainen et al. 2020). Cobalt is included in three of these assessments (orthomagmatic Ni-Cu, Outokumpu- and Kuusamo-type) and the results are depicted in Table 18. The mean estimate of combined contained Co is 270 000 t and at the highest confidence level 17 200 t. Again, it should be stressed that these are hypothetical and speculative tonnages and that these figures also contain some of the tonnage of the known resources. However, they also indicate prospectivity for Co in the areas delineated by the permissive tracts.

Table 18. Estimated undiscovered cobalt resources of some Finnish Co deposit types.

Orthomagmatic intrusion-hosted Ni-Cu deposits						
Metal	**At least the indicated amount at the probability of**				**Probability of**	
	0.9	0.5	0.1	Mean	Mean or greater	None
Co (t)	3400	23 000	110 000	44 000	0.31	0.01
Ni (t)	72 000	480 000	2 300 000	360 000	0.31	0.01
Cu (t)	32 000	200 000	930 000	360 000	0.32	0.01
Ore (Mt)	12	84	420	160	0.32	0.01
Orthomagmatic komatiite-hosted Ni-Cu deposits						
Metal	**At least the indicated amount at the probability of**				**Probability of**	
	0.9	0.5	0.1	Mean	Mean or greater	None
Co (t)	1300	10 000	44 000	18 000	0.31	0.02
Ni (t)	39 000	280 000	1 100 000	430 000	0.34	0.02
Cu (t)	10 000	59 000	280 000	110 000	0.29	0.02
Ore (Mt)	5.9	64	290	110	0.34	0.02
Outokumpu-type Cu-Zn-Co-Ni deposits						
Metal	**At least the indicated amount at the probability of**				**Probability of**	
	0.9	0.5	0.1	Mean	Mean or greater	None
Co (t)	2900	53 000	150 000	68 000	0.41	0.05
Ni (t)	3000	41 000	100 000	49 000	0.43	0.05
Cu (t)	24 000	580 000	2 100 000	860 000	0.39	0.05
Zn (t)	13 000	220 000	700 000	300 000	0.39	0.05
Ore (Mt)	2.7	33	77	37	0.45	0.05
Kuusamo-type Au-Cu-Co deposits						
Metal	**At least the indicated amount at the probability of**				**Probability of**	
	0.9	0.5	0.1	Mean	Mean or greater	None
Co (t)	9600	100 000	310 000	140 000	0.40	0.02
Au (t)	14	85	240	110	0.41	0.02
Ore (Mt)	10	83	220	1000	0.42	0.02

Figure 29 presents the delineated permissive areas for magmatic Ni-Cu deposits, Outokumpu-type Cu-Zn-Co-Ni deposits and Kuusamo-type Au-Co-Cu deposits. Permissive areas for intrusion-hosted magmatic deposits in central and southern Finland are based on so-called Svecofennian-type Ni-Cu-Co deposits and occurrences. Permissive areas for komatiite-hosted deposits are more restricted on areas where komatiitic volcanic rocks are known to occur, i.e. in eastern Finland and central Lapland. Likewise, permissive areas for Outokumpu-type deposits are located in a restricted area in eastern Finland where Outokumpu-belt rocks are known to occur. Permissive areas for Kuusamo-type deposits are more widespread in southern and central Lapland, based on the occurrence of similar rock types of the same age group as the Kuusamo deposits themselves.

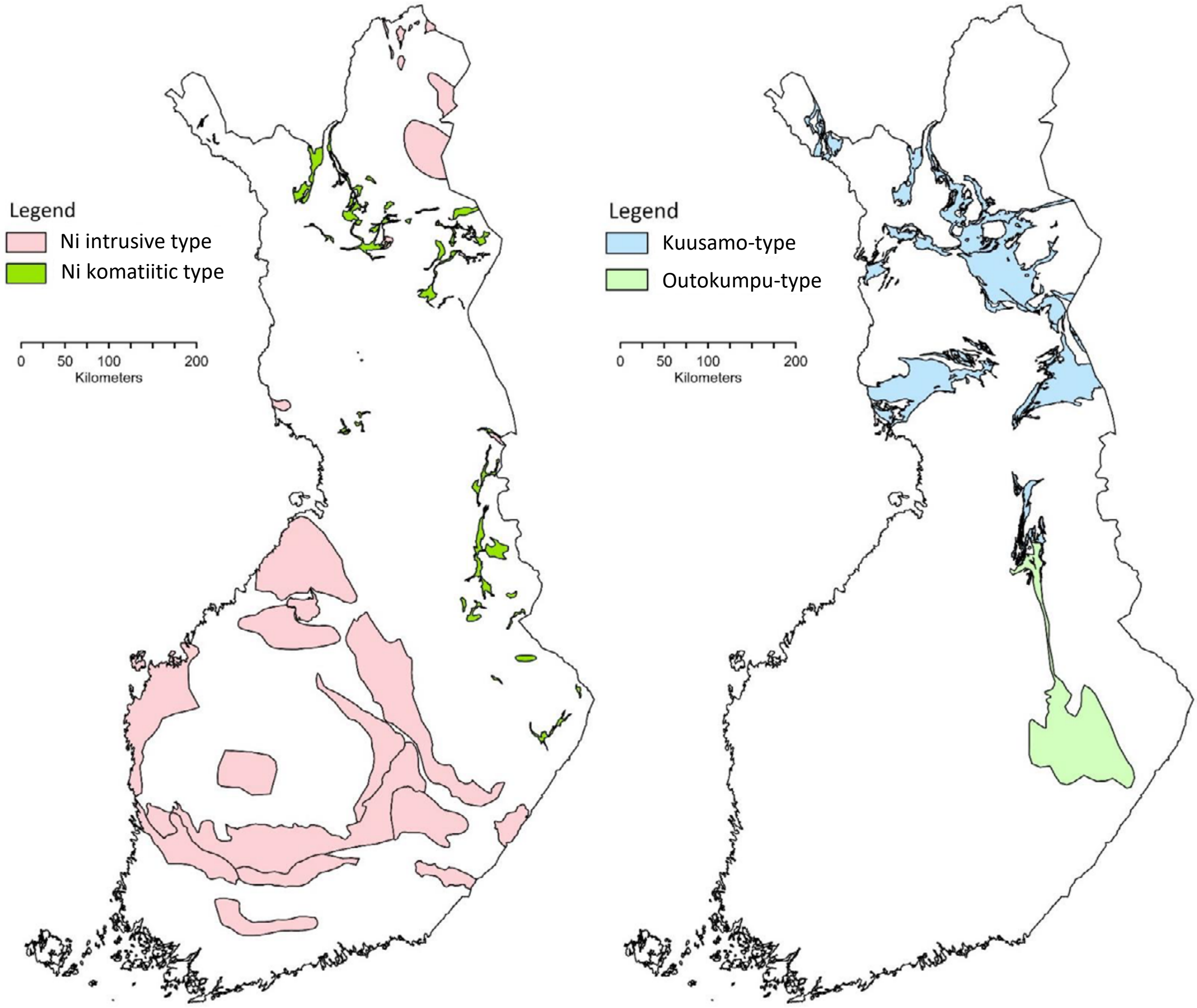

Fig. 29. Delineated permissive areas for orthomagmatic Ni-Cu-Co deposits on the left and for Outokumpu-type and Kuusamo-type deposits on the right.

10 SUMMARY AND CONCLUSIONS

Finland has a long history of cobalt mine production, either in the form of Ni-Co concentrates from magmatic Ni-Cu deposits or as a dedicated Co concentrate from the Outokumpu-type deposits, in addition to the production of finished cobalt products from smelters and the associated refinery (Harjavalta), as well as the Kokkola cobalt refinery. In recent years, cobalt has been in production from three mines: Kevitsa, Sotkamo (Talvivaara) and Kylylahti (production ended in 2020), with an annual production of 1000–1500 t of Co (equivalent to 85 000–125 000 mid-sized FEV battery packs). Currently, Finland is the only primary cobalt producer in the EU and a globally significant producer of refined cobalt products (~10% share). Finland hosts a diverse suite of Co-containing deposits, some of which will probably come into production in the (near) future. There is also potential for new discoveries or of renewed interest in known historical deposits, especially if cobalt demand increases as predicted due to the future electrification of society, especially in Europe, and the drive to source the required resources locally from the EU.

In this report, we have collected data on the most prominent deposit types, including grade-tonnage data, mineralogical hosts of cobalt, beneficiation of cobalt from different deposit types, as well as available downstream treatment methods for different Co concentrates. In addition, other possible cobalt sources, such as sulphur-rich tailings (e.g., Kylylahti, some IOCG-type deposits) or unconventional deposits (e.g., massive Co-bearing pyritic deposits) have been considered. Based on our data, Finnish deposits contain some 480 000 t of cobalt, equivalent to 3,5 years of world cobalt production. About 60% of all contained cobalt occurs in one mine, i.e., the Terrafame Sotkamo mine. Other significant deposits include the Kevitsa mine, Sakatti, Hannukainen, Ahmavaara and Juomasuo, each containing more than 10 000 t of cobalt. The majority of cobalt is hosted in a relatively few minerals, with pentlandite and cobaltpentlandite being the most important in many deposit types. Other Co-rich phases include cobaltite–gersdorffite and linnaeite–siegenite, which are generally minor Co carriers. Pyrite can be a significant Co-containing phase in some deposits.

There are several caveats that should be kept in mind with the total contained cobalt: It includes "old" resource figures, which are not JORC compatible, some resources occur in closed mines and might not be available for future mining, especially in old underground mines, typically only a certain percentage of mineral resources can be converted to mineral reserves, i.e., mineable tonnages, and only 30–75% of mined cobalt ends up in final products due to losses in flotation and downstream treatment processes. Conflicting land use is also one constraint to be taken into account when considering the resources for any commodity. For example, nature conservation areas may prevent the exploitation of a significant part of Co, Ni and Cu resources.

In addition to cobalt, Finland also has potential to produce lithium as well as graphite, for example, for rechargeable lithium-ion batteries. Keliber Oy plans to start battery-grade lithium hydroxide production in the early to mid-2020s with a targeted annual production of 15 000 t, equivalent to 400 000 42-kWh battery packs.

Data on concentrates and downstream processes indicate that they are not necessarily very efficient in utilizing available cobalt in the deposits, and there is a need to improve these technologies and develop and utilize new downstream processing technologies for better resource efficiency.

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APPENDIX 1: List of Co deposits with tonnage data.

Deposit	Type	Status	Total Mt	Co (t)	Ni (t)	Cu (t)	Zn (t)	Au (t)	2PGE (t)	Code
Hitura	Svecofennian Ni-Cu	Closed mine	4.72	944	23 612	8 717				JORC
Vammala	Svecofennian Ni-Cu	Closed mine	1.6	640	7 040	4 640				JORC
Laukunkangas	Svecofennian Ni-Cu	Closed mine	5.912	1 773	31 333	9 459				Old
Ruimu	Svecofennian Ni-Cu	Deposit	3.5	1 400	11 200	9 800				Old
Sääksjärvi	Svecofennian Ni-Cu	Deposit	3.5	1 050	8 400	11 550				Old
Niinimäki	Svecofennian Ni-Cu	Deposit	2.7	486	10 800	3 780				Old
Pitkäneva	Svecofennian Ni-Cu	Deposit	1.7	340	3 740	1 020				Old
Sahakoski	Svecofennian Ni-Cu	Deposit	1.6	480	10 400	3 040				JORC
Rytky	Svecofennian Ni-Cu	Deposit	1.54	462	10 934	4 466				JORC
Oravainen	Svecofennian Ni-Cu	Deposit	1.3	390	12 350	2 080				Old
Revonmäki	Svecofennian Ni-Cu	Deposit	1.3	260	3 120	2 990				Old
Ekojoki	Svecofennian Ni-Cu	Deposit	1.052	242	5 155	4 418				JORC
Kovero-oja	Svecofennian Ni-Cu	Closed mine	0.46	78	1 840	1 518				Old
Makola	Svecofennian Ni-Cu	Closed mine	0.665	332	4 921	2 926				Old
Hyvelä	Svecofennian Ni-Cu	Deposit	0.807	274	4 196	2 098				Old
Kusiaiskallio	Svecofennian Ni-Cu	Deposit	0.798	79.8	1 915.2	1 276.8				Old
Makkola	Svecofennian Ni-Cu	Deposit	0.526	178	2 735	946				Old
Mäntymäki	Svecofennian Ni-Cu	Deposit	0.466	46	3 401	932				Old
Hälvälä	Svecofennian Ni-Cu	Closed mine	0.199	149	2 985	716				Old
Rausenkulma	Svecofennian Ni-Cu	Deposit	0.375	86	1 350	1 838				Old
Särkiniemi	Svecofennian Ni-Cu	Closed mine	0.196	123	1 372	686				JORC
Liakka	Svecofennian Ni-Cu	Deposit	0.25	50	925	1 950				Old
Ilmolahti	Svecofennian Ni-Cu	Deposit	0.21	84	777	588				Old
Sulkavanniemi	Svecofennian Ni-Cu	Deposit	0.194	650	4 160	1 170				Old
Sarkalahti	Svecofennian Ni-Cu	Deposit	0.19	51	1 938	627				JORC
Tevanniemi	Svecofennian Ni-Cu	Deposit	0.182	54	1 146	273				Old
Talluskanava	Svecofennian Ni-Cu	Deposit	0.15	30	495	285				Old
Hanhisalo	Svecofennian Ni-Cu	Deposit	0.143	29	872	286				Old
Petolahti	Svecofennian Ni-Cu	Closed mine	0.11	22	517	473				Old
Mäkisalo	Svecofennian Ni-Cu	Deposit	0.104	31	447	291				Old
Eko	Svecofennian Ni-Cu	Deposit	0.088	17.6	589.6	228.8				Old
Niinikoski	Svecofennian Ni-Cu	Deposit	0.083	37	357	108				Old
Rietsalo	Svecofennian Ni-Cu	Deposit	0.056	8	297	297				Old
Heiskalanmäki	Svecofennian Ni-Cu	Deposit	0.055	8	302	137				Old

Code: JORC indicates more recent resource estimates based on modern JORC-compliant codes, old indicates older, non-compliant historical estimates.

Where the contained Co is highlighted in red, the tonnage is estimated or inferred from drill core analyses or the Ni content (see Fig. 11 of report)

In addition, there are a number less well-defined Svecofennian intrusion-hosted Ni-Cu occurrences, komatiitic Ni occurrences, and black schist-hosted Ni-Zn-Cu occurrences.

APPENDIX 1: Cont.

Deposit	Type	Status	Total Mt	Co (t)	Ni (t)	Cu (t)	Zn (t)	Au (t)	2PGE (t)	Code
Kekonen	Svecofennian Ni-Cu	Deposit	0.05	9	270	105				Old
Liuksiala	Svecofennian Ni-Cu	Deposit	0.05	10	150	100				Old
Härmäniemi	Svecofennian Ni-Cu	Deposit	0.037	14.8	310.8	88.8				Old
Vehmasjoki	Svecofennian Ni-Cu	Deposit	0.036	21.6	338.4	248.4				Old
Pisamaniemi	Svecofennian Ni-Cu	Deposit	0.027	2.97	180.9	27				Old
Pihlajasalo	Svecofennian Ni-Cu	Deposit	0.02	4	168	34				Old
Rantala	Svecofennian Ni-Cu	Deposit	0.02	4	106	68				Old
Honkamäki	Svecofennian Ni-Cu	Deposit	0.01	1.6	35	20				Old
Kevitsa	Other Ni-Cu	Mine	307.5	30 750	663 680	1 001 930		25.9	77.9	JORC
Sakatti	Other Ni-Cu	Deposit	44.4	20 424	426 240	843 600		14.652	50.172	JORC
Kaukua	Layered intrusion PGE-Ni-Cu	Deposit	21.86	1 311.6	18 581	30 604		1.86	21.01	JORC
Haukiaho	Layered intrusion PGE-Ni-Cu	Deposit	23.2	1 392	32 480	48 720		2.32	9.97	JORC
Konttijärvi	Layered intrusion PGE-Ni-Cu	Deposit	75.24	3 009.6	37 620	75 240		5.3	91.8	JORC
Ahmavaara	Layered intrusion PGE-Ni-Cu	Deposit	187.77	13 144	129 561	328 598		18.8	185.9	JORC
Vaaralampi	Layered intrusion PGE-Ni-Cu	Deposit	32	6 400	32 000	96 000			29.76	JORC
Niittylampi	Layered intrusion PGE-Ni-Cu	Deposit	1.037	477	6 948	5 081			0.98	Old
Vaara	Komatiitic Ni	Deposit	8.241	824	26 041	1 648			1.78	JORC
Arola	Komatiitic Ni	Deposit	1.5	195	6 900	150				JORC
Hietaharju	Komatiitic Ni	Deposit	1.083	606	8 610	4 364			1.8	JORC
Peura-aho	Komatiitic Ni	Deposit	0.495	188	2 985	1 995			0.42	JORC
Tainiovaara	Komatiitic Ni	Closed mine	0.43	43	2 150	129			0.06	Old
Kauniinlampi	Komatiitic Ni	Deposit	0.5	50	2 250					Old
Sika-aho	Komatiitic Ni	Deposit	0.18	21	1 206	18				Old
Ruossakero	Komatiitic Ni	Deposit	35.6	5 589	149 520	1 352				Old
Hotinvaara	Komatiitic Ni	Deposit	0.42	126	2 100					Old
Iso-Siettelöjoki	Komatiitic Ni	Deposit	0.5	75	1 450	50			1.16	Old
Lomalampi	Komatiitic Ni	Deposit	3.06	306	4 896	1530			5.22	Old
Sotkamo	Black schist Ni-Zn-Cu	Mine	1 525	289 750	3 812 500	2 135 000	7 930 000			JORC
Pappilanmäki	Black schist Ni-Zn-Cu	Deposit	34.26	4 111	65 779	34602	129 503			JORC
Lintumäki	Black schist Ni-Zn-Cu	Deposit	4	480	7 680	4040	16 000			Old
Kettukumpu	Outokumpu Cu-Zn-Co	Deposit	0.4	400	720	1760	400			Old
Hietajärvi	Outokumpu Cu-Zn-Co-Ni	Deposit	0.341	477	613	2285	3 853			Old
Riihilahti	Outokumpu Cu-Zn-Co-Ni	Deposit	0.7	630	210	5040	630			Old

Code: JORC indicates more recent resource estimates based on modern JORC-compliant codes, old indicates older, non-compliant historical estimates.

Where the contained Co is highlighted in red, the tonnage is estimated or inferred from drill core analyses or the Ni content (see Fig. 11 of report)

In addition, there are a number less well-defined Svecofennian intrusion-hosted Ni-Cu occurrences, komatiitic Ni occurrences, and black schist-hosted Ni-Zn-Cu occurrences.

APPENDIX 1: Cont.

Deposit	Type	Status	Total Mt	Co (t)	Ni (t)	Cu (t)	Zn (t)	Au (t)	2PGE (t)	Code
Hautalampi	Outokumpu Cu-Zn-Co-Ni	Deposit	3.16	3 476	13 588	11376	2 212			JORC
Vuonos Cu	Outokumpu Cu-Zn-Co-Ni	Closed mine	0.76	1 140	988	18012	12 160			Old
Sola	Outokumpu Cu-Zn-Co-Ni	Deposit	0.1	100	150	2000	1 000			Old
Perttilahti	Outokumpu Cu-Zn-Co-Ni	Deposit	1.324	1 324	1 986	28466	25 156			Old
Kylylahti	Outokumpu Cu-Zn-Co-Ni	Closed mine	6.88	7 774	19 195	26969	15 548			JORC
Saramäki	Outokumpu Cu-Zn-Co-Ni	Deposit	3.4	5 917	3 440	48848	43 344			Old
Luikonlahti	Outokumpu Cu-Zn-Co-Ni	Closed mine	0.85	1 020	765	10200	5 525			Old
Hoikka	Outokumpu Cu-Zn-Co-Ni	Deposit	0.2	80	300	1000				Old
Juomasuo	Kuusamo Au-Cu-Co	Deposit	24.2	15 660		2420		15.55		JORC
Haarakumpu	Kuusamo Cu-Co	Deposit	4.68	7 769		15912				Old
Kouvervaara	Kuusamo Au-Cu-Co	Deposit	1.58	2 371		4742		0.6		Old
Meurastuk-senaho	Kuusamo Au-Cu-Co	Deposit	0.892	1 784		20516		2		Old
Hangaslampi	Kuusamo Au-Cu-Co	Deposit	0.96	499		403		3		JORC
Säynäjävaara	Kuusamo Au-Cu-Co	Deposit	0.4	240		80		0.4		Old
Lemmonlampi	Kuusamo Au-Cu-Co	Deposit	0.14	336		574		0.05		Old
Pohjasvaara	Kuusamo Au-Cu-Co	Deposit	0.34	217		390		0.75		JORC
Apajalahti	Kuusamo Au-Cu-Co	Deposit	0.129	26		65		0.65		Old
Iso-Rehvi	Kuusamo Au-Cu-Co	Deposit	0.04	20		40		0.16		Old
Sivakkaharju	Kuusamo Au-Cu-Co	Deposit	0.05	15		60		0.36		JORC
Rajapalot	Ylitornio Au-Co	Deposit	9	5 130				18.9		JORC
Vähäjoki	IOCG (Tervola)	Deposit	10.5	3 045		16800		2.1		Old
Hannukainen	IOCG(Kolari)	Closed	221	29835		397800		17.68		JORC
Kuervitikko	IOCG (Kolari)	Deposit	43	4 300		81 700		3.14		JORC
Cu-Rautu-vaara	IOCG (Kolari)	Deposit	2.8	1 338		12 000		0.5		Old
Rautuoja	IOCG (Kolari)	Deposit	8.4	840		17 640		1.58		Old
Pahtavuoma	VMS	Closed mine	21.1	2 110		63 300	14 137			Old
Saattopora Cu	VMS (?)	Deposit	11.6	1 160	11 600	71 920		2.9		Old
Kelujoki	Hydrothermal Cu-Co	Deposit	1.5	450		3 000				Old
Jouhineva	Hydrothermal Cu-Co-Au-Ag	Deposit	0.45	810		3 645		0.4		Old

Code: JORC indicates more recent resource estimates based on modern JORC-compliant codes, old indicates older, non-compliant historical estimates.

Where the contained Co is highlighted in red, the tonnage is estimated or inferred from drill core analyses or the Ni content (see Fig. 11 of report)

In addition, there are a number less well-defined Svecofennian intrusion-hosted Ni-Cu occurrences, komatiitic Ni occurrences, and black schist-hosted Ni-Zn-Cu occurrences.

APPENDIX 2: List of Li and graphite deposits. In addition, there are some 33 known minor Li occurrences.

Deposit	Type	Status	Total Mt	Li2O (t)	Code
Emmes	Pegmatite	Deposit	1.076	13 127	JORC
Hirvikallio	Pegmatite	Deposit	0.100	1 780	Old
Kietyönmäki	Pegmatite	Deposit	0.400	6 000	Old
Leviäkangas	Pegmatite	Deposit	0.468	4 680	JORC
Länttä	Pegmatite	Deposit	1.328	13 811	JORC
Outovesi	Pegmatite	Deposit	0.281	4 018	JORC
Rapasaari	Pegmatite	Deposit	8.214	83 782	JORC
Rosendal	Pegmatite	Deposit	1.300	156	Old
Syväjärvi	Pegmatite	Deposit	2.827	33 924	JORC

Deposit	Type	Status	Total Mt	Graphite (t)	Code
Aitolampi	Flake graphite	Deposit	27	1 276 794	JORC
Viistola	Amorphous	Deposit	4.2	1 201 200	Old
Kuusivaara	Flake graphite	Occurrence			
Piippumäki	Flake graphite	Occurrence			
Kärpälä	Flake graphite	Occurrence			
Haapamäki	Flake graphite	Occurrence			
Rääpysjärvi	Flake graphite	Occurrence			
Soukko	Undefined	Occurrence			
Kolari	Amorphous	Occurrence			
Käpysuo	Flake graphite	Occurrence			