Translation of government assignment

Mapping of innovation-critical metals and minerals

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Cover photo: Drillcore containing lithium from Järkvissle.
Photo: Specim.

Full title of the government assignment: Uppdrag att kartlägga Sveriges möjligheter att utvinna metaller och mineral för miljö- och teknikinnovationer.

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THE ASSIGNMENT

SGU has been instructed by the Swedish government to map the potential for extraction in Sweden of metals and minerals that are needed to manufacture new environmental and technical innovations being developed in Sweden and Europe. The project includes mapping and knowledge building of both primary and secondary sources of innovation-critical minerals and metals and mapping of the most important mining waste deposits in the Bergslagen mining district. In a parallel project, the Swedish Agency for Growth Policy Analysis (Growth Analysis) has analysed the future need for innovation-critical metals, including the possibility of locating the whole production chain from raw material extraction to final product in Sweden.

This document is a translation of the final report on the government assignment. The report (to the Ministry of Enterprise and Innovation, journal no. N2016/06368/FÖF) was published in December 2018 (SGU journal no. 311-2379/2016, in Swedish) An interim report was published in February 2018.

SUMMARY

In the interim report on this government assignment SGU concluded that Sweden has geological potential for a number of innovation-critical raw materials and showed that there are already several deposits with ore estimates that include these raw materials. This final report expands and updates the information on deposits with ore estimates to include more raw materials (see Figure 1 and Table 5). The number of deposits with ore estimates including critical raw materials evidences Sweden's good geological potential.

The interim report also showed the locations where SGU's sampling and compilations indicated elevated levels of some critical raw materials. This report relates this knowledge to statistical information on mining production and exploration projects.

A prerequisite for economically sustainable extraction of critical raw materials as a by-product in the extraction of a main metal (iron, base or precious metals) is that there are mineable resources of main metals. SGU has identified several mines and mining areas (most of them closed), as well as several exploration projects, where new analyses or digitised older analyses showed one or more critical metals together with main metals (see Table 1). These demonstrated relationships are not comparable with a proper ore estimate, since there are too few new analyses. However, they show that the deposits are worth more detailed investigation. In all cases, sampling and analysis of drill core, rock samples and mining waste have added new information on the presence of critical raw materials. These findings are shown in the map in Figure 1 under the heading "New analyses", and in Table 1. Brief descriptions of several of the deposits can be found in the section "Old deposits – new analyses".

Active exploration and research is currently under way on extraction of critical raw materials at several of the areas and deposits that have been identified. Detailed mapping and mineral deposit documentation by SGU are ongoing in several areas in Bergslagen.

Among all these deposits, only the Kankberg gold–tellurium mine is in operation. Tellurium is not currently regarded as a critical raw material, but Kankberg is the first Swedish example for several decades of a new raw material being extracted from an iron, base or precious metal mine.

No critical raw materials are currently being produced at any Swedish mine. However, there are projects, including those where an ore estimate has been presented, that have stalled in the

permit processes required to open a mine in Sweden. Good geological and economic potential and functioning mining industry infrastructure are not enough to start extraction of critical raw materials in Sweden. At present it is unclear whether mining waste extraction falls under the Minerals Act.

The results of the study show that reconnaissance sampling and analysis of drill cores and mining waste are quick and cost-effective methods of obtaining an overview of the presence of both critical raw materials and main metals. By relating these analytical results to other information on mines and concentrators gained from mining statistics, such as quantity and metal content of ore and mining waste, it is possible to gain knowledge about the existence of critical raw materials in the remaining ore and tailings. The methods used in the project also apply to identifying and quantifying the presence of harmful substances, although this has not been done in the project. The collection, systematisation and compilation of chemical analyses from various sources and the results of sampling and analysis of drill cores, rock samples and mining waste have been compiled in the MALMKEMI-db database, which contains just over 30,000 entries. The database can be downloaded from the SGU website www.sgu.se.

SGU is currently engaged in projects aimed at improving our knowledge of raw materials in Sweden's bedrock. Most of them rely on temporary funding from the state and the EU.

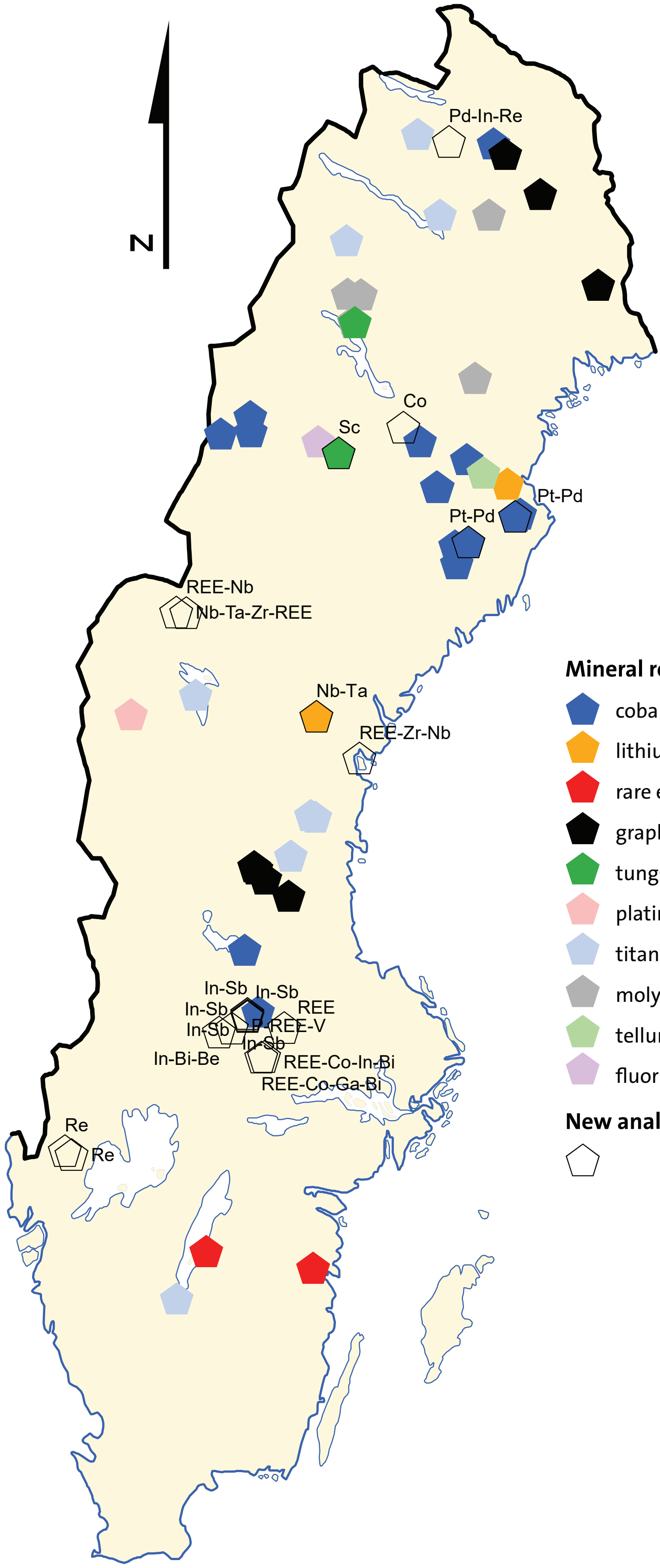

Figure 1. The map shows deposits with ore estimates that include some critical raw materials (see Table 5). The map also shows discoveries where new analyses or digitised older analyses have demonstrated the presence of some critical raw materials in closed mines, in mining waste or in exploration projects (see Table 1).

Table 1. Mines and mining areas (most now closed) with known production history, and exploration projects where new analyses indicate one or more critical metal associated with main metals.

SKARN IRON ORE WITH SULPHIDES AND/OR REE		
	Main metal(s)	**Potential by-product(s)**
Källfallsfältet	Fe	REE, Co, Ga, Bi, Mo
Östanmossen	Fe	REE
Bäckegruvan	Fe, Cu	REE, Co, In, Bi
Stollbergsfältet	Zn	In, Sb
APATITE IRON ORE		
	Main metal(s)	**Potential by-product(s)**
Grängesberg area	Fe	P, REE, V
PEGMATITES		
	Main metal(s)	**Potential by-product(s)**
Järkvissle	Li, Sn	Nb, Ta
COPPER MINERALISATIONS		
	Main metal(s)	**Potential by-product(s)**
Adakfältet	Cu	Co
Viscaria	Cu	Co, Pd, In, Re, REE
Dingelvik	Cu, Ag	Re
TUNGSTEN MINERALISATIONS		
	Main metal(s)	**Potential by-product(s)**
Yxsjöbergsfältet	Cu, W	In, Bi, Be
Svärtträsk	W	W
NICKEL-COPPER MINERALISATIONS		
	Main metal(s)	**Potential by-product(s)**
Rörmyrberget	Cu, Ni	Co, Pt, Pd
Lappvattnet	Cu, Ni	Co, Pt, Pd
ALKALINE INTRUSIONS		
	Potential products	
Alnö-Sundsvall area	REE, Zr, Nb	
Åkersjön	REE, Nb	
Holmslättmyran	Nb, Ta, Zr, REE	

CRITICAL RAW MATERIALS – AN OVERVIEW

Access to raw materials is fundamental in a functioning, modern and sustainable society. Population growth around the world, economic growth in developing countries, and technological development have increased global demand for many raw materials. Modern technological developments and innovations generate increasingly complicated products that require access to a number of "new" metals and raw materials.

Achieving the targets set by the Paris Agreement and Agenda 2030 will require lower emissions from the transport sector and industry. Transition to fossil-free systems for energy production, energy storage and transport are drivers, and will require a large increase in production of certain critical raw materials (Speirs et al. 2014). The ongoing transition from fossil fuel-driven vehicles to electric ones means that the automotive industry needs large quantities of "battery" metals. If the industry cannot access the necessary raw materials, technological development and the transition to a sustainable society with lower emissions will be hampered.

Many of the critical metals are very important constituents in products, but they are rarely used in large volumes and are minor components compared with base metals (copper, zinc, lead, aluminium) and iron. Any substitution may result in reduced performance, higher prices or both. The substitute is often another critical metal and transfers the supply problem from one critical raw material to another (Hageluken & Meskers 2010).

The term "Critical Raw Materials" (CRMs) has no universal definition, but usually refers to metals and minerals that are of high economic importance to an industry, industrial sector or geographical area, and for various reasons risk being in short supply (Graedel et al. 2015). Criticality for a given raw material can change over time and reflects factors such as current and expected future demand, global political conditions and technological development (Bedder 2015).

The EU critical list

With only about 3% of the world's metal ore production and 25–30% of the world's metal consumption, Europe is heavily dependent on imports of many raw materials (Tiess 2010, Brown et al. 2016). The EU Commission launched the Raw Materials Initiative in 2008 as part of the efforts to secure the EU's access to critical raw materials. This is an integrated strategy that includes:

- Safe and sustainable supply of raw materials from international markets
- Sustainable supply from European sources
- Increased resource efficiency and recycling

One priority was to establish a list of critical raw materials at EU level. The two basic criteria for a raw material to be defined as critical by the EU are (i) a relatively high supply risk because world production is concentrated in only a few countries with potential geopolitical constraints; and (ii) its economic importance, i.e. the share of each raw material associated with industrial megasectors in the EU. Ensuring stable and affordable access to critical raw materials is therefore an important issue for the EU, particularly since extraction and production are concentrated in just a few countries (see Table 2). Many of the critical raw materials defined by the European Commission are metals (exceptions include graphite, phosphate, fluorspar). The list of critical materials was first published in 2011 and was updated and expanded in 2014

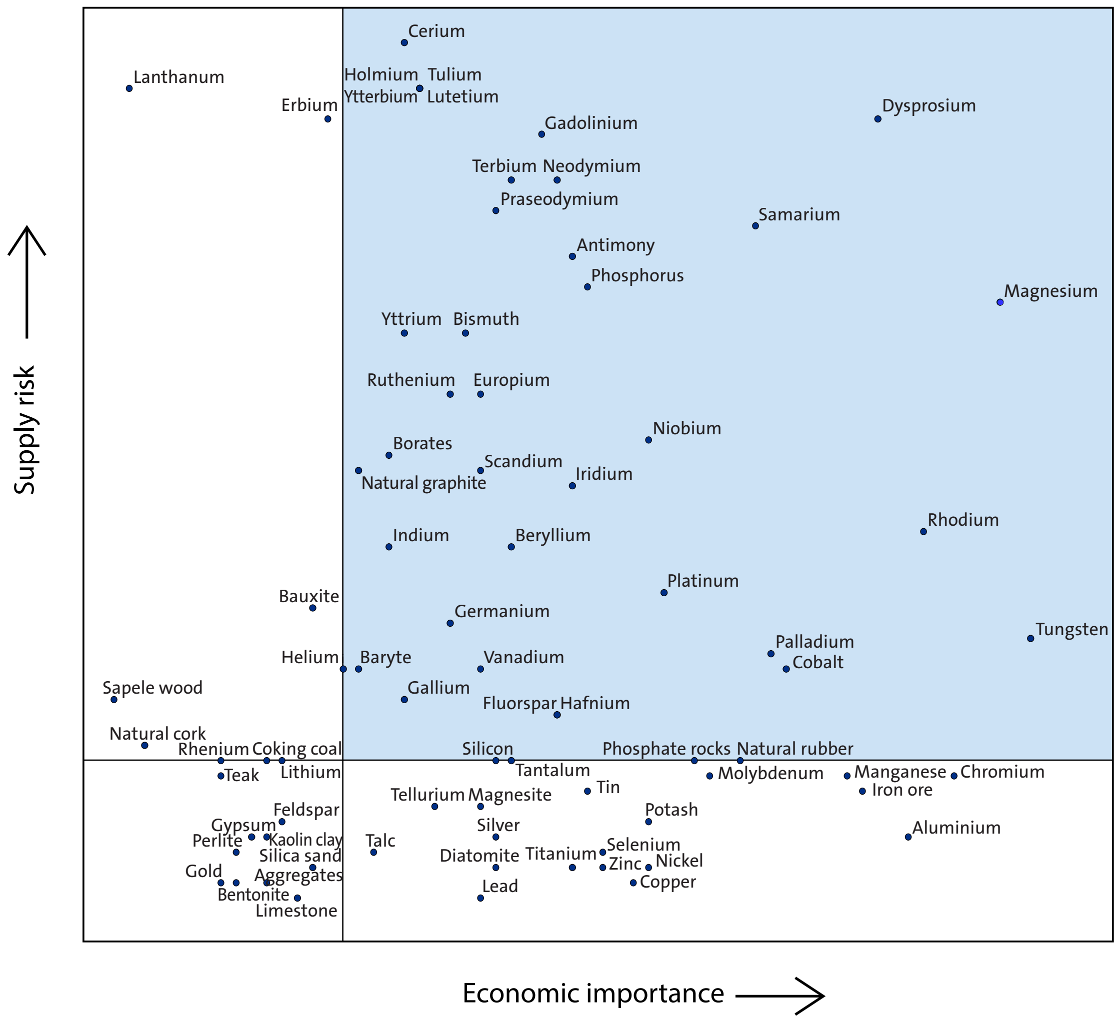

Figure 2. EU critical raw materials (EU Commission 2017a). The Rare Earth Elements (REE) comprise scandium and yttrium, as well as the lanthanoids: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium. Note that promethium has no stable isotopes and lanthanum and erbium are outside the "critical" field (in blue). The platinum group metals (PGM) consist of ruthenium, rhodium, palladium, osmium, iridium and platinum.

and 2017. It now includes 27 critical raw materials; see Figure 2 and Appendix 1. The list is updated every three years.

Recycling is very important to achieve resource efficiency and reduce environmental impact. However, the recycling rate for several of the critical raw materials is still low (see Table 3). Even with a very high recycling rate, recycling will not suffice to meet future demand. Primary mining of critical materials will still be needed (EASAC, 2016).

Critical raw materials for Sweden

In a previous government assignment : "Survey and Analysis of Extraction and Recycling Potential for Swedish Metal and Mineral Resources", SGU compiled a list of critical metals and mine-

Table 2. A selection of critical raw materials and the largest producer countries. China accounts for a large share of global production of CRMs. Other countries with a large share of global production of certain CRMs include Brazil, Democratic Republic of Congo (DRC), Russia, South Africa, and the United States. Source: EU Commission (2017d).

Raw material	Producing country	Share of global production (%)
REE	China	95
Antimony	China	87
Tungsten	China	84
Gallium	China	73
Natural graphite	China	69
Niobium	Brazil	90
Beryllium	USA	90
Platinum	South Africa	70
Cobalt	Democratic Republic of Congo	64
Palladium	Russia	46

Table 3. Functional recycling rate for critical raw materials. Data from UNEP (2013). Functional recycling means that the physical and chemical properties of the material are retained after recycling. This includes recycling where metal in an EoL product is separated and sorted to produce recycled material that can return to a production process to produce a given metal or metal alloy (Graedel et al. 2011).

Recycling rate (%)	Critical raw material (EU 2017)
< 1	Be, B, Sc, V, Ga, Ge, In, Ta, Hf, Bi, Os, REE
1–10	Sb
> 10–25	W, Ru
> 25–50	Mg, Ir
> 50	Co, Nb, Pt, Pd, Rh

rals relevant to Sweden (SGU 2014). It differs somewhat from the EU list, mainly because Sweden is a major manufacturer of special steels and hard metals, an industry that requires highly specific raw materials.

The Swedish Agency for Growth Policy Analysis, which analysed the entire value chain for innovation-critical raw materials, specifically mentions lithium, REE, graphite, tungsten and cobalt as critical for the establishment of entire production chains in Sweden (Tillväxtanalys 2017a, b). It also identifies the main market risks associated with developing Swedish or European value chains in competition with large foreign players, such as Chinese clusters.

Conflict minerals

Conflict minerals are minerals and metals that are extracted in areas of political instability, civil war or other armed conflict, and where trade in these minerals is used as a source of income by armed groups and warlords. Extraction may involve forced labour, child labour, human rights violations and corruption. In 2017 the EU adopted a regulation to counteract trade in conflict minerals (EU Commission 2017c). The regulation enters into force on 1 January 2021, and imposes a duty on anyone importing tin, tungsten, tantalum and gold ("3TG") to the EU to abide by OECD guidelines to ensure that imports are from responsible sustainable sources.

FACTORS INFLUENCING EXRTACTION POTENTIAL

Geological potential

The earth's crust contains large amounts of all the metals and minerals discussed in this report and there is no theoretical risk that they will be exhausted. However, the availability of a given metal or mineral cannot be based solely on its average content in the earth's crust; it must be present in quantities and concentrations that are economically recoverable. More than half of the naturally occurring elements in the earth's crust occur in average concentrations of less than 5 grams per tonne (Rudnick & Gao 2003). The ability of an element to concentrate in ore bodies is thus a fundamental property that enables recovery. Geologically, many critical metals usually occur in low concentrations in ores together with base metals such as copper and zinc.

Main metals and by-products

Critical metals rarely form their own mineable mineral deposits; they usually occur at low concentrations in ores mined for other metals. They can thus be considered companion metals. If they are extracted, it is as a by-product in the latter stages of the production chain – in smelters or in metal refining. In these cases, the main metal is the economic driver of mining and extraction. For example, a zinc ore may contain small concentrations of other elements such as indium, germanium, tellurium and selenium (see Figure 3).

If the by-products can be extracted at a profit, this increases the ore value, but companion metals may cause problems that add to production costs (Hageluken & Meskers 2010). This means that although many associated metals are present in ores that are currently mined, not all of them are extracted. Extraction often requires sophisticated metallurgical processes, which in turn require major investments in the extraction chain and entail extra expense. So recovery of the by-product depends not only on the mining production of the main metal but also on recovery being profitable and there being technology in place to recover the by-product at some stage of the production process. Some metals are by-products of a metal that is itself a by-product of a main metal.

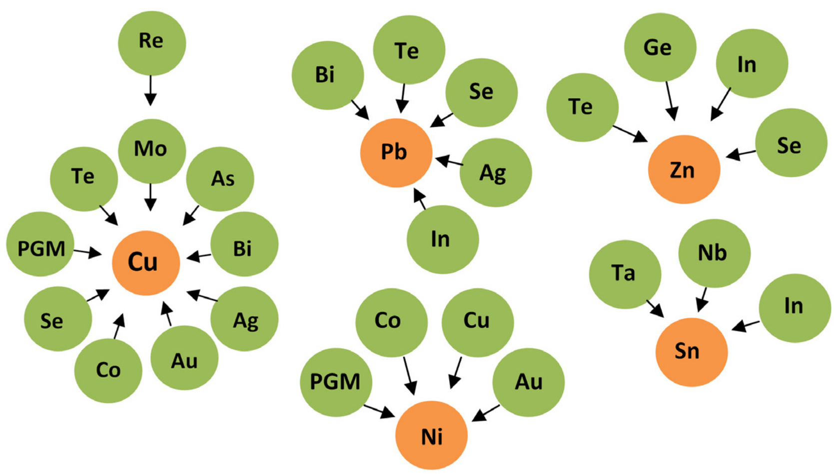

Figure 3. Relationship between a number of common main metals and by-products ("companion metals"). Modified from Hageluken & Meskers (2010).

This applies, for example, to rhenium, which is usually a by-product of molybdenum production (which itself may be a by-product of copper extraction). In some cases, a metal is a by-product of a main metal, but in others it may be extracted on its own, as with gold, silver, platinum group metals (PGM), tantalum and cobalt. Table 4 shows a general overview of the most important main metals and associated metals.

The extraction method and technology are key to whether or not an associated metal can be recovered. Generally, extraction of metals from ores requires a combination of mining, crushing, milling, smelting and refining, using physical, pyrometallurgical or hydrometallurgical techniques. The exact stage in the process at which associated metals can be recovered depends on factors such as the primary ore and the processing method used (Mudd et al. 2014). Gallium, for example, is extracted mainly hydrometallurgically as a by-product during purification and dissolution of bauxite using the Bayer process in aluminium production (Lu et al. 2017).

Economic factors

Because many critical metals are by-products, the dynamics between supply and demand can be complex. Supply is often relatively inelastic; i.e. even if demand and price rise, production does not increase. Increased volume depends on demand for, and production of, the main metal (Nassar et al. 2015, Vesborg & Jaramillo 2012). This is an important distinction between by-products and main metals. Whereas most base metals are traded in large volumes and priced on metal exchanges, many critical metals are not. However, there are exceptions: molybdenum and cobalt have been traded on the London Metal Exchange since 2010 (Fizaine 2015). Historically, many of these metals have been regarded as elements that have created problems in extracting the main metals and not a useable resource. Mining and metal extraction are only economically sustainable if they are profitable. This also applies to many critical metals that are usually extracted as by-products from other metal extraction and require their own processes in the mine, concentrator, metal production or metal refining.

Investments in such extraction technology always compete with investments in the extractive company's core business and, given the volatile raw material prices for critical raw materials and the uncertain future demand for them, investments will usually be made in the core business. However, a metal producing company can gain some advantages by diversifying its operations

Table 4. Relationships between main metals and associated metals. Modified from Mudd et al. (2014).

Main metal	Associated metal(s)
Fe	V, La, Ce, Pr, Nd, Sc
Cu	As, Se, Mo, Te, Re, Co, Ag, Au
Zn	In, Ge, Cd, Ag, Tl
Pb	Sb, Tl, Bi, Ag
Ni	Co, Sc, Ru, Rh, Pd, Os, Ir
Al	Ga, V
Ti	Zr, Hf
Mo	Re
Au	Ag
REE	Y, Th

to include more than one or a few raw materials. When demand and prices for the main metal are low, special metals can generate profits or relieve periods of low profitability; the companies simply have more products to sell. Boliden's extraction of gold and tellurium at the Kankberg mine is one such example. Working with other companies in the sector, LKAB is planning to start extracting phosphorus and rare earth elements from by-products of iron ore concentration (LKAB 2018). In a situation where the availability of some raw materials essential to industry is limited or interrupted, which is a scenario envisaged by the EU critical list, priorities other than those based on purely commercial criteria may be called for.

Legal factors

Exploration and processing of mineral deposits in Sweden is governed by the Minerals Act (Minerallag (1991:45)) provided that the minerals are "concession" minerals. Although the act does not specifically say so (except in the case of iron), the law is aimed at concession minerals found in the bedrock, where the state reserves the right to mineral deposits. It makes no difference whether exploration and processing take place in newly discovered deposits or in areas that have been mined in the past; the Minerals Act applies. However, it is currently unclear whether exploration and processing of mining waste deposits (waste-rock and tailings) are covered by the Minerals Act. Mining waste always contain one or several concession minerals, as the main metal or as by-products, but also constitutes non-consolidated deposits, equated with till or other glaciofluvial deposits, and hence covered by other legislation. Future extraction of raw materials from mining waste requires that these issues be clarified by the legislature.

Mineral exploration

Mineral exploration is essential in order to find economically viable ore deposits. Exploration carries a high financial risk, and most exploration projects do not yield deposits that can be extracted economically. Mineral exploration takes place in several steps that can take many years and requiring a number of permits and substantial investments for drilling and other exploration work. Many exploration companies, known as junior companies, are dependent on the availability of venture capital via the stock market or private investors.

METHODOLOGY AND DATA

Ample knowledge of the main metals

Sweden is one of Europe's leading mining countries, with a mining history stretching back more than 1,000 years. Through the gathered documentation of mining and exploration, available in SGU archives and databases, we have good knowledge of how much iron, base metals (copper, zinc, lead, nickel) and precious metals have been mined in the past and how much is available in the forms of resources and reserves. But we know very little about where other metals, including CRM, occur and in what quantities. This is because demand for these metals has historically been low, and they have been of little interest to the mining and exploration industry. Even when Swedish mining operators were more numerous, fifty or a hundred years ago, mining companies concentrated on virtually the same raw materials as they do today. There are exceptions, such as the mining of tungsten, lithium, nickel, graphite, tellurium and cobalt, but these metals have been produced in small quantities compared with the classic metals.

All critical raw materials

When the CRMs, defined by various sources, are highlighted in the periodic table, it turns out that a large proportion of all known elements excluding the transuranes, noble gases and the halogens, can be considered critical in some respects (see Figure 4). If metals and minerals that are currently close to the critical field in Figure 4 are also included, it becomes clear that a broad

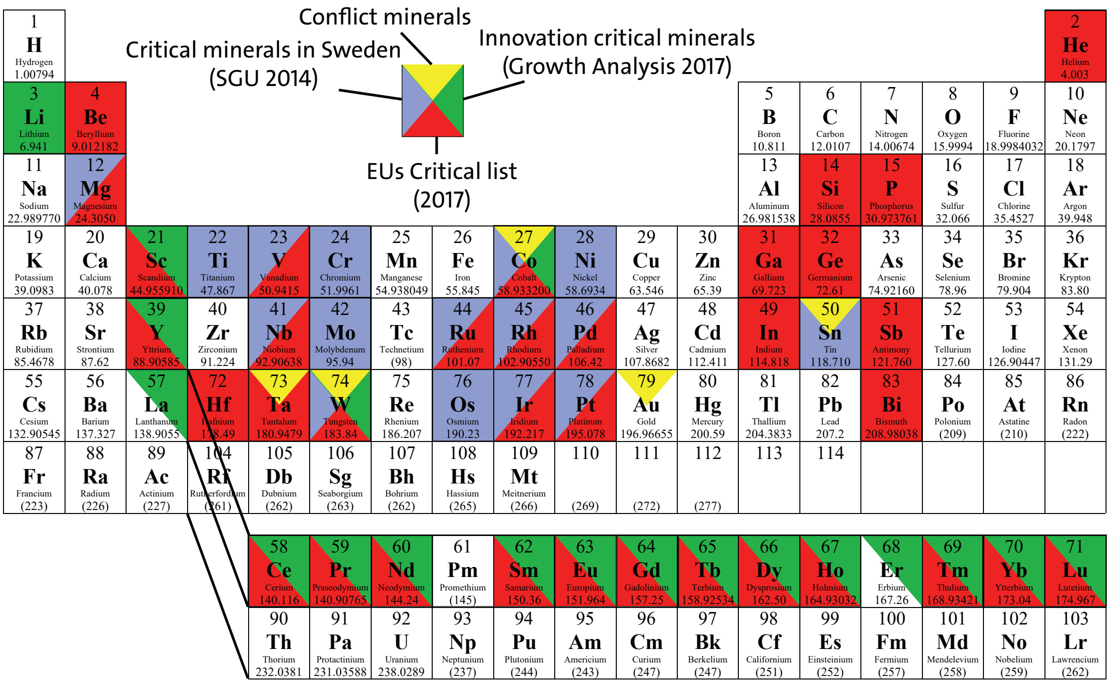

Figure 4. Periodic table of critical raw materials according to different sources. The EU critical list (2017) also contains the industrial minerals graphite, baryte and borates, which contain the elements carbon, barium and boron, but have not been highlighted. The raw material coking coal is also excluded.

survey and a complete characterisation of Swedish ores, deposits and mining waste deposits will be necessary to meet the goals of this project and to be able to respond to future, as yet unknown, demands that will be made of an innovative industry. Most of the critical raw materials are described in Appendix 7.

A chemical ore database – MALMKEMI-db

To improve our knowledge of where and in what concentrations critical raw materials do occur in Sweden, we have collected chemical data from several sources: documentation projects, EU projects, drill core protocols, exploration reports, etc. (see Appendix 2). We have also performed numerous new analyses of selected drill core and mine waste samples (see Appendix 5). These multi-element analyses provide new and important information about where and how much CRMs exist and the main elements with which they associate. Many innovation-critical metals occur in small amounts in ores that are mined for other metals and the tailings are often so fine-grained that individual ore minerals cannot be distinguished. In both cases, chemical analysis is needed to provide information about the critical raw materials – their presence and content are not visible in the ore or in the mining waste.

We have collated the chemical data in a common and well-structured database, MALMKEMI-db, which currently contains about 30,000 records. This gives us a powerful tool to investigate the presence of elements that were previously of little or no interest, e.g. CRMs, and also to detect harmful and hazardous elements. The information in the database is classified so information representative of a larger volume of rock, for example an ore estimate, can be distinguished from analyses of drill core representing sections of a few metres of rock material, to single boulders or outcrops that are only representative of the sampled boulder or outcrop, but that may still provide important information. The map in Figure 5 shows the distribution of analyses included in the database by type of sample material. The database structure is presented in Appendix 3.

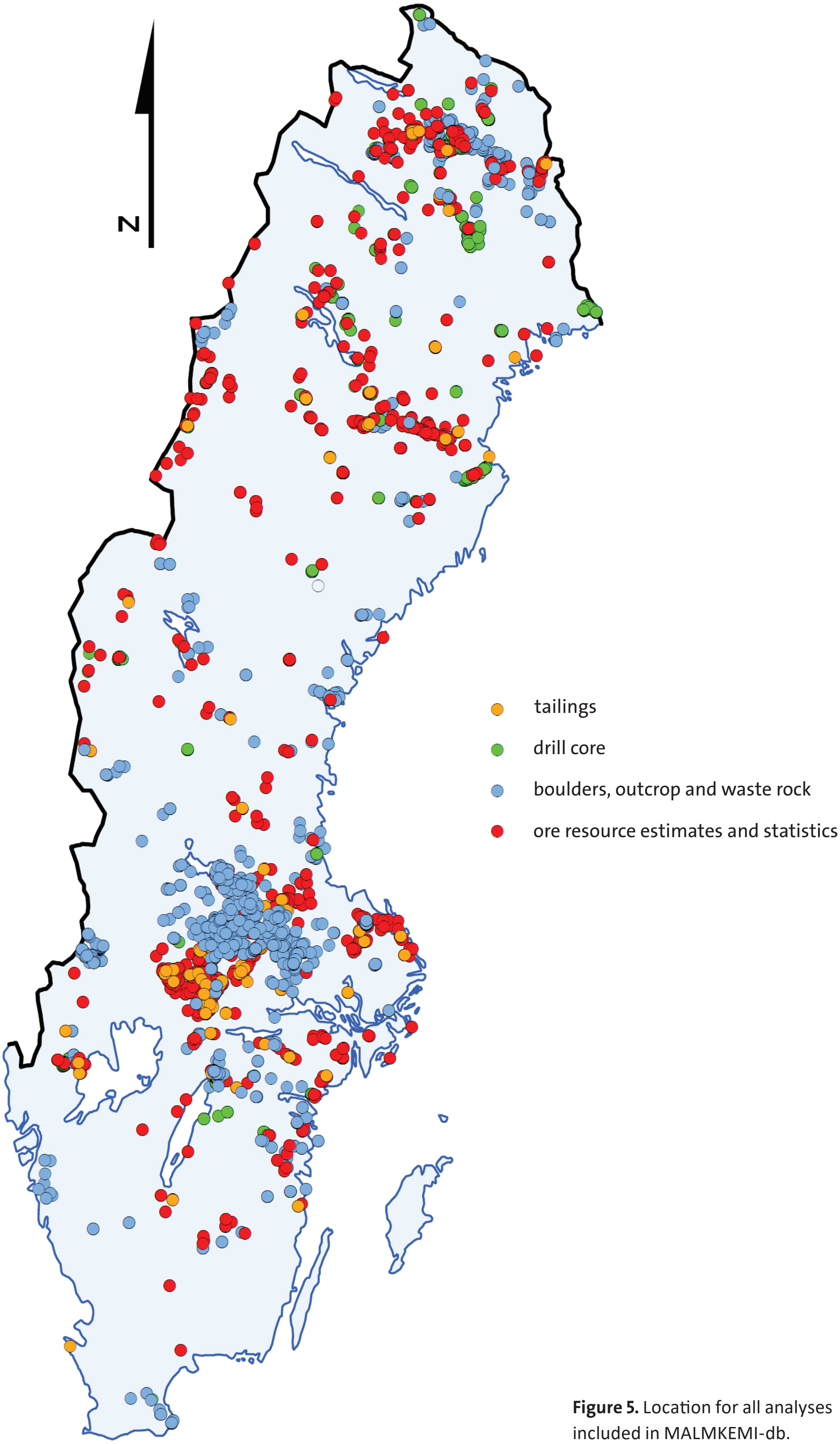

Figure 5. Location for all analyses included in MALMKEMI-db.

POTENTIAL FOR EXTRACTION IN SWEDEN

Swedish bedrock has several active base metal, precious metal and iron ore mines and several documented deposits indicating good geological potential for many metals and minerals. Interest among exploration companies in battery metals (e.g. cobalt, graphite and lithium) has increased in line with growing demand for raw materials for lithium-ion batteries from the car industry, although traditional metals such as copper and gold still predominate. Of the valid exploration permits for 2017, gold and copper are listed as concession minerals in 55% of cases. Cobalt had a share of 10%, with lithium, tungsten and graphite accounting for 5% (Bergverksstatistik, 2017).

Geological potential

The bedrock of Sweden can be divided into six major lithotectonic units. These units, with subunits and ore provinces, are described in Appendix 4. The most important unit in terms of ore geology is the Svecokarelian orogen, in which most of the rocks have an age of c. 2.0–1.8 billion years. Important ore districts within this unit are northern Norrbotten, the Skellefte district and Bergslagen (see Figure 6). Other major lithotectonic units are the Sveconorwegian (about 1.1–0.9 billion years) and the Caledonian orogen (0.5–0.4 billion years), the latter being the fourth of Sweden's four classic ore districts. Ore potential also exists outside these areas.

Deposits with ore estimates

A successful exploration project concludes with an ore estimate. A project may have been initiated based on a discovery of a boulder or outcrop sample with interesting minerals, followed up with mapping and drilling, which, if the results are still encouraging, have been completed with a careful mineral resource estimation. The mineral resource estimate is based on many analyses of many drill cores that combine to define an ore body. The mineral resource may be classified as an inferred, indicated or measured mineral resource (Figure 7). Table 5 shows several deposits where such ore estimates exist. The next step towards mining is to carry out a feasibility study, which will show whether mining will be profitable. In the feasibility study, the ore is reported as a probable or proven mineral reserve.

The most reliable information on the content of metals and minerals of economic interest, including some critical raw materials, comes from mining and exploration companies reporting their resources and reserves in accordance with internationally accepted reporting standards (e.g. JORC code, NI 43-101, FRB standard, PERC and UNFC). Several of the reported ore estimates in Table 5 are of an earlier date, published before international systems existed. Although these are not as reliable as the more modern calculations, they provide a good basis for identifying potential deposits. They require additional exploration work to be classified in line with modern standards, however. Table 5 and the map in Figure 1 show that there are ore estimates for several of the critical raw materials. Despite this knowledge, no Swedish mine is currently producing critical raw materials. Some projects, even those with ore estimates reported according to internationally accepted standards, have stalled in the permit processes required to open a mine in Sweden.

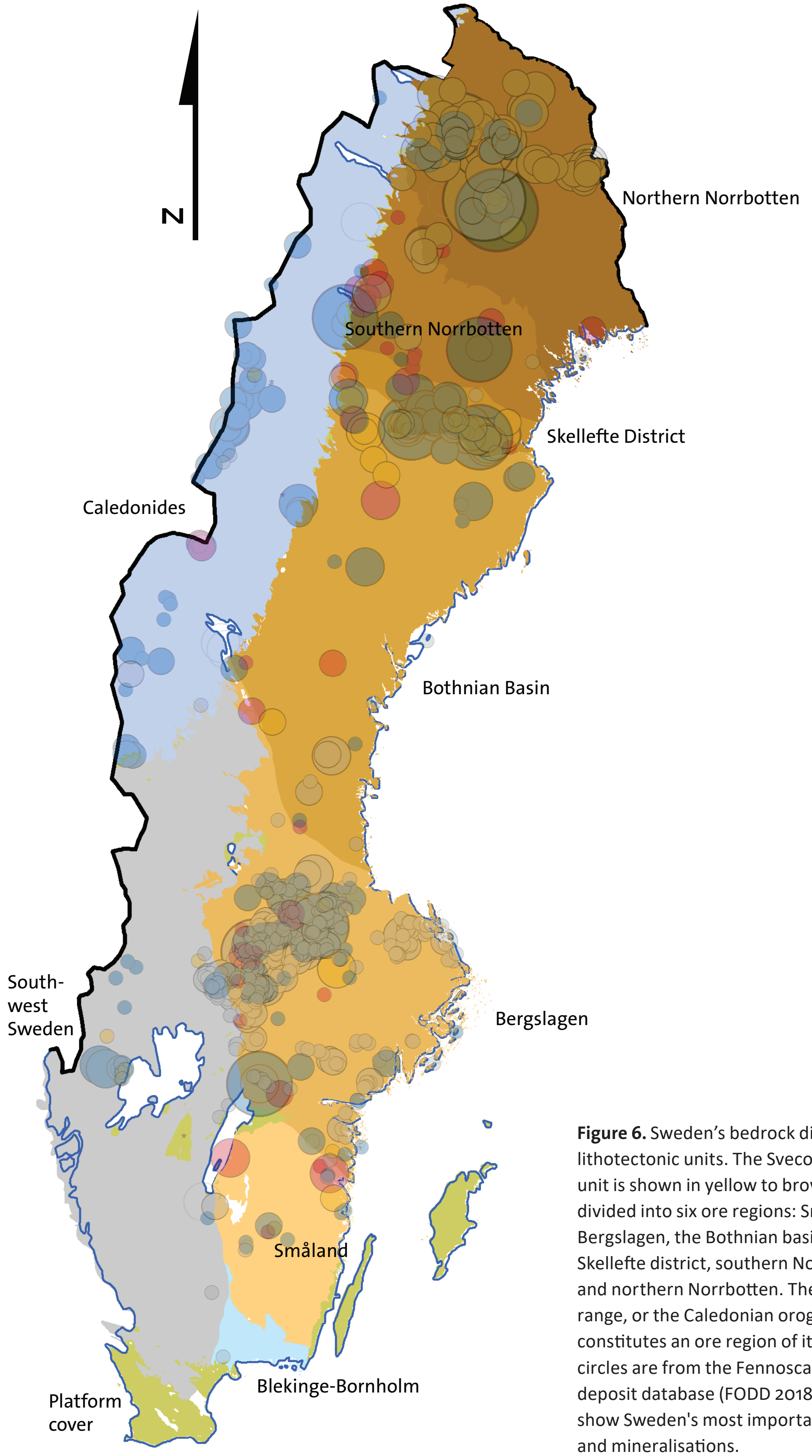

Figure 6. Sweden's bedrock divided into lithotectonic units. The Svecokarelian unit is shown in yellow to brown and is divided into six ore regions: Småland, Bergslagen, the Bothnian basin, Skellefte district, southern Norrbotten and northern Norrbotten. The mountain range, or the Caledonian orogen, constitutes an ore region of its own. The circles are from the Fennoscandian ore deposit database (FODD 2018), and show Sweden's most important ores and mineralisations.

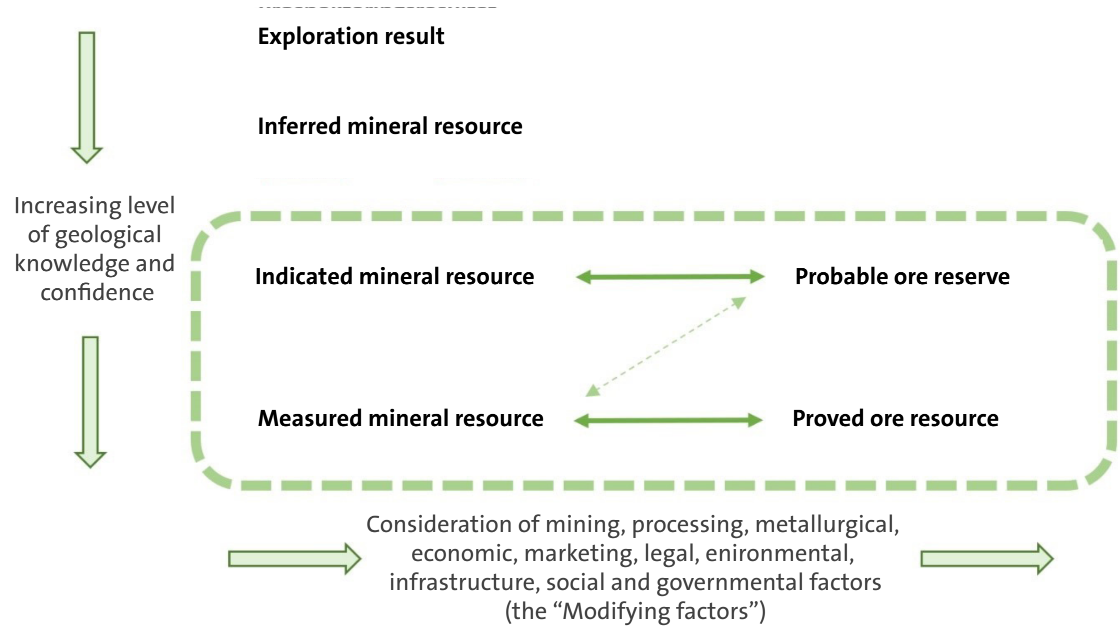

Figure 7. Mineral reserves and mineral resources.

Table 5. Ore estimates of critical raw materials. Mt = million tonnes.

NATURAL GRAPHITE

	Mineral resource	Reporting std*	Tonnage (Mt)	Graphite (%)
Kringeltjärn[1]	indicated	NI43-101	1.86	10.63
Kringeltjärn[1]	measured	NI43-101	0.99	10.68
Gropabo[1]	inferred	NI43-101	0.70	8.65
Gropabo[1]	indicated	NI43-101	1.50	8.83
Mattsmyra[1]	inferred	NI43-101	1.18	8.35
Mattsmyra[1]	indicated	NI43-101	3.43	8.37
Månsberg[2]	inferred	historic	1.35	9.44
Raitajärvi[3]	inferred	JORC-code	0.90	6.4
Raitajärvi[3]	indicated	JORC-code	3.40	7.3
Jalkunen[3]	inferred	JORC-code	31.5	14.9
Nunasvaara[3]	inferred	JORC-code	1.60	23.9
Nunasvaara[3]	indicated	JORC-code	10.70	25.7

RARE EARTH ELEMENTS

	Mineral resource	Reporting std	Tonnage (Mt)	TREO[4] (%)
Olserum[5]	inferred	NI43-101	3.30	0.63
Olserum[5]	indicated	NI43-101	4.50	0.60
Norra Kärr[6]	indicated	NI43-101	31.11	0.61
Norra Kärr[6]	probable reserve	NI43-101	23.5	0.59

NICKEL-COPPER-COBALT

	Mineral resource	Reporting std*	Tonnage (Mt)	Cu (%)	Ni (%)	Co (%)	Cr (%)
Gårkälen[7]	inferred	historic	0.04	0.18	0.4	0.04	-
Kälen[7]	inferred	historic	0.07	0.27	0.41	0.04	-
Njuggträskliden A[7]	inferred	historic	0.11	0.17	0.69	0.05	-
Njuggträskliden C[7]	inferred	historic	0.19	0.11	0.7	0.05	-
Njuggträskliden D[7]	inferred	historic	0.26	0.41	0.73	0.03	-
Brännorna[7]	inferred	historic	0.35	0.04	0.63	0.02	-
Mjövattnet[7]	inferred	historic	0.17	0.19	1.29	0.02	-
Lainejaur[8]	inferred	JORC-code	0.46	0.7	2.2	0.15	-
Lappvattnet[9]	inferred	NI43-101	1.14	0.19	0.91	0.02	-
Rörmyrberget[9]	inferred	NI43-101	6.37	0.04	0.35	0.01	-
Rönnbäcken[10]	inferred	NI43-101	12.20	-	0.085	0.004	-
Rönnbäcken[10]	indicated	NI43-101	319.90	-	0.103	0.003	-
Kroksjön S[11]	inferred	historic	0.30	-	0.3	0.0181	0.69
Njeretjakke[11]	inferred	historic	38.30	-	0.28	0.0149	0.43
Älgliden[12]	inferred	historic	13.0	0.7	0.2	0.03	-
Kiskamavaara[13]	inferred	historic	2.87	0.6	-	0.09	
Slättberg[14]	inferred	historic	0.3	0.5	0.6	0.06	-
Såggården[15]	inferred	historic	0.7	-	-	0.06	-

*Many of the resource estimates are "historic"; pre-dating JORC-code, NI-43-101, and Fennoscandian Review Board (FRB).

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Table 5. Ore estimates, continued. Mt = million tonnes.

LITHIUM-TIN-TANTALUM

	Mineral resource	Reporting std*	Tonnage (Mt)	Li (%)	Sn (%)	Ta (ppm)
Varuträsk[16]	inferred	historic	0.40	0.12	-	-
Järkvissle[17]	inferred	historic	0.60	0.45	0.07	80

TUNGSTEN

	Mineral resource	Reporting std*	Tonnage (Mt)	W (%)
Svärtträsk[18]	inferred	historic	0.25	0.2
Maldok[19]	inferred	historic	0.07	0.17

MOLYBDENUM

	Mineral resource	Reporting std*	Tonnage (Mt)	Mo (%)	Cu (%)	Au (ppm)
Nautanen[20]	inferred	FRB	7.50	0.008	1.5	0.6
Nautanen[20]	indikerad	FRB	8.20	0.009	1.7	0.9
Laver-Nya[20]	inferred	FRB	550.60	0.003	0.21	0.10
Laver-Nya[20]	indicated	FRB	512.40	0.004	0.22	0.13
Laver-Nya[20]	measured	FRB	1.10	0.002	0.20	0.11
Skarjaviken[21]	inferred	historic	0.08	0.120	-	-
Allebouda Lilla[22]	inferred	historic	0.25	0.140	-	-
Björntjärn[23]	inferred	historic	1.80	0.110	-	-
Munka[24]	inferred	historic	1.70	0.156	-	-

PLATINUM-PALLADIUM

	Mineral resource	Reporting std*	Tonnage (Mt)	Pt (ppm)	Pd (ppm)	Au (ppm)	Cu (%)
Storsjö kapell[25]	inferred	historic	0.20	-	0.4	0.2	0.7
Lainejaur[8]	inferred	JORC-code	0.46	0.2	0.68	0.65	0.7

TELLURIUM

	Mineral resource	Reporting std*	Tonnage (Mt)	Te (ppm)	Au (ppm)	Ag (ppm)
Kankberg-nya[20]	proved reserve	FRB	2.40	190	3.80	11.0
Kankberg-nya[20]	probable reserve	FRB	2.10	186	3.50	10.0
Kankberg-nya[20]	measured	FRB	0.19	130	3.80	8.0
Kankberg-nya[20]	indicated	FRB	0.31	117	4.70	8.0
Kankberg-nya[20]	inferred	FRB	1.36	168	5.50	8.0

IRON-TITANIUM-VANADIUM

	Mineral resource	Reporting std*	Tonnage (Mt)	Fe (%)	V (%)	Ti (%)
Smålands Taberg[24]	inferred	historic	150	28.0	0.12	3.0
Masugnsberget[26]	inferred	historic	1	-	0.19	-
Simesvallen[27]	inferred	historic	3	-	0.19	2.2
Sumåssjön[28]	inferred	historic	21	-	0.22	-
Eustilljåkk[24]	inferred	historic	5	30.0	0.25	-
Akkavare[29]	inferred	historic	230	18.5	-	2.7
Routivare malmfält[24]	inferred	JORC-code	140	39.1	0.20	5.7
Häggån[30]	inferred	-	2 350	-	0.15	-

FLUORSPAR

	Mineral resource	Reporting std	Tonnage (Mt)	Fluorspar (%)
Storuman[31]	indicated	JORC-code	25.0	10.28
Storuman[31]	inferred	JORC-code	2.7	9.57

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Old deposits – new analyses

Samples of drill cores and mining waste from closed mines and concentrators make up much of the material analysed in this project. By relating this data to additional information about the mines and the concentrators, e.g. amount and metal content of mined ore and mining waste, it is possible to learn more about CRM in residual ore and tailings.

Available information about closed mines and concentrators contains relatively few analysed elements but is based on a very large number of samples, unlike the new analyses made in this project, which come from a limited number of samples but with a large number of analysed elements. This means that our estimates in this chapter are not comparable with the ore estimates reported. Rather, they should be viewed as an indication of the presence of critical raw materials.

This section presents a selection of sampled and analysed deposits that display anomalous levels of any metal. Tables 6–17 are summaries showing compositional variations of some CRMs from analysed cores and tailings. To allow comparison, ore estimates, where available, are also reported in the tables.

The presence of anomalous metal content in the drill cores indicates where interesting metal content occurs, but we emphasise that this become economically important only when other adjacent drill cores show significant metal content and the results from several drill cores can be correlated and form the basis for an ore estimate.

Järkvissle

At Järkvissle, Sundsvall municipality, there are several pegmatitic dykes and dyke swarms of LCT type hosting lithium, tantalum and tin mineralisations. An ore estimate was made based on drilling conducted in the 1980s (see Tables 5 and 6). SGU stores drill cores from that drilling campaign in the SGU drill core archive at Malå. A number of sections from those drill cores have been sampled and analysed in this project. Table 6 shows the range of data from these new analyses together with the older ore estimate.

Riddarhyttefältet

Mining in the Riddarhytte field, located in Skinnskatteberg municipality in Västmanland, is documented from the late 14th century. Geijer (1923) defines the Riddarhytte field as all the mines and mining areas that fit within an approximately 2-kilometre-wide and 6-kilometre-long zone that extends north-east from Lake Lien in the southwest to the Älgtorps field in the northeast. Iron ore has been the dominant product, but copper, cobalt, rare earth elements and molybdenum have been intermittently produced, and it has long been known that the Ridderhytte field differs from other iron ore districts in that odd minerals and metals are present there. Mining at the Riddarhytte field ceased when the Bäckegruvan mine was closed in 1979, followed by the concentrator a year later. On closure, mining had reached the 360-metre level, a modest depth by today's standards. In this project, we have collected and digitised about 80 analyses from older publications and exploration reports,

Table 6. Analyses of selected elements in Järkvissle pegmatite. Mt = million tonnes.

Site	Data	Li (%)	Ta (ppm)	Nb (ppm)	Sn (%)	Cs (ppm)
Järkvissle	Drill core[1] (n = 5)	0.09–0.87	10–83	20–79	0.01–0.16	30–85
Järkvissle	Mineral resource[2] (0,6 Mt)	0.45	80	-	0.07	-

[1]Interval shows the lowest and highest analytical value from drill core sections analysed in this project; data from MALMKEMI-db.
[2]Tuuri & Ek (1986).

65 analyses from EURARE project data, and have calculated the quantity and content of ore production and the production of tailings. In addition, we have sampled and analysed three drill core sections and twelve samples from the old and new tailings at Bäckegruvan and from the Källfallet tailings (all data with references are in the MALMKEMI-db database).

The metal content of the Riddarhytte field is reflected in the composition of the tailings, particularly in the sand from the old tailings that were deposited at a time when the concentrator was less efficient. It seems that much of the copper was not recovered but was deposited in the tailings. The cobalt content is remarkably high and approaching minable levels. The content of gold, bismuth, indium and REE is also high, particularly in the old tailings. At the same time, the levels of arsenic are extremely high in the old tailings, all four analyses show more than 250 ppm As. EMX Royalty Corp. currently has an exploration permit for the area.

Figure 8. Overview of Bäckegruvan in the Riddarhytte field. The two main tailings can be distinguished: the northern, enclosed part, which is mainly covered by trees and other vegetation, and the southern part adjacent to Nedre Skärsjön. Photo: Google Earth.

Table 7. A selection of analysed elements from various sites in Riddarhyttefältet.

Site	Data	Fe (%)	Cu (%)	Co (%)	Mo (%)	REE (%)	Au (ppm)	Bi (ppm)	Ga (ppm)	In (ppm)
Riddarhytte odalutmål	Mined ore[1]	37.10	0.44	-	-	-	-	-	-	-
Bäckegruvan	Old tailings[2] (n = 4)	15.3–23.2	0.11–0.32	0.01–0.11	0.01	0.13–0.18	0.17–0.35	126–223	12–14	3.59–4.75
Bäckegruvan	New tailings[2] (n = 5)	9.9–18.5	0.09–0.14	0.01–0.02	0.00	0.03–0.11	0.01–0.04	9–19	8–10	2.56–4.62
Källfallsfältet	Ore[1]	48.00	-	-	-	-	-	-	-	-
Källfallsfältet	Tailings[2] (n = 3)	9.8–12.0	0.02–0.04	0.00	0.02–0.03	0.11–0.36	0.01–0.04	11–41	20–38	0.25–0.63

[1]FODD (2018).

[2]Interval shows the lowest and highest analytical value from tailings analysed in this project; data from MALMKEMI-db.

Figure 9. Tailings at Bäckegruvan in the Riddarhytte field. The lake Nedre Skärsjön is in the background. Photo: Helge Reginiussen.

Stollbergsfältet

Mining has taken place in the Stollberg field since the Middle Ages. The Stollberg area features several mines and ore fields, from the Lustigkulla mine in the north via the Svartberg field and the Dammberg field to Brusmalmen in the south, a distance of approximately 4.5 kilometres. The mines are connected underground from Brusgruvan in the south to the Svartberg field in the north. The ores in the Stollberg field consist of iron–manganese and zinc ore. Both ore types were mined and concentrated for long periods. In earlier times, when the field was called Väster Silvberg, lump ore was produced, but when concentration started, the ore was processed at "Gamla verket" and "Mellanverket", both located at Silvhyttan. Mining restarted in the 1940s; the concentrator was moved to newly discovered Brusmalmen in the southern part of the field, and a larger tailings facility was established at the site. Mining and concentration ended in 1982.

Several research projects generating a large amount of data have been conducted at Stollberg. In addition, several of the waste rock dumps have been sampled and analysed, and the tailings at Brusmalmen have been drilled, sampled and analysed. These data are included in the MALMKEMI-db database.

As part of the current project, four samples of drill core and eight samples of tailings sand have been analysed, four from the tailings at Lake Staren and four from Brusmalmen. The metal content is generally lower in the newer tailings at Brusmalmen, reflecting better recovery. The analyses show that ore and tailings contain anomalous levels of indium and antimony, two critical raw materials. The analyses of tailings show a relatively good correlation between zinc and indium, which can be used to estimate the indium content of remaining ore, waste rock and tailings.

Figure 10. Stollberget. Photo: Anders Hallberg.

Table 8. Mine production and a selection of analysed elements from Stollbergsfältet. Mt = million tonnes.

Site	Production[1] (Mt)	Fe (%)	Cu (%)	Zn (%)	Pb (%)	Ag (ppm)	Bi (ppm)	In (ppm)	Sb (ppm)
Dammbergsfältet	0.029	-	-	40.0	0.00	-	-	-	-
Stollbergsfältet/zinc	3.476	18.3	0.07	2.4	3.24	81	-	-	-
Stollbergsfältet/iron	0.362	31.8	-	0.6	2.51	-	-	-	-
Svartbergsfältet	0.242	39.4	-	-	-	-	-	-	-
Stollberg drill core[2] (n=4)		9.1–34.6	0.01–0.08	0.1–10.1	1.1–20.0	2–355	0–129	1.0–18.4	0.3–250[3]
Stollberg tailings[2] (n=4)		6.3–9.8	0.01–0.02	0.2–0.4	0.2–0.5	5–14	1.7–2.2	0.2–0.6	8.1–19.5
Silvhyttan tailings[2] (n=4)		14.8–20.8	0.01–0.02	0.8–1.3	0.5–1.1	7–15	2.2–8.6	1.2–1.8	18.9–21.6

[1]FODD (2018).

[2]Interval shows the lowest and highest analytical value from drill core sections and tailings analysed in this project; data from MALMKEMI-db.

[3]250 ppm is the upper detection limit for this element.

The nickel line

During nickel exploration by SGU and SGAB in the 1970s and 80s several interesting nickel-occurrences were found in an approximately 15 x 100-km-long east–northeast oriented zone south of the Skellefte district. This "nickel line" contains several Ni-Cu deposits associated with ultramafic rocks. The deposits are magmatic sulphide mineralisations that share many similarities with known large Ni-Cu deposits in otherparts of the world. As a group, magmatic Ni-Cu sulphide deposits, along with laterites, are the most important global source of nickel.

At Lappvattnet, which is one of the largest nickel deposits in the nickel line, the mineralisation occurs as dissemination and massive ore in mafic to ultramafic sills and intrusions, and as fragments in the enveloping gneiss. The mineralisation is 620 metres long and 1–20 metres wide (Åkerman 1987, SGU 2007).

Rörmyrberget is a differentiated ultramafic sill that is 1.7 km long and 320 metres wide (Åkerman 1987, SGU 2007). Nickel mineralisations are found along the entire length of the sill, but only the western part of the intrusion has been considered to have grades that are of interest.

Yxsjöberg and Svärtträsk

Most of the tungsten produced in Sweden in the modern era comes from a number of skarn deposits located in an area around Ludvika in Bergslagen. The largest producer was the mine at Yxsjöberg, which is by far the largest tungsten deposit in Sweden, accounting for 92 per cent of

Table 9. A selection of elements from the Nickel line. Mt = million tonnes.

Site	Data	Ni (%)	Cu (%)	Co (%)	Cr (%)	Pt (ppm)	Pd (ppm)
Lappvattnet	Drill core[1] (n=12)	0.30–5.33	0.04–1.28	0.01–0.07	0.01–0.09	0.01–0.26	0.01–0.27
Lappvattnet	Mineral resource[2] (1.14 Mt)	0.91	0.19	0.02	-	-	-
Rörmyrberget	Drill core[1] (n=5)	0.89–3.03	0.05–0.13	0.02–0.08	0.07–0.17	0.03–0.06	0.07–0.08
Rörmyrberget	Mineral resource[2] (6.37 Mt)	0.35	0.04	0.01	-	-	-

[1]Interval shows the lowest and highest analytical value from drill core sections analysed in this project; data from MALMKEMI-db.
[2]Blackstone Ventures Inc (2009).

Table 10. A selection of elements from Yxsjöberg and Svärtträsk. Mt = million tonnes.

Site	Data	W (%)	Cu (%)	Sn (%)	Ga (ppm)	Au (ppm)	Ge (ppm)	In (ppm)	Bi (ppm)	Be (ppm)
Yxsjöberg	Drill core[1] (n=10)	0.08–0.95	0.04–0.84	0.00–0.14	15–49	0.02–0.54	0–21	1.04–8.54	21–250[2]	-
Yxsjöberg/ Morkull-tjärnen	Tailings[1] (n=4)	0.03–0.22	0.02–0.14	0.02–0.06	17–24	0.10–0.14	3–18	3.29–5.74	250–452	116–162
Svärtträsk	Drill core[1] (n=2)	0.22–0.68	0.01	0.01	12–14	0.01–0.02	< 5	0.03	5–18	-
Svärtträsk	Mineral resource[3] (0.25 Mt)	0.20	-	-	-	-	-	-	-	-

[1]Interval shows the lowest and highest analytical value from drill core sections and tailings analysed in this project; data from MALMKEMI-db.
[2]250 ppm is the upper detection limit for this element.
[3]Holmquist (1979).

all produced tungsten. Yxsjöberg was known as a copper deposit in the early 18th century. In total, 5.17 million tonnes of ore were mined, with a content of 0.27% W (FODD 2018). Analyses of drill cores and tailings from Yxsjöberg show elevated content of several critical metals, including indium, bismuth and beryllium.

The tungsten deposit at Svärtträsk in Storuman municipality was discovered in the late 1970s.

Viscaria

Viscaria copper mine, located in Kiruna, was in operation from 1982–1997, and produced 12.5 million tonnes of copper ore, which was concentrated at the nearby concentrator. The average content of the ore was 2.23% copper, with moderate gold and silver content. Ore from the Pahtohavare mine was also processed at the concentrator from 1990 until closure. In recent times, exploration has shown further mineralisation in the A-zone, and also in several underlying layers: the B- and D-zones. The C-zone consists of graphite-rich rocks. The ten drill core analyses show that Viscaria has anomalous content of several elements, among them several critical raw materials such as cobalt, indium and REE.

Adak

The mines in the Adak field operated from 1932 to 1977, the first eight years under the name Kourbevare. A total of 6.34 million tonnes of ore was produced, most of which was concentrated on site.

A number of drill cores have been analysed in this project, but the covered tailings have not been sampled. Extensive drilling and sampling of the tailings sand was carried out in 1989 and two-metre sections of the drilling samples were analysed for gold, silver, copper, zinc and

Table 11. A selection of elements from Viscaria. Mt = million tonnes.

Site	Data	Cu (%)	Co (%)	Pd (ppm)	In (ppm)	Re (ppm)	Se (ppm)	REE (%)
Viscaria	Mined ore[1] (12.5 Mt)	2.23	-	-	-	-	-	-
Viscaria	Mineral resources[2] in A-zone (21.6 Mt)	1.51	-	-	-	-	-	-
Viscaria	Drill core[3] (n=10)	1.0-12.6	0.007–0.045	0.003–0.084	0.44–7.38	0.01–0.07	3.9–34.9	0.01–0.22

[1]FODD (2018).
[2]Sunstone Metals (2018).
[3]Interval shows the lowest and highest analytical value from drill core sections analysed in this project; data from MALMKEMI-db.

Table 12. A selection of elements from Adak. Mt = million tonnes.

Site	Data	Cu (%)	Zn (%)	Co (%)	Au (ppm)	Ag (ppm)	Se (ppm)	As (ppm)
Adak	Mined ore[1] (6.34 Mt)	1.97	0.10	-	0.35	8	-	-
Adak	Drill core[2] (n=11)	0.29–7.87	0.01–0.17	0.001–0.026	0.00–0.25	1–36	2.6–150.5	30–250
Adak	Tailings[3] (n=15)	0.04–0.22	0.04–0.23	0.006–0.017	0.15–0.50	0–7	-	3000–30000

[1]FODD (2018).
[2]Interval shows the lowest and highest analytical value from drill core sections analysed in this project; data from MALMKEMI-db
[3] Interval shows the lowest and highest analytical value from tailings (Lindberg, 1989, 1990).

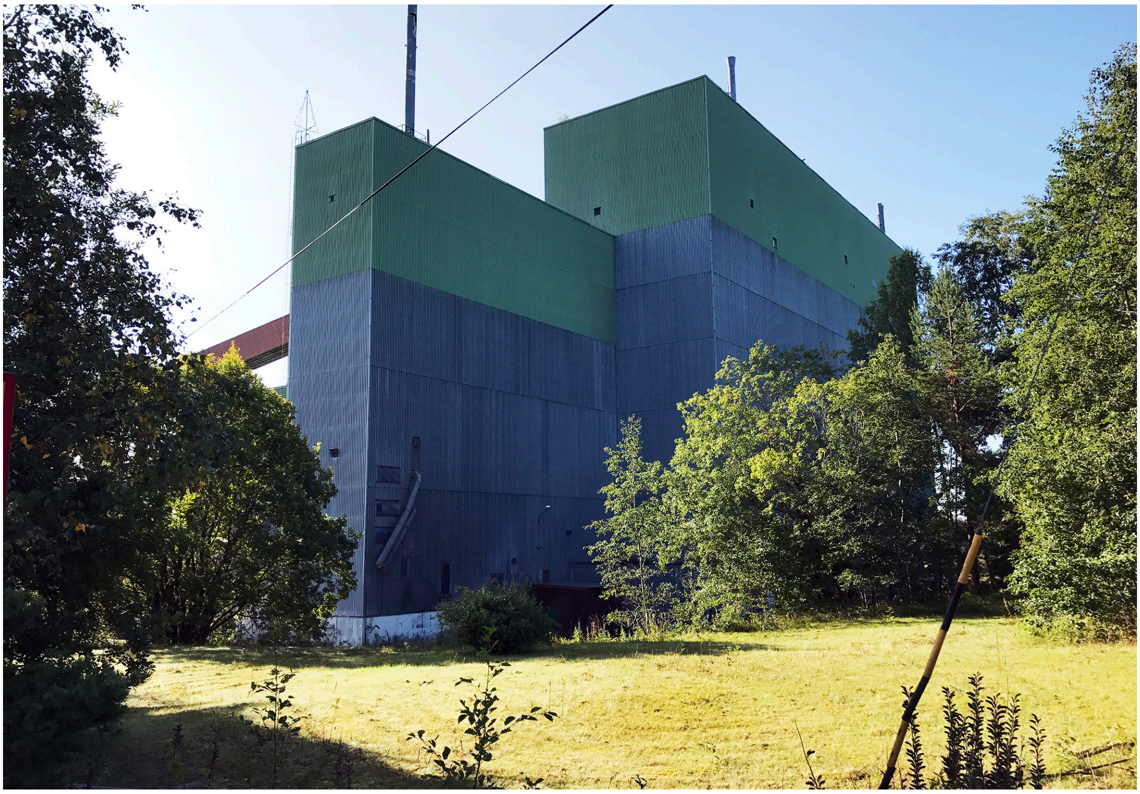

Figure 11. Södra verket at Grängesberg. Photo: Helge Reginiussen.

lead (Lindberg, 1989, 1990). More extensive analyses were made of three of the drill cores, including cadmium, cobalt, mercury and sulphur, a total of 15 samples. The compilation of analyses of drill core and tailings sand (Table 12) indicates that much of the copper content was recovered during concentration, but much of the cobalt ended up in the tailings. According to the report from the drillings, the metal content of the tailings sand is 1,140 kg Au, 7,200 tonnes Cu, 7,200 tonnes Zn and 42,000 tonnes As, but the sample material is too limited to draw any further conclusions about the cobalt content. As a result of the very high arsenic content, the tailings were eventually covered, and the ongoing environmental monitoring programme at Adak was initiated.

The Grängesberg area

The apatite iron ores in the Grängesberg area are the largest ore deposits in Bergslagen. Apatite in the iron ore often contains rare earth elements, which not only applies to Bergslagen's apatite iron ore, but also the large ore deposits in Norra Norrbotten such as at Kirunavaara and Malmberget.

Over the past 250 years, 156 million tonnes of ore has been extracted from the mines in the area. Most of the ore was lump ore used in various blast furnaces, where any critical raw materials ended up in slag and other residual products, and thus disappeared from the area. Thirty-one per cent or nearly 49 million tonnes of ore, has been concentrated at two major concentrators; the tailings have been deposited in three sizeable dams.

In this project, we have sampled and analysed drill cores and tailings from the three landfills and collated older analyses. The results of the best-quality analyses are summarised in Table 14. Mean values show that the sampled drill cores contain 0.17% REE, and tailings sand

Table 13. Mine production in the Grängesberg area. Data from FODD (2018). Mt = million tonnes.

Site	Year of production	Mineral resources (Mt)	Production (Mt)	Fe (%)	Mn (%)	P (%)	S (%)
Grängesbergs-fältet	1783–1989	148.3	132.8	49.87	0.14	2.01	0.01
Risbergsfältet	1783–1979	-	20.4	41.66	0.19	1.43	0.01
Ormbergsfältet	1783–1926	-	2.3	58.00	-	0.18	0.02
Lombergsfältet	1817–1947	-	0.6	54.50	-	0.28	0.01

Table 14. A selection of elements in Grängesberg. Mt = million tonnes. Production data from FODD (2018).

Concentrator	Year of production	Tailings (Mt)	Fe (%)	Mn (%)	P (%)	V (%)	Sn (%)	REE (%)
Södra verket	1970–1989	5.6	38.68	0.07	-	-	-	-
Grängesberg	1944–1953	0.4	19.82	-	0.63	-	-	-
Bergslagsschaktet	1929–1979	8.4	12.50	-	0.50	-	-	-
Västra Ormberg	1919–1927	0.1	33.99	-	0.10	-	-	-
Lomberget	1906–1919	0.1	25.50	-	0.09	-	-	-
Tailings[1] (n=8)			12.9–36.4	0.04–0.16	0.27–2.90	0.03–0.09	0.0–0.03	0.0–0.23
Drill core[1] (ore) (n=10)			17.4–64.8	0.09–0.32	0.07–2.90	0.04–0.20	0.0–0.05	0.02–0.47

[1] Interval shows the lowest and highest analytical value from drill core sections and tailings analysed in this project; data from MALMKEMI-db.

0.12% REE. The analyses also show that ore and tailings contain significant concentrations of vanadium and tin.

Mining at Grängesberg ended in 1989 when it had reached a depth of approximately 650 metres. Geophysical surveys suggest that the ore continues to a depth of at least 1,700 metres, and modern estimates indicate there are 148 million tonnes of ore remaining in the mine. In addition, there are 14.4 million tonnes of tailings in the three dams.

Östanmossen

Mining around Norberg has a very long history, and the area also has Europe's oldest blast furnace, dating back to the late 12th century. The main product from the Norberg area is iron ore, but some of the iron ores have anomalous content of rare earth elements, including the mines in the Smörberg, Getback and Rödberg fields. Ore from these mines was processed at the Östanmossen concentrator, which operated from 1910 (or earlier) until 1960. During this period 2.61 million tonnes of ore was processed. The EURARE project and our sampling of tailings have produced new data on the content of REE and other critical elements. REE analyses are not available from the ore statistics or concentrator statistics.

The three ore samples confirm that the ore in the Östanmossan mine is REE-rich, containing about 3% total REE, but the analyses show low iron levels, which indicates that REE-rich but iron-poor parts of the ore were chosen for the sampling. The tailings contain up to one tenth of the REE content of the ore samples. It is worth noting that tailings from other ore fields in the Norberg area contain only 0.02% REE.

Dingelvik-Henneviken

In Dalsland there are several copper mineralisations that are considered to be of sediment-hosted copper type, an ore type that accounts for a large part of global copper production and also that of silver and cobalt.

In this project, we have digitised and systematised a large amount of analytical data from drill core reports, older exploration reports and from more modern exploration campaigns. We also have sampled and analysed drill cores from Dingelvik and Henneviken, the two largest deposits that have ore estimates. The table below compares a compilation of these drill core analyses with the metal content stated in the ore estimates.

The copper content in the analysed drill cores is in line with the content stated in the ore estimates, Henneviken being slightly richer in copper than Dingelvik. The deposits appear to have a low cobalt content, with no analysis showing more than 0.007% Co. The elevated rhenium content in the samples from Dingelvik is of interest. Rhenium is usually associated with molybdenum, but apparently not so here.

An additional 720 drill core analyses from Dingelvik, Henneviken and Åsnebo are reported in the MALMKEMI-db database. These analyses include mainly copper, silver and in a few cases also cobalt.

Table 15. A selection of elements at Östanmossen.

Site	Data	Fe (%)	P (%)	Mn (%)	S (%)	Cu (%)	REE (%)
Östanmossen	Mined ore[1]	31.3	0.01	-	0.20	-	-
Östanmossen	Ore samples[2] (n=3)	14.6–19.0	-	0.03–0.12	0.06–0.07	0.04–0.05	2.9–3.8
Östanmossen	Tailings[3] (n=5)	9.5–12.0	0.01	0.15–0.17	0.01–1.4	0.02–0.04	0.07–0.36

[1]FODD (2018).
[2]Data from MALMKEMI-db.
[3]Interval shows the lowest and highest analytical value from tailings analysed in this project; data from MALMKEMI-db.

Table 16. Selection of elements in Dingelvik and Henneviken. Mt = million tonnes.

Site	Data	S (%)	Cu (%)	Co (%)	Ag (ppm)	Re (ppm)
Dingelvik	Resource estimate[1] (26.1 Mt)	-	0.77	-	22	-
Henneviken	Resource estimate[1] (11.75 Mt)	-	1.05	-	21	-
Dingelvik	Drill core (n=8)[2]	0.04–2.07	0.03–1.04	0.000–0.005	1–33	0.006–1.185
Henneviken	Drill core (n=3)[2]	1.09–1.34	0.21–1.12	0.004–0.005	5–18	0.009–0.022

[1]FODD (2018).
[2]Interval shows the lowest and highest analytical value from drill core sections analysed in this project; data from MALMKEMI-db.

Alkaline intrusions

Unlike other intrusive rocks such as granites and gabbro, alkaline intrusions are usually small, but show large compositional variations. Mineralisations associated with these rocks also show a great diversity; from diamonds to phosphate, REE and much more. Well-known alkaline intrusions in Sweden include Norra Kärr, which contains high levels of REE and zirconium, and the intrusion on northern Alnö.

To gain an idea of the potential of these rock types, we have compiled available analyses and included them in the MALMKEMI-db database. Table 17 is an excerpt from the database, including analyses from several sources, together with reported reserves and resources for Norra Kärr.

Table 17. A selection of elements in some alkaline intrusions.

Site	Nb (ppm)	Ta (ppm)	Zr (ppm)	Th ppm)	REE (%)
Norra Kärr resources [1]	-	-	-	-	0.29
Norra Kärr-reserves[1]	-	-	13600	6.63	0.32
Holmslättmyran[2] (n=9)	3000–13000	70–700	394–2625	-	-
Åkersjön[2] (n=2)	67–731	0–7	1–9	3–5	0.20–0.23
Ramvik[2] (n=4)	150–193	8–11	269–284	15–17	0.06–0.07
Alnö[2] (n=17)	2–2500	0–78	3–1040	0–102	0.00–0.25
Sundsvallsområdet[2] (n=37)	10–1656	1–44	44–1347	3–65	0.01–0.17

[1]Tasman Metals (2015).
[2]Data from MALMKEMI-db.

The potential of Sweden's industrial infrastructure

Sweden is an attractive mining country. Modern legislation covers the entire chain from exploration to the manufacture of products. Easily accessible basic geoscientific information as well as a technical and scientific infrastructure within most areas of activity in metal extraction are in place.

Important parts of this infrastructure:

- Good information on ore geology, geochemistry and geophysics. This information is fundamental to the early stages of exploration. SGU offers open archives with access to geodata.
- Well-developed road, rail and power networks facilitate exploration as well as mining.
- Many consulting companies and drilling companies allow efficient exploration.
- Skilled contractors are available to conduct mining operations.
- Several large Swedish companies in the mining equipment industry ensure safe and efficient mining operations.
- Expertise in mining technology, concentrator/processing technology and smelting technology, facilitates ore and metal processing.
- Ongoing research at several universities/colleges within different stages of the metal extraction process.
- Concentrators, blast furnaces and smelters in operation.
- A large domestic metal industry, engineering industry, and manufacturing industry using metals.
- Ongoing R&D at all stages of the process.

Growth Analysis (Tillväxtanalys 2017b) points out that the cluster that has developed around iron and base metal extraction and metal production is strong, but also stresses that the mining and exploration industry in Sweden is dominated by a few players who do not have critical minerals and metals in their core business. There are signs that the permit processes have become an obstacle to operations.

FURTHER WORK

Precious metals, base metals and iron have been mainstay of the Swedish mining industry for more than 1,000 years. Today, by its own efforts and those of others, SGU has a good knowledge of where these raw materials are, how much has been extracted and how much is left. It is also known that Swedish ores and the Swedish bedrock contain other raw materials, but since these have not been in demand, their occurrence has been of only academic interest.

Rapid technological developments in recent years, not least in the green industry, have changed this picture. Demand for knowledge of these "new" raw materials, from industry but also from the authorities and the public, has revealed major gaps in knowledge.

Over the past few years SGU has been working on bridging these gaps, by participating in various fixed-time EU projects, in government-instigated projects like this one, but also by ongoing documentation, such as the Bergslagen project. We now have better knowledge about the "new" raw materials, but still have much to do before we can say that we have a good knowledge of where the "new" raw materials are, how much has been extracted but ended up in mining waste and slag and how much remains in the Swedish bedrock.

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APPENDIX 1. CRITICAL RAW MATERIALS FOR THE EU (2017)

Antimony
Baryte
Beryllium
Bismuth
Borate
Cobalt
Coking coal
Fluorspar
Gallium
Germanium
Hafnium
Helium
Heavy rare earth elements (HREE)
Indium
Light rare earth elements (LREE)
Magnesium
Natural graphite
Natural rubber
Niobium
Platinum group metals (PGM)
Phosphate rock
Phosphorus
Scandium
Silicon metal
Tantalum
Tungsten
Vanadium

APPENDIX 2. DATA SOURCES

Analogue data that are digitised (large number of observations, few analysed elements, represent the sampled site, usually unknown analysis method):

- Drill hole protocols with chemical analyses
- Exploration reports
- Environmental reports
- Research reports

Digital data with few analysed elements (large number of observations, few analysed elements, represent ore bodies, usually unknown analysis method):

- The MALM-db database with production data from mines and concentrators
- The MALM-db database with information on resources and reserves

Digital data with modern analyses (fewer observations, multi-element analyses, represent sampled sites, known analysis method):

- EURARE Project Results (http://www.eurare.eu)
- Ores, industrial minerals and rocks in the county of Dalarna SGU RM 139
- Ores, industrial minerals and rocks in the county of Västmanland, ongoing)

New sampling and modern lithogeochemical analysis (small amount of data, multi-element analyses, representing sampled sites, known analysis method):

- Drill cores
- Tailings
- Waste rock dumps

Ore estimates:

The ore estimates documented in FODD (2018) are either modern information that is in line with internationally accepted reporting systems or older estimates that were made before the current regulations existed. The collective documentation of ore production and mineral exploration has now given us good information on how much iron, base metals and precious metals have been extracted and how much remain in Swedish deposits.

APPENDIX 3. LITHOGEOCHEMICAL ANALYSES

Lithogeochemical analyses are complicated because most methods for chemical analysis of rocks require dissolution of the sample in a liquid before analysis and rocks are difficult to dissolve.

A common method of dissolving the sample is to melt it together with a flux (usually some form of lithium borate) into a glass which subsequently can be dissolved in an acid solution, usually hydrochloric and nitric acid. This procedure results in a total dissolution of the sample but with the disadvantage that volatile elements such as mercury, sometimes also arsenic, zinc and indium, evaporate during the melting process. Sulfide-rich samples can be difficult to dissolve with this method.

Another method used for dissolving silicates is to treat samples with a mixture of hydrofluoric acid, hydrochloric acid, nitric acid and perchloric acid. A disadvantage of the method is that it does not give a total dissolution of the sample but often leaves a residue of acid-refractory minerals.

Simpler methods, which should rather be regarded as leaching of the sample, uses aqua-regia (hydrochloric acid mixed with nitric acid) or nitric acid alone. These methods leave a part of the sample undissolved but have the advantage of not losing volatile elements.

After dissolution, the dissolved sample can be analyzed by a spectroscopic or mass spectroscopic method.

Other methods for analysis are X-ray fluorescence (XRF) and Instrumental neutron activation analysis (INAA). During XRF analysis, the sample is irradiated with X-rays that excite electrons in the electron shells of the atoms. When excited electrons fall back to their stable positions, characteristic radiation of the element is emitted. The characteristic radiation and intensity are used to determine the amount of the element in the sample. The analysis can be done directly on a fresh rock surface (for hand-held XRF instruments), on a finely ground powder of the rock or mixed with a flux and fused into a glass bead.

During INAA analysis, the sample is irradiated with neutrons, which creates new unstable elements. When these decay into other isotopes, they emit a radiation characteristic of the newly formed unstable element whose intensity is used to determine the amount of the element in the sample. The method is limited by the fact that all elements do not form suitable new elements when irradiated and that the method requires access to a nuclear reactor for the neutron radiation. One of the advantages is that the method can give accurate analytical results of very small concentrations.

Commercial laboratories today offer several combinations of two or more methods to provide a complete analysis of approximately 70 different elements.

APPENDIX 4. THE MALMKEMI-DB DATABASE

The MALMKEMI-db database created for this assignment can be divided into two parts: one describing the sample and one containing the analytical data. The description (see Table 18) includes the sample ID (in red), geographical location (green), name of the sampled site (yellow), brief information about the rock type (grey), the type of material sampled (orange), information about the laboratory, analytical method and quality (light blue), as well as comments and references to the information and analysis results. Several of the observations contain code lists. One of the code lists describes the analysed material; whether the analysis refers to a single rock sample, sampling of tailings, estimated metal content in mined-out tonnage or a mineral resource.

Table 18. Description of analysed sample.

Column header	Explanation	Associated code lists
SGU_ID	ID code for sample in the SGU lithogeochemical database	
ALT_ID	ID code for sample in the SGU lithogeochemical database	
N_SWEREF	North coordinate in SWEREF	
E_SWEREF	East coordinate in SWEREF	
depth	Depth from point of reference (applies to mines and drill holes)	
H_möh	Height above sea level (metres)	
N_RT90	North coordinate in RT90	
E_RT90	East coordinate in RT90	
N	North coordinate in other reference system specified in KOMMENTAR	
E	East coordinate in other reference system specified in KOMMENTAR	
ORE_AREA_CODE	ID code in the SGU MALM database	MALM-db
ORE_AREA	Name of mine/mining area in the SGU MALM database	MALM-db
Lokal	Sample locality	
bh_kod	ID code in the SGU drill hole database	bh-data
bh	Drill hole number	
from	Start of drill core section	
to	End of drill core section	
Bergart_fri	Free text for rock description	
BG_kod	Code for simplified rock description	kod för bergartsgrupp
Berg_grp	Simplified rock description	bergartsgrupp
MATERIAL	Type of analysed material	analyserat material
LAB_TXT	Analytical laboratory	laboratorium
BATCH	Batch	
n	Number of analyses in combined result	
ANALYSDATU	Date of analysis	
MALFAT_TXT	Milling equipment	malfat
METOD_TXT	Code for analytical method	analysmetod
Q	Quality designation	analyskvalitet
REFERENCE	Reference	referenslista
KOMMENTAR	Comments	

The records in the database differ greatly in terms of number of analysed elements, sample digestion and analytical method, the general quality of the analyses and the significance of the analysis. This information has been weighed together in a quality designation (Q) for each item.

The analytical results in the database have differing significance. The results can be divided into the following categories of increasing significance:

- An analysis of a single rock sample, outcrop or tailings sand represents only the specific rock sample, outcrop or sand that is sampled. The analysis may indicate the presence of any economically significant metal, including a critical metal, but says nothing about the extent and volume of the mineralisation. These data therefore have low significance.
- Analysis of a drill core section where some economically significant metal is detected, shows that there is a certain mineralisation over the number of metres sampled. These data are of moderate significance.
- The mineral and metal concentrations stated in reported resources and reserves and production data from mines and concentrators are based on hundreds to thousands of analyses, which together represent a very large amount of mineralised rock and therefore have high significance.

The data have been collected from various sources, where they are reported in different ways and using different units of measure: as pure element or as oxide, as a percentage or parts per million (ppm). This means that the list of elements analysed contains 170 columns, much longer than the periodic table, containing 92 elements, not counting the transuranes. Since this is a database containing raw data, the information was stored in its original format and processed into a common format at a later stage. Table 19, which is an example from the raw database, shows the different ways of reporting silicon, manganese, tantalum and cerium.

This variation in reporting is typical for most elements. The data is therefore converted into a common format and reported as a single element ($Ta_2O_5 \rightarrow Ta$ etc.). Major elements and ore metals such as copper, zinc and lead etc. are reported as a percentage. Other elements are reported in ppm.

Table 19. Excerpt from the MALMKEMI-db database.

Silicon	Manganese	Tantalum	Cerium
SiO_2 %	MnO_2 %	Ta %	Ce ppm
Si %	MnO %	Ta_2O_5 %	Ce %
	Mn_3O_4	Ta_2O_5 ppm	CeO_2 %
	Mn %	Ta ppm	Ce_2O_3 %
	Mn ppm		

APPENDIX 5. GEOLOGICAL OVERVIEW

The Swedish bedrock can be divided into six major lithotectonic units (see Figure 12) that differ in predominant rock type, age of formation and subsequent geological events. The most important unit in terms of ore geology is the Svecokarelian orogen, in which the majority of rocks have an age of about 2.0–1.8 billion years. This orogen includes ores in Norrbotten, the Skellefte district and Bergslagen. Other major lithotectonic units are the Sveconorwegian (about 1.1–0.9 billion years) and the Caledonian orogen (0.5–0.4 billion years), the latter being the fourth of Sweden's four classic ore districts. Ore potential also exists outside these areas.

The Svecokarelian orogen

Much of Sweden's bedrock formed or was tectonically affected by the Svecokarelian orogenesis at 2.0 to 1.8 billion years ago. The orogen can be divided into a number of sub-units, three of which constitute three of Sweden's four classic ore districts: norra Norrbotten, Skellefte district and Bergslagen. Mines are currently active in these ore districts. The other sub-units, southern Norrbotten, the Bothnian basin and Småland, do not lack ore and mineralisations but have never constituted significant ore districts (see Figure 12).

Isotopic data show that the rocks in ***northern Norrbotten*** rest on a basement of archaean (= older than 2.5 billion years) granites and gneisses. In the far north, the archaean rocks are exposed, but elsewhere they are covered by metamorphosed greenstone belts, sedimentary rocks, other volcanic rocks and granitoids. Sizeable deposits of copper and iron ore are found both in the greenstone belts (Viscaria and Kaunisvaara respectively) and in the younger volcanic rocks (Aitik and Kirunavaara respectively).

The rock types in ***southern Norrbotten*** share similarities with those in northern Norrbotten and the Skellefte district,but differs from northern Norrbotten in that there is no proven archaean basement. The volcanic rocks appear to have been deposited on land and not in a volcanic arc such as the Skellefte field. The mineralisations also have other characteristics. Several copper mineralisations in southern Norrbotten resemble porphyry-type deposits. The area is also known to host uranium mineralisations. No mining has taken place in the modern era.

The rocks in ***the Skellefte district*** consist of volcanic rocks deposited in a volcanic arc environment 2.0 to 1.8 billion years ago. Within the Skellefte district there are several massive sulphide deposits, with base metals like copper, zinc and lead and gold and silver, ores that are typical of volcanic arcs. There are also several known gold deposits in the Skellefte field. The field has been mined for almost a century and there are currently about 150 known base and precious metal deposits, of which approximately 30 have been or are in production.

As its name suggests, ***the Bothnian basin*** is a basin that was filled with sediments (greywackes) about two billion years ago. Minor areas of volcanic activity have formed massive sulphide deposits. Mafic and ultramafic rocks with associated copper-nickel-cobalt mineralisations occur in the north of the area. Pegmatites containing lithium and tin occur in the area's central parts. The only mine that has operated in modern times is Enåsen (Au) in the southwest of the area.

The oldest rocks in ***Bergslagen*** consist of metamorphosed greywackes deposited about two billion years ago. During the Svecokarelian orogeny, intensive volcanic activity took place in the area and formed the ores that are characteristic of Bergslagen: skarn iron ore, banded iron formations, sulphide ores formed by reaction with limestone and zinc-lead deposits that were deposited on the seabed. Hydrothermally altered felsic volcanic rocks associated with carbonate and calc-silicate rocks are common host rocks for the deposits in Bergslagen. Here, mining has been going on for more than a thousand years and at present we know of more than 7,000 mineralisations with iron, 1,500 with base metals and 150 with other metals, including critical raw materials.

The ***Småland*** sub-unit predominantly comprises granitoid rocks belonging to the trans-Scandinavian igneous belt. In parts of the northeastern and central areas there are metamorphosed sedimentary and volcanic rocks with minor gold and sulphide mineralisations. No mining has taken place in the modern era.

The Sveconorwegian orogen

The bedrock in the southwest of Sweden is influenced by the Sveconorwegian orogeny, which took place about 1.1–0.9 billion years ago. During continental collision and orogenesis, parts of the bedrock underwent high pressure metamorphism, resulting in the formation of eclogites and high pressure granulites. Older bedrock with traces of previous orogenesis is preserved within the orogen. The orogen has not hosted any significant mines.

The Caledonian orogen

During collision between Europe and North America and the closure of the Iapetus Ocean during the Caledonian orogeny (about 490–390 million years ago), various rock units consisting of oceanic crust, volcanic arcs and sediments were thrust onto the older basement of the Fennoscandian shield. Important deposits formed shortly before or during the Caledonian orogeny are massive sulphide ores in an island arc environment and lead-zinc ores that fill the pore space in sandstones. Some copper deposits are possibly of the "sediment-hosted copper" type. There are no longer any mines operating in the area, but Stekenjokk and Laisvall were active a few decades ago.

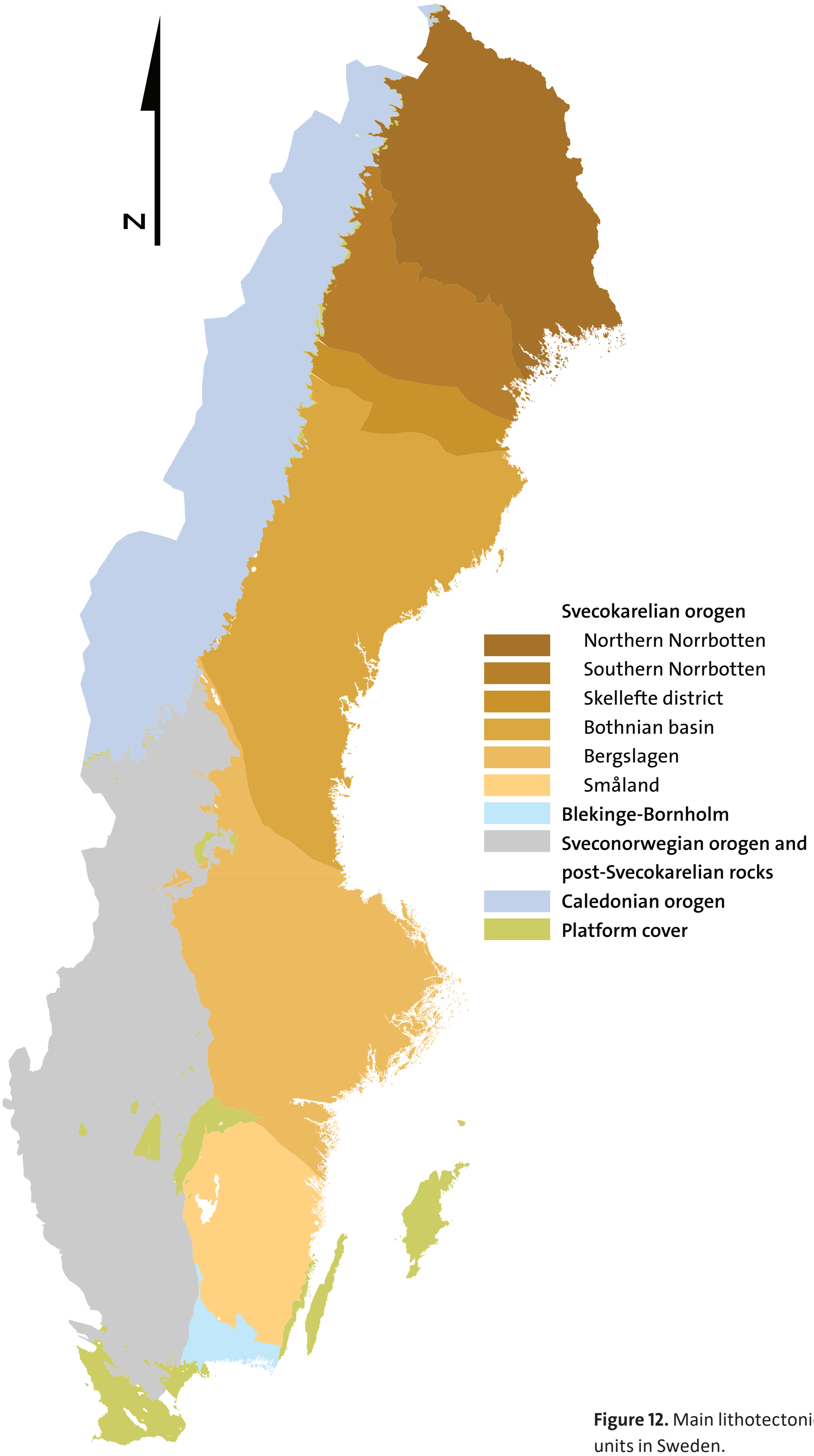

Figure 12. Main lithotectonic units in Sweden.

APPENDIX 6. NEW SAMPLING OF DRILL CORES AND TAILINGS

Sampling and analysis of drill cores 2016–2017

As a first step to increasing our knowledge of primary sources of innovation-critical metals and minerals, SGU has carefully sampled and analysed selected cores at the SGU drill core archive at Malå. More than 3 million metres of publicly available drill core from 18,000 boreholes is stored at the archive. The drill cores have been collected from more than a hundred years of drilling, and come from different parts of Sweden. The cores constitute a unique collection in which many deposits of many different types are represented, and the archive is an important resource used by mining companies, exploration companies, researchers and others.

Many drill cores in the Malå archive have not previously been the subject of detailed investigations, and it is considered likely that traces of new, undiscovered mineral deposits, including innovation-critical ones, may be among the large volumes in the archive.

The SGU drill core scanning project (2014–2016) produced a very comprehensive new and modern dataset. A total of 233,000 metres (approximately 1,600 drill cores), covering many Swedish mineralisations and deposit types, have been photographed and scanned using hyperspectral infrared technology. The scanning project is unique of its kind, both in the large volume of drill core scanned and the technology used.

The scanning data, together with the SGU mineral resource database, the Fennoscandian ore deposit database (FODD), the SGU MALM-db database, digitised exploration reports, borehole logs, descriptions and maps, constitute an excellent basis for identifying potential sites of interest to the current project. Initially, we therefore focused on analysing existing drill cores in Malå (see Table 20).

Figure 13. Drill core tray containing LCT pegmatite from Järkvissle. The red line marks sections that have been analysed. Analytical results for selected elements are shown. Photo: Specim.

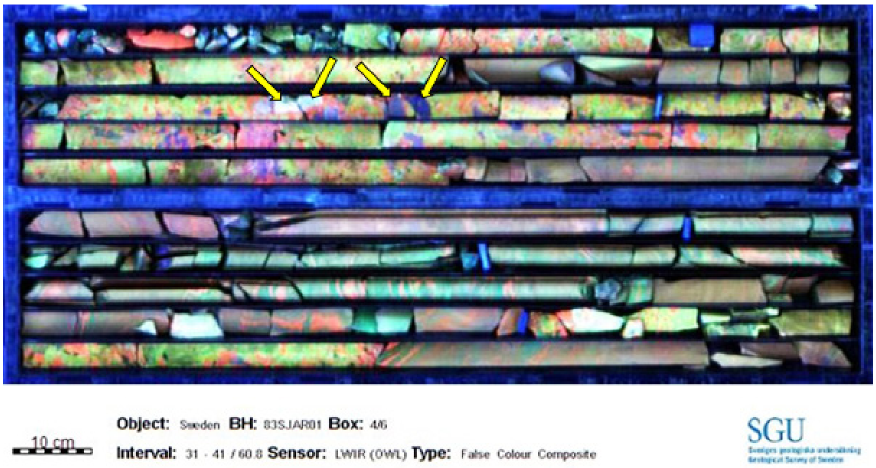

Figure 14. The same tray as in Figure 13 photographed with an infrared camera. The image is a False Colour Composite image with data from the long wavelength (LWIR) portion of the infrared spectrum. The lithium mineral spodumene (yellow arrows) can be identified in this image. Photo: Specim.

Table 20. Analysed drill core sections.

Object	Drillhole-ID	Tray #	Section
Allebouda	ALB79722	5	58,2–59,0
Bastnäsorten	EXTG371	7	52.00–53.00
Bastnäsorten	EXTG371	7	53.00–54.00
Bastnäsorten	EXTG371	8	58.00–59.00
Björntjärn	BJT71212	8	61,05–62,05
Björntjärn	BJT72209	6	46,53–47,53
Brännmyran	BRM57069	9	159.33–160.33
Brännmyran	BRM57069	9	160.33–161.33
Brännmyran	BRM57069	9	161.33–162.40
Brännmyran	BRM58106	12	201,4–202,4
Brännmyran	BRM58106	12	202,4–203,55
Båtens	BÅT86001	-	70–71
Båtens	BÅT86001	-	81,6–82,6
Dannemora	SVE3206	28	153–154
Dannemora	SVE3206	29	158–159
Dannemora	SVE3206	35	191–192
Dingelvik	DIN82002	11	133.48–134.73
Dingelvik	DIN82002	11	131,46–132,46
Dingelvik	DIN82002	11	132,46–133,48
Dingelvik	DIN82002	12	134,73–135,8
Dingelvik	DIN82002	12	135,8–136,8
Dingelvik	DIN82005	3	22.90–23.90
Dingelvik	DIN82005	3	24.40–25.40
Dingelvik	DIN82306	9	94.0–95.0
Ekströmsberg	EKS65803	10	106–107
Ekströmsberg	EKS68801	10	102–103
Ekströmsberg	EKS51003	3	80–81
Ekströmsberg	EKS51003	4	90–91
Ekströmsberg	EKS51003	5	116.8–117.8
Enåsen	END173	12	120.50–121.50
Enåsen	END173	13	126.25–127.25
Enåsen	END173	13	128.35–129.35
Falu gruva	FLU88012	3	20.60–21.45
Falu gruva	FLU88012	3	22.85–23.85
Falu gruva	FLU88012	4	30.50–31.50
Falu gruva	FLU88012	6	46.50–47.50
Gruvberget/Sumåsjön	SUM81005	3	23,5–24,5
Gruvberget/Sumåsjön	SUM81005	3	24,5–25,5
Gråberget	GRT76008	17	181.6–182.6
Grängesberg	GMD82601	1	6.45–6.85
Grängesberg	GMD82601	1	6.95–7.25
Grängesberg	GMD82601	1	7.95–8.25
Grängesberg	GMD86825	10	74.50–75.50

Table 20. Continued.

Object	Drillhole-ID	Tray #	Section
Grängesberg	GMD86825	10	75.50–76.25
Harmsarvet	HMR008	8	64.85–65.85
Harmsarvet	HMR008	8	69.9–70.85
Henneviken	HEN83003	2	19.5–20.5
Henneviken	HEN83003	2	20.5–21.5
Henneviken	HEN83003	2	21.5–22.5
Hornkullen	HRK86001	14	158,40–159,8
Hournaisenvuoma	HUO86052	23	264.0–264.45
Hournaisenvuoma	HUO86052	23	264.45–265.55
Hournaisenvuoma	HUO86052	23	265.55–267.0
Hournaisenvuoma	HUO86052	23	267.0–267.6
Hournaisenvuoma	HUO86061	4	44.6–45.45
Hournaisenvuoma	HUO86061	4	45.45–46.45
Hournaisenvuoma	HUO86061	4	46.45–47.45
Hournaisenvuoma	HUO86061	4	47.45–48.5
Hournaisenvuoma	HUO86061	4	48.5–49.2
Hournaisenvuoma	HUO86061	4	49.2–50.2
Hournaisenvuoma	HUO86061	4	50.20–51.20
Hournaisenvuoma	HUO86063	5	58.0–59.0
Iekelvare	IEK75002	12	126,7–128
Iekelvare	IEK75002	14	154–155
Iekelvare	IEK75004	2	20–21
Iekelvare	IEK75004	6	58–59
Jervas	JER50003	9	88,31–89,31
Jervas	JER50003	9	89,31–90,16
Järkvissle	83SJAR01	4	33,0–34,0
Järkvissle	83SJAR01	4	34,0–35,0
Järkvissle	83SJAR03	3	31,6–32,6
Järkvissle	83SJAR06	2	18.30–19.30
Järkvissle	83SJAR06	2	21.30–22.30
Kiskamavaara	KIS75001	6	60.4–61.4
Kiskamavaara	KIS77007	9	94.0–95.0
Kiskamavaara	KIS80004	4	48.0–49.0
Kiskamavaara	KIS80004	4	49.0–50.5
Kiuri	84SKIU37	7	66,0–67,0
Kiuri	84SKIU37	7	67,0–68,0
Kläppsjö	KLP88101	1	3.5–4.5
Kläppsjö	KLP88101	1	4.5–5.5
Kläppsjö	KLP88101	1	5.5–6.5
Kläppsjö	KLP88101	1	6.5–7.5
Kläppsjö	KLP88101	2	17.5–18.41
Kläppsjö	KLP88101	3	18.41–19.5
Kläppsjö	KLP88101	3	19.5–20.5

Table 20. Continued.

Object	Drillhole-ID	Tray #	Section
Laisvall	LAQ34	5	94.00–95.00
Laisvall	LAQ34	6	113.50–114.65
Laisvall	LAQ34	6	114.65–115.65
Lappvattnet	LPV75002	7	98.43–90.43
Lappvattnet	LPV75002	7	90.43–91.23
Lappvattnet	LPV75002	7	91.23–92.30
Lappvattnet	LPV75002	7	92.3–93.18
Lappvattnet	LPV75002	7	93.18–94.18
Lappvattnet	LPV75004	13	152.6–154.14
Lappvattnet	LPV75004	13	154.14–154.48
Lappvattnet	LPV75004	13	154.48–154.87
Lappvattnet	LPV75004	13	154.87–155.37
Lappvattnet	LPV75004	13	155.37–155.57
Lappvattnet	LPV75004	13	155.57–156.21
Lappvattnet	LPV76001	11	131.38–132.19
Lappvattnet	LPV76001	11	132.19–132.47
Leja	LEJ81010	4	44,0–45,0
Leja	LEJ81010	4	45,0–46,0
Lindsköld–Kourbevare	LSK047	6	91.76–92.76
Lindsköld–Kourbevare	LSK047	6	92.76–93.76
Lindsköld–Kourbevare	LSK047	6	93.76–94.76
Lindsköld–Kourbevare	LSK047	7	94.76–95.76
Lindsköld–Kourbevare	LSK047	7	95.76–96.76
Lindsköld–Kourbevare	LSK047	7	96.76–97.76
Lulepotten	LUL64201	3	29.13–30.13
Lulepotten	LUL64201	3	30.13–31.13
Lulepotten	LUL68207	6	67.69–68.69
Lulepotten	LUL68208	10	119.3–120.15
Lulepotten	LUL78211	13	141.95–143.25
Lulepotten	LUL78211	13	144.8–145.8
Lulepotten	LUL78211	13	145.8–146.8
Lustigkulla	LGK79009	?	225,85–226,9
Lustigkulla	LGK79009	?	226,9–227,9
Lövstrand	LOV283	1	21.00–22.00
Lövstrand	LOV283	1	16,95–18,25
Mangen	MNG72001	?	40,78–41,86
Masugnsbyn	MAS67515	11	130–131
Maurliden	MAU58103	2	43.64–44.64
Maurliden	MAU58103	4	67.00–68.00
Myrviken	MYR78003	5	53.44–54.40
Myrviken	MYR78003	5	55.50–56.50
Myrviken	MYR78003	6	64.05–65.05
Nautanen	NAU70005	6	58.71–59.63

Table 20. Continued.

Object	Drillhole-ID	Tray #	Section
Nautanen	NAU70005	6	60.24–61.47
Nautanen	NAU83002	4	40.7–41.7
Nautanen	NAU83002	4	41.7–42.7
Nautanen	NAU83002	4	42.7–43.7
Nautanen	NAU83012	16	180.2–181.6
Pahtohavare	PAH88057	5	60.7–62
Pahtohavare	PAH88057	5	63.4–64.5
Pahtohavare	PAH88057	5	64.5–65.5
Persberg	EXTS124	2	11.00–12.00
Persberg	EXTS124	3	25.00–26.00
Puolalaki	PNO98009	8	47,7–48,7
Puolalaki	PNO98029	6	40,1–41,2
Ramundberget	RMU75012	1	5.5–6.5
Ramundberget	RMU75012	1	6.5–7.5
Routevare	ROU71009	9	100,0–101,0
Rävliden	RAV002	27	334.67–335.48
Rävliden	RAV002	27	335.46–336.48
Rävliden	RAV002	27	339.00–340.00
Rävliden	RAV002	27	340.00–341.00
Rävlidmyran	RVM103	6	109.25–110.25
Rävlidmyran	RVM103	6	110.25–111.25
Rörmyrberget	ROR80004	29	328.41–329.41
Rörmyrberget	ROR80004	29	329.41–330.60
Rörmyrberget	ROR80004	30	335.77–336.77
Rörmyrberget	ROR80008	17	194.00–195.00
Rörmyrberget	ROR80008	17	195.00–196.00
Sautusvara	SAU67705	27	294.5–295.5
Saxå	SAX91005	3	11,91–12,9
Saxå	SAX91005	3	16,2–17,2
Silvberg	SIL009	6	53.65–54.65
Silvberg	SIL009	6	55.4–56.5
Silvberg	SIL009	9	86,0–87,0
Silvberg	SIL009	9	89,3–90,3
Silvberg	SIL009	9	90,3–91,3
Stekenjokk	STE68005	26	290.50–291.50
Stekenjokk	STE68005	27	302.00–303.00
Stekenjokk	STE68005	28	304.00–305.00
Stollberg (Lustigk)	LGK79007	32	243.16–244.0
Stollberg (Lustigk)	LGK79007	37	279.75–280.75
Storliden	SLI03702	3	15,87–16,8
Storliden	SLI03702	3	16,8–17,8
Storliden	SLI03703	4	18,5–19,7
Storliden	SLI03703	4	19,7–20,7

Table 20. Continued.

Object	Drillhole-ID	Tray #	Section
Storliden	SLI03703	4	21,0–22,0
Stråssa	EXTO707	16	144–145
Stråssa	EXTO707	22	203–204
Svärtträsk	SVT77009	5	44.6–45.6
Svärtträsk	SVT77009	5	45.6–46.6
Sylarna	SYL77002	2	24,3–25,2
Ultevis	ULT013	10	137.1–137.6
Vargisträsk	VRG68001	12	130.45–131.45
Vargisträsk	VRG68005	7	80.7–81.7
Vingesbacke	GHV041	36	319.5–320.5
Vingesbacke	GHV041	36	323–324
Vingesbacke	GHV041	37	325.5–326.5
Vingesbacke	GHV042	33	333,3–334,3
Vingesbacke	GHV042	35	351,69–352,69
Viscaria	VIS3831	14	151.10–152.0
Viscaria	VIS3831	14	152.0–153.0
Viscaria	VIS4698	2	14.20–15.20
Viscaria	VIS4698	2	15.20–16.00
Viscaria	VIS4698	3	19.25–20.21
Viscaria	VIS4698	3	20.57–21.00
Viscaria	VIS6474	5	38.84–40.10
Viscaria	VIS6474	5	40.10–41.40
Viscaria	VIS6474	5	41.40–42.30
Viscaria	VIS6474	5	42.30–43.30
Vuolep Räskevare	VLP86006	4	41.15–42.15
Vuolep Räskevare	VLP86010	4	39.3–40.3
Yxsjöberg	FD007	9	64.0–65.0
Yxsjöberg	FD007	9	67.0–68.0
Yxsjöberg	FD007	9	70.0–71.0
Yxsjöberg	FD010	23	173,3–174,3
Yxsjöberg	FD010	23	174,3–175,3
Yxsjöberg	KD002	10	93,0–94,0
Yxsjöberg	KD002	10	94,0–95,0
Yxsjöberg	KD004	4	37.70–38.70
Yxsjöberg	KD004	4	38.70–39.70
Yxsjöberg	KD004	4	39.70–40.70
Yxsjöberg	YXS81020	9	68,1–69,4
Åggojaure	AGG80005	6	45.9–46.9
Älgsjöhöjden/Fredriksberg	ALG84005	-	38,65–39,30
Älgsjöhöjden/Fredriksberg	ALG84005	-	51,8–52,3

Mining waste

Millions of tonnes of ore and mining waste are produced annually in Sweden. Statistical data (dating back to the 1830s) indicate total ore production of 3,344 million tonnes (SGU MALM-db). Of this, iron ore predominates (67 per cent), base metals have a share of 32 per cent (mainly copper, lead and zinc, but also minor amounts of cobalt and nickel). Precious metals and silver constitute 1 per cent. A small amount, about 0.16 per cent, consists of other metals and minerals, including tungsten, molybdenum, graphite, fluorspar and andalusite.

Mining waste (waste rock and tailings) is generated during mining and processing of ore in a concentrator (see Figure 15). Figure 16 shows the amount of tailings produced from concentrators. Other types of waste may also be generated in mining operations, such as till, soil, sand and gravel, which must be removed in order to expose the bedrock before mining, but amounts of this waste are in most cases negligible.

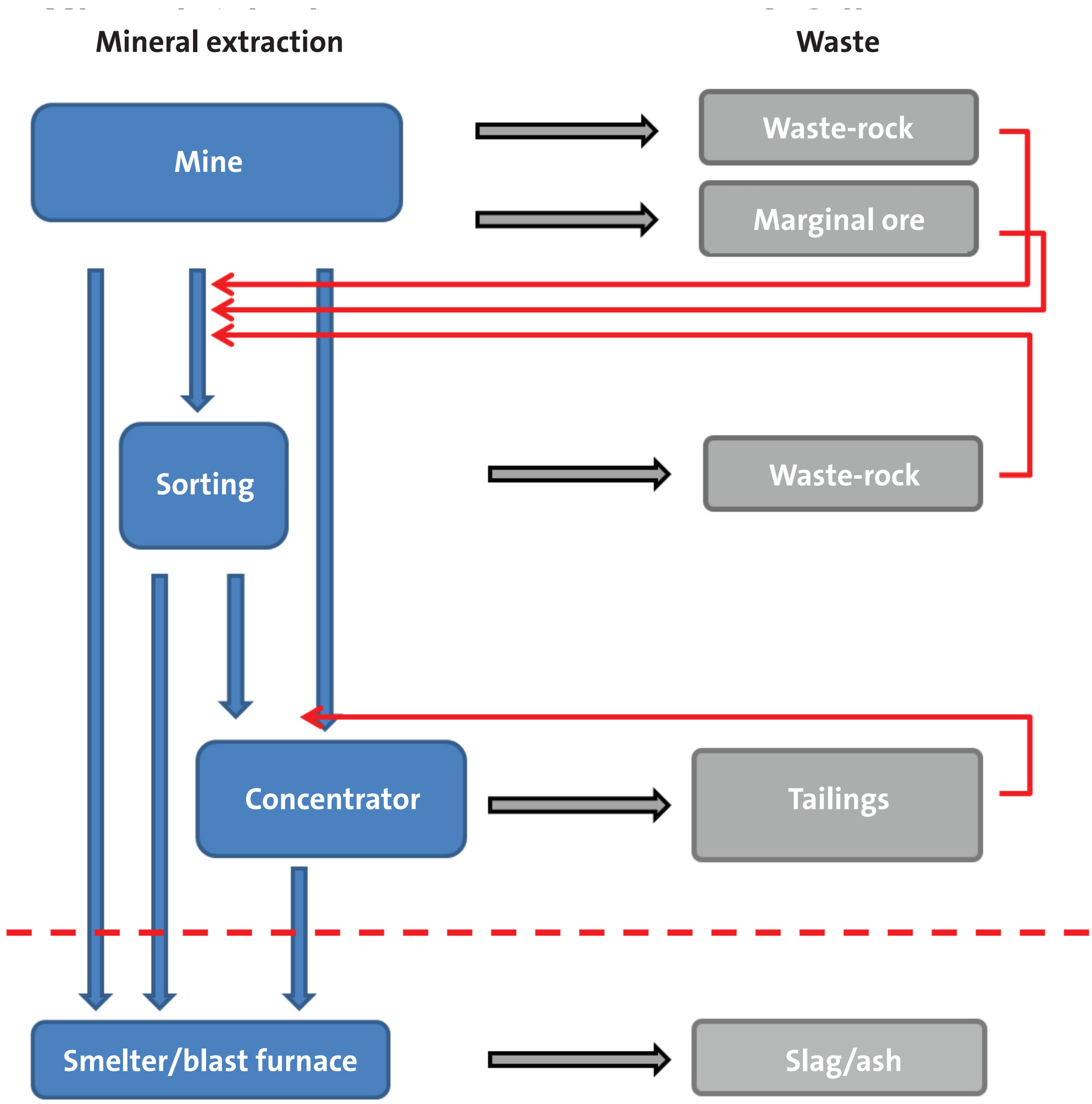

Figure 15. Mineral extraction and different types of waste.

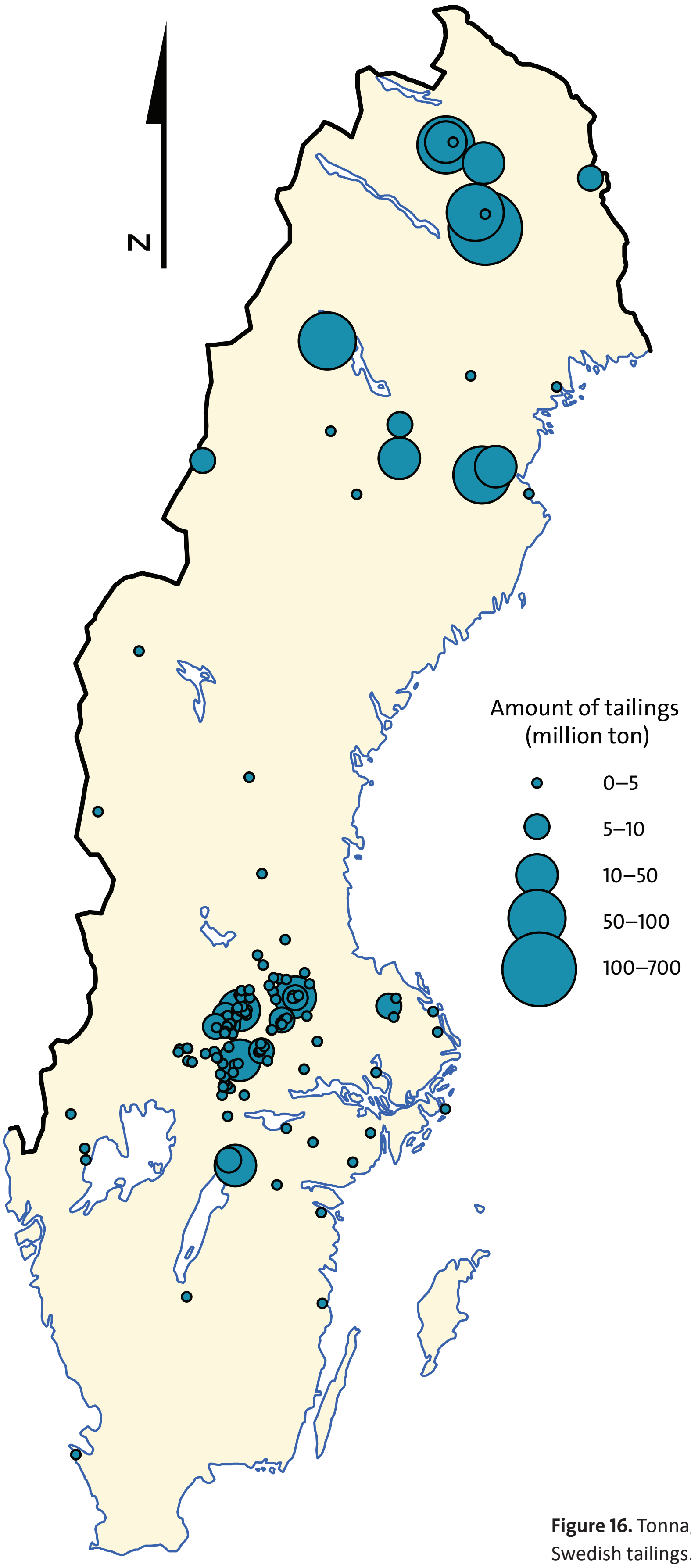

Figure 16. Tonnages in Swedish tailings.

Waste from the mine itself

Waste generated by mining itself at the mine site is called waste rock. It mainly consists of barren rock that must be removed to access the ore body. The material may include material from tunnels or parts of the open pit that have been removed to expose the ore. Weakly mineralised rock, known as "marginal ore", which was considered sub-economic at the time of mining can also be found in waste rock dumps. At some mines this material has been deposited separately from barren waste rock for possible later processing.

More modern and more efficient ore processing in combination with periods of high metal prices means that such material can potentially be processed at a profit. The material can also be used to take advantage of periods of high capacity in the concentrator.

Residues from sorting of coarse crushed ore can sometimes be found in waste dumps and pieces of ore have occasionally ended up in the waste pile. Waste rock is generally made up of coarser material such as boulders, with a minor amount of finer-grained material.

Due to its low economic value, the waste is usually deposited very close to the mine. Aggregates can be used for constructing roads or dams at the mining site and as backfill in the mine. In some cases, the material may also offer potential for use as aggregates outside the mining area.

Since waste rock consists of coarse material and can be very heterogeneous in composition, it is almost impossible to perform a sampling that gives a statistically reliable estimate of its metal content (Sädbom & Bäckström 2018; annex to this report).

There are currently statistical data on the amount of waste rock produced at over 600 mines and mining areas in Sweden. Data are also available on the geographical location of an additional 10,000 mines that were closed before statistics on waste rock production began to be collected in the late 19th century.

Processing waste

Mining waste generated during ore processing is usually called tailings. The material is a residual product after the ore has undergone some form of mechanical, gravimetric or chemical process to concentrate the economically interesting minerals. The tailings are deposited in a landfill or pond near the concentrator. Usually, the ore is first crushed, then sorted and milled to a suitable grain size during concentration. This is followed by a process, or a combination of processes, depending on the ore type.

For most sulphide ores, as well as other ore types, flotation may be a suitable method. In flotation, air is blown into a mixture of water, chemicals and finely-ground ore. The ore must be milled down to a suitable liberation-size so that individual mineral grains are released. The surface properties of the ore minerals and the chemicals render the ore minerals hydrophobic and cause air bubbles to stick to them and lift them to the surface as a foam. The foam containing the ore minerals is recovered, while the minerals to which the air bubbles do not stick remain in the flotation tank and are deposited as tailings.

No concentrator process is 100 per cent effective. The term recovery is used to indicate the ratio between metal recovered through the process and the amount of metal contained in the ore. Recovery can vary widely between different ore types, between different concentrator plants, and also at the same plant over time. Generally, technological developments improve ecovery; hence, older tailings potentially contain higher grades of metal than younger ones. This effect is further reinforced by the fact that technological developments over time have also allowed profitable extraction of ore with progressively lower concentrations of economic minerals.

Figure 17. Waste rock dump and tailings. Tomtebo. Photo: Helge Reginiussen.

Figure 18. Tailings at Bäckegruvan, Riddarhyttefältet. Photo: Helge Reginiussen.

If statistics are available on the input tonnage and the amount of concentrate produced, or on metal content and recovery, it is possible to estimate the metal content in the tailings. There are large differences between different types of ore when it comes to the fraction of mined ore that eventually ends up as concentrate. For many low-grade sulphide ores (for example "porphyry-type" copper deposits such as Aitik) and gold ores, only a small fraction of the ore becomes concentrate. The remainder is tailings that will be deposited in landfills, or in some cases used as backfill in the mine. There are major variations in Swedish massive polymetallic sulphide ores, but a benchmark may be that about 20 per cent become mineral concentrate and 80 per cent tailings (SGU 2014). In processing apatite iron ore with high iron content, flotation can be used to remove apatite, with the result that the tailings sand makes up a considerably smaller proportion than the concentrate.

Figure 19. The Stråssa mine, including tailings and concentrator. Photo: Google Earth.

The concentrator is often optimised for minerals that contain the main commodity, and the loss is greatest for by-product metals, particularly if these occur in separate minerals and are not included in the same mineral as the main metal. Generally, the loss during the concentrating process that generates tailings is usually greater than the loss to slag (Mudd et al. 2014). Depending on the ore type, the tailings may also contain environmentally harmful and toxic substances. Exposure of the waste to oxygen and water can cause leaching of metals, known as "acid rock drainage".

The concentrator plant and the deposited tailings are usually close to the mine where the ore was mined, but there are examples where ore was transported several kilometres to a central concentrator, which processed ore from various mines in different campaigns. The sand in the tailings then originates from several deposits with different characteristics and may have a complex composition reflecting this. The total metal content of the tailings is thus a cumulative result of the composition and tonnage of the different incoming ores, as well as the efficiency and recovery of the various processing methods.

Secondary processes, i.e. various sedimentary and chemical processes that have taken place in the tailings after deposition, may also affect composition. Like natural sedimentary material, tailings may be affected by sedimentary processes and erosion during and after deposition, which can change and redistribute the material.

The above factors relating to production, processing and extraction of the main metal and by-product have meant that, in addition to the main metals, unknown but probably large quantities of CRM have been deposited as waste in tailings. This conclusion is supported by studies from Canada that have shown that mining waste potentially contains significant amounts of critical metals, and that recycling of mining waste together with recycling from electronic scrap may be an important future source of indium, for example (Werner et al. 2015). Although recycling cannot replace primary production (EASAC, 2016), it has advantages from an environmental viewpoint, and may serve as a complement to primary production.

Figure 20. Tailings showing stratified layers, Bastkärn. Photo: Helge Reginiussen.

Tailings sand is basically depleted ore; it is relatively fine-grained and has become homogenised during concentration. The sand may be economically significant if it is homogeneous and available in large volumes. A complicating factor in sampling and characterising tailings is that there may be lateral and vertical variations (see Figure 21) resulting from variations in the composition of the deposited material, as well as deposition and secondary processes in it. The grain size of the material may vary considerably within a given quantity of tailings.

Sampling of tailings in Bergslagen

The tailings in Bergslagen that have been sampled and analysed in this project are listed in Figure 27. We would stress that sampling so far is in the nature of reconnaissance, with surface sampling only and no drilling to test deeper parts of the tailings. However, the results give indications and a basis for follow-up investigations.

To facilitate better and statistically representative sampling, SGU has commissioned Bergskraft Bergslagen AB to produce a manual describing a sampling methodology for mining waste. Bergskraft Bergslagen AB has extensive experience of sampling mining waste from various mining areas in Bergslagen, and the report describes strategies for sampling mining waste to achieve a regional and local degree of detail (Sädbom & Bäckström 2018).

Several of the sampled tailings contain large tonnages that potentially contain critical metals. We would emphasise that the main aim of this project is not to evaluate the economic and technical aspects of extraction from tailings. The focus has been on documenting the potential content and grades of critical minerals that may become a raw material base in the future. However, the economic and technical factors for extraction are extremely important, and very much determine whether or not extraction will be possible. Before recycling can be considered, the mineralogy and texture of the tailings must be carefully characterised, and potential processing and extraction methods investigated.

Sampling– strategy

Thanks to historical mining statistics, we know a fair amount about the metals that have been extracted in Swedish mines: Fe, P, S and Mn in iron ores, Cu, Zn, Pb, Au, Ag in non-ferrous ores and other metals and minerals such as W, Ni and graphite. However, we know little about any other metals present. A quick and cost-effective method of expanding the knowledge base is to carry out a random sampling of tailings. Since recovery never reaches 100 per cent, a certain portion of the metals contained in the ore will be present in the tailings – the "metal signature" of the ore is preserved. Anomalous grades of other metals can also be quickly identified. The information obtained from sampling of this kind is not sufficient to make estimates of mineral resources, but does give an indication for follow-up sampling and investigations.

Sampling – methodology

Information on concentrators, their approximate location, quantity and content of the processed ore, amount of concentrate produced, and the origin of the processed ore has been digitised from the following sources:

- Bergshanteringen, 1833–1977
- Bergverksstatistik, 1977–2017

Further information has been digitised from publications entitled "Bergmästerens Relationer". Information from mining companies, which forms the basis of SGU's Mining Statistics, has also been digitised.

The exact location of concentrators and associated tailings has been obtained from:

- GSD-Fastighetskartan
- GSD-Höjddata
- GSD-Ortofoto
- SGUs mineralresursdatabas
- SGUs malmdatabas

This information has been used to determine the location of concentrators and approximately 140 tailings, mostly in Bergslagen. These data have been used to plan sampling campaigns.

Sampling has been carried out with a spade or hand-held Edelman auger (see Figures 22 and 23). Many tailings are now used for activities that may have affected the sand, such as motocross tracks, golf courses, bird lakes etc. Hence, sampling has been confined to those parts of the tailings that look relatively undisturbed to the naked eye. At the sampling point, an approximately 60-cm-deep pit was excavated or drilled to access unweathered material and to avoid organic material in the sample, i.e. basically the same method as for till sampling. In some cases, where previous excavations have exposed deeper horizons, samples have been taken there. Approximately 1–2 kg of tailings sand has been sampled at each locality, and sample numbers, coordinates in SWEREF99TM, sample depth, colour of the sample and grain size have been recorded.

The aim was to take three or more samples at each of the tailings so as to gain an overview of compositional variations, but sometimes fewer samples were taken at small tailings. Some tailings, particularly those containing sand from concentration of sulphide ore, have been restored by covering the sand with moraine, sludge or other material. This makes sampling impossible with the simple tools described above. However, at some of these tailings there are areas with insufficient coverage due to landslides and erosion where sampling could be carried out.

After each sampling campaign, a portion of the sample was prepared for analysis. The material was air-dried, packaged in plastic bags and then sent to a commercial laboratory for analysis together with standard samples. Reference material from all tests has been saved for future in-depth studies.

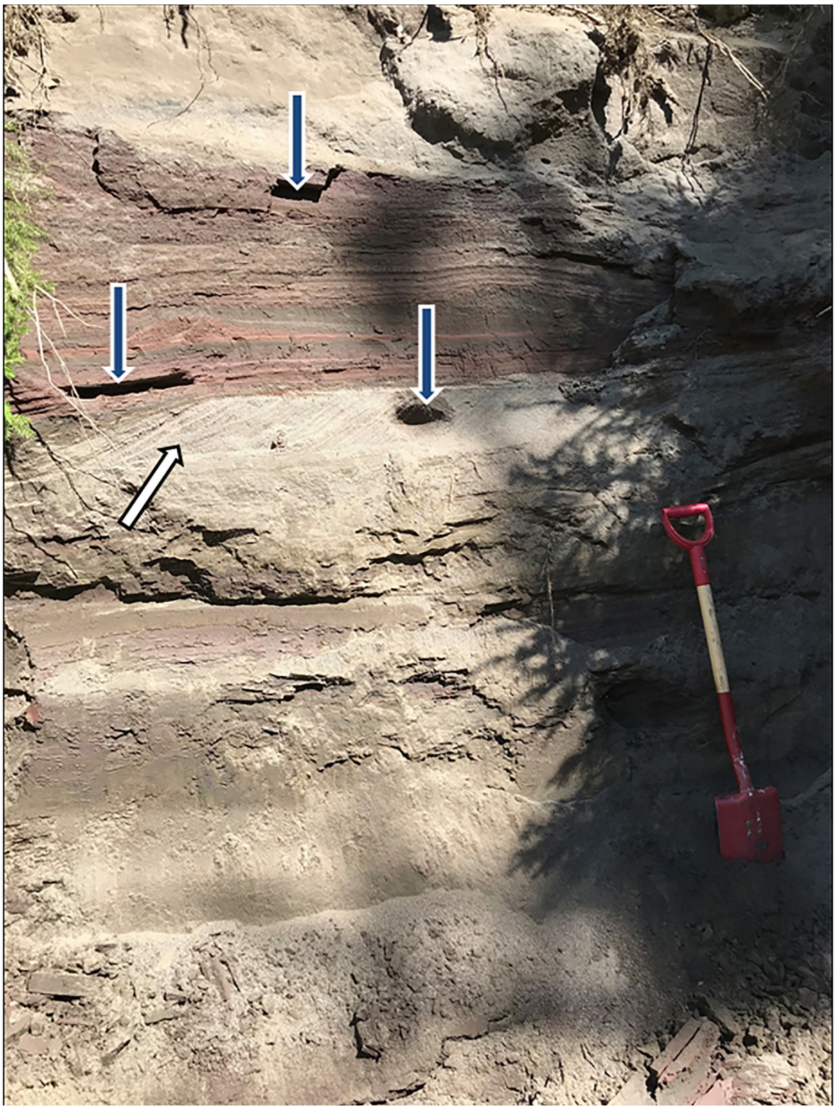

Figure 21. Stratified tailings at Åsboberg. Sedimentary structures, including cross-bedding and graded bedding are visible in sandy layers (white arrow). Blue arrows show sample location for chemical analysis. Photo: Helge Reginiussen.

Figure 22. Sampling of tailings using Edelman auger. Photo: Anders Hallberg.

Figur 23. A and B. Sampling of tailings at Kanntorp. Photo: Helge Reginiussen.

Figur 24. A and B. Sampling of tailings at Sätra. Photo: Helge Reginiussen

Figur 25. A and B. Sampling of tailings using Edelman auger. Photo: Helge Reginiussen.

Figur 26. Drying of samples from tailings. Photo: Helge Reginiussen.

Sampled and analysed tailings

Several tailings in Bergslagen have been sampled and analysed in the project (Figure 27 and accompanying list). We would stress that sampling so far is in the nature of reconnaissance; we have only performed surface sampling and have not drilled to test deeper parts of the tailings. However, results from sampling and analysis give indications and a basis for possible follow-up.

Sampled tailings 2016–2018 (new analyses)

Andersbenning
Asköfältet
Baggetorp
Bastkärn
Blötberget
Bodåsgruvan
Bredsjö
Bålsjö
Bäckegruvan
Dannemora
Förola
Grängesberg
Håksberg
Intrånget
Kalvsbäcken
Kantorp
Kaveltorp
Källfallet
Lekomberg
Lövsvedgruvan
Lövåsen
Mimer
Nyberget
Persberg
Pershyttan
Ramhäll
Sikfors
Sköttgruve-Mossgruvefälten
Stollberg
Striberg
Stripa-Guldsmedshyttan
Stråssa
Sätra
Tomtebo
Tuna Hästberg
Yxsjöberg
Åsboberg
Östanmossen

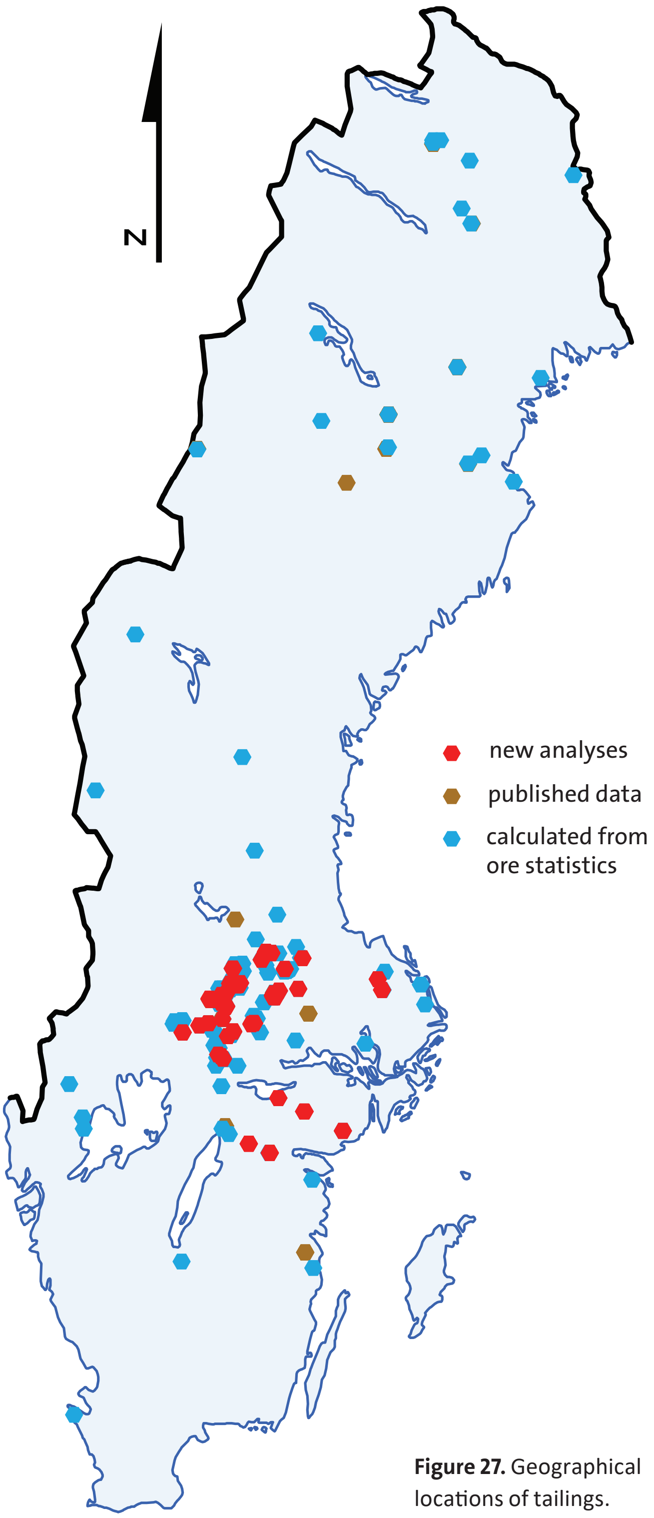

Figure 27. Geographical locations of tailings.

APPENDIX 7. OCCURRENCES OF SELECTED CRITICAL METALS AND MINERALS

Below are descriptions of several critical metals and minerals, focusing on deposit types, applications and producer country. Swedish deposits are also described.

Antimony

The average crustal abundance of antimony is 0.2 ppm (Rudnick & Gao 2003). Stibnite is the most common mineral with economic potential. Antimony is also found in small quantities associated with certain precious and base metal ores and is also extracted as a by-product from their production. China dominates the global antimony market. The consumption of antimony in the EU is about 18,000 tonnes per year (EU Commission 2017b). The most important uses are in flame retardants and batteries. Antimony is also used in the production of plastics, glass and pigments.

Sweden: Sb-anomalous massive sulphide deposits in the Skellefte field and Bergslagen.

Baryte

Baryte is a barium sulphate mineral with the chemical formula $BaSO_4$. The mineral has a high density (4.5), is inert and non-toxic. Baryte deposits can be classified into three main types: stratiform, vein and residual. Stratiform deposits are the most important source of industrial baryte. These are formed by precipitation of baryte on the seabed, often associated with massive sulphide mineralisations. The main use of baryte is as an additive in drilling fluid in the oil and gas industry. Baryte and barium compounds are also used as additives in rubber, paints, ceramic products, glass, concrete and medical products and more. China (44 percent) is the largest producer country, followed by India, Morocco, the US and Kazakhstan (EU Commission 2017b).

Beryllium

Beryllium is a relatively rare element with an average concentration in the earth's crust of about 2 ppm (Rudnick & Gao 2003). The most important source of beryllium is the mineral bertrandite. Small amounts of beryllium are extracted from the mineral beryl.

There is currently no production of beryllium in the EU. The United States accounts for about 90 percent of the world mining production and a mine at Spor Mountain in Utah is the world's largest producer. Global production of beryllium amounted to approximately 230 tonnes in 2017 (USGS 2018). The EU imports about 50 tonnes of Be a year in the form of processed beryllium products, i.e. no primary ore is imported by the EU. 80 percent of the beryllium that is consumed in the EU is used as copper-alloy material (EU Commission 2017b) and beryllium is an important component of a range of products in a variety of industries such as electronics, telecom, defense, medicine and the aerospace industry.

Sweden: There are no known deposits in Sweden where beryllium is considered to be economic. At Sels-Vitberget in Västernorrland, a small amount of beryl has been mined. The Yxsjöberg deposit in Bergslagen has elevated concentrations of beryllium.

Bismuth

Bismuth is a rare metal with an average content of the earth's crust of about 0.18 ppm. Bismuth mineralisations are found in different geological environments, including in different skarn deposits, tin pegmatites and in hydrothermal mineralisations associated with granites. Bismuth is mainly produced as a by-product of lead and tungsten extraction. Bismuth is non-toxic and is used in pharmaceutical and cosmetic industries. It is an environmentally friendly substitute for lead, for example in hunting ammunition and fishing equipment. Another area of use is low temperature alloys. World production (from refinery) in 2017 amounted to 14,000 tonnes (USGS 2018).

Sweden: Some sulphide-bearing iron-ores in the Riddarhytte field and the tungsten deposit Yxsjöberg in Bergslagen contain anomalous levels of Bi.

Borates

Borates is the collective name for minerals containing the element boron (B). The average content of boron in the crust is 11 ppm (Rudnick & Gao 2003). There are more than 150 borates. The most important industrial raw materials are tincal, kernite, colemanite and ulexite. Borates are often located in arid areas of volcanic activity. Largest deposits are found in Turkey, in the Mojave Desert in California, USA and in the Andes of South America. Borates are important ingredients in a variety of products, such as fiberglass, glass, fertilizers, detergents, hygiene products, ceramics, tiles and pest control agents. World production in 2016 was approximately 1 million tonnes (EU Commission 2017b). There are no known deposits of borates in the EU, but a large deposit of lithium borates is under development in Serbia (Rio Tinto, 2018).

Sweden: There are no known deposits in Sweden. Tourmaline bearing pegmatites can be a possible source.

Cobalt

Cobalt has been used for centuries as blue pigment in ceramics and porcelain. It has previously been mined at several places in Sweden, including Los, Vena, Tunaberg, Gladhammar and Kleva. Modern applications of cobalt are in alloys, rechargeable batteries (lithium ion batteries) and catalysts. The ongoing electrification of cars has led to increased demand, which is expected to continue in the coming years. Cobalt-rich minerals include cobaltite and skutterudite. Cobalt can substitute in other sulphide minerals such as arsenopyrite, pyrrhotite, pyrite and pentlandite. The only mine in the world where cobalt is mined as the main product is at Bou Azzer in Morocco, and today most cobalt is extracted as a by-product of nickel and copper production (Smith 2001, Mudd et al. 2013). Finland is the only country within the EU that produces cobalt using ore from domestic mines (by-product of nickel and copper extraction). The Democratic Republic of Congo is the world's largest producer. Global annual mine production is approximately 135,500 tonnes (average period 2010–2014; EU Commission 2017b).

Important deposit-types are:

- **Magmatic.** This type comprises mainly mafic and ultramafic intrusives, containing massive or disseminated Fe-Ni-Cu sulphides. Cobalt minerals are rarely found in this type, but cobalt occurs in sulphide minerals such as pentlandite, pyrrhotite and pyrite. Examples of this deposit type are Norilsk-Talnakh in Russia, Sudbury in Canada and Kevitsa in Finland. Swedish examples are Lappvattnet and Lainejaur in Västerbotten.
- **VMS (Volcanic Massive Sulphide).** These are deposits formed by submarine volcanic activity. The massive sulphide ores of the Skellefte district are examples. Outokumpu in Finland is an example of a Co-rich VMS deposit.

- **Sediment-hosted.** These are rocks of sedimentary origin (shales, dolomites, etc.) containing Cu-Co mineralisations. The Katanga region in the Central African Copperbelt is an example of this type.
- **"Vein-type".** These are usually small, Co-rich deposits that are mined specifically for cobalt. They are often rich - Bou Azzer in Morocco has an average of 1.2 percent Co in veins (Mudd et al. 2013).
- **Skarn, contact metamorphic or magmatic hydrothermal.** Intrusives containing magnetite, chalcopyrite and Co-rich pyrite. Formation in "porphyry type" environment or through contact metamorphism of carbonate-rich sediments. Includes IOCG (iron oxide copper gold) mineralisations. Kiskamavaara in Norrbotten is an example.

Sweden: Cobalt has been mined at several places in Sweden during the 18th and 19th centuries. Most of this production was as raw material for blue pigment production. The element cobalt was first discovered by G. Brant in 1735 in ore from the Riddarhytte field in Bergslagen. The earliest known extraction of cobalt in Sweden was in Los cobalt mines in Gävleborg county where mining began in 1738 (Tegengren et al. 1924). At present, almost all cobalt produced globally is as by-product of copper and nickel production. Some of the deposits described under the section nickel in this appendix also contain cobalt and to avoid repetitions these have not been included here.

Kiskamavaara

The Kiskamavaara copper-cobalt (gold) mineralisation is located about 40 km east of Kiruna. It was found in 1972 by SGU following indications from geochemical and geophysical investigations. During the 1970s, SGU investigated Kiskamavaara and drilled many boreholes, which resulted in an ore estimate of 2.87 Mt with 0.6 percent copper and 0.09 percent cobalt (Persson 1980, 1982). The deposit is epigenetic and located close to the Karesuando-Arjeplog deformation zone (KADZ), which is a significant shear zone in northern Norrbotten (Bergman et al. 2001). In 2018, SGU designated Kiskamaavara as a mineral deposit of national interest. Talga Resources currently has exploration permits at Kiskamarvaara. The company has drilled four diamond boreholes during 2014–2015 and metallurgical tests have been carried out. Three mineralised sulphide lenses along a 900-meter zone have been detected (Talga Resources 2018b). The most important ore minerals are pyrite (cobalt-rich) and chalcopyrite, magnetite and hematite. The ore minerals occur as matrix infill in a hydrothermal breccia of metavolcanic origin. The bedrock in the area exhibits different types of alteration, including scapolite alteration, K-feldspar alteration and sericitisation. Kiskamavaara may possibly represent an IOCG-type deposit (Martinsson, 2011).

Ahmavouma

Ahmavuoma is located about 2 km south of Lannavaara in Norrbotten. Geophysical anomalies were tested with drilling and sampling during 1982–1986. This resulted in the discovery of a sulphide mineralisation in the Ahmnavouma area containing copper, cobalt and gold (Lehto 1987). The exploration company Tertiary Minerals PLC drilled five diamond boreholes in 2004. At present, the company Talga Resources has exploration permits in the area. The mineralisation occurs in a sequence of intermediate to felsic volcanics and consists of chalcopyrite-bearing pyrite veins. Cobalt is associated with pyrite. Anomalous levels of molybdenum and gold occur in certain sections.

Los

Mining in Los, Gävleborg County started in 1738 and lasted for about 30 years. During the 19th century, attempts were made to resume production without results (Tegengren et al. 1924). The discovery of the element nickel was made by Cronstedt in 1751 by analysis of an ore sample from Los containing the mineral gersdorffite. The mineralisation occurs in an amygdoidal amphibolite. The most important cobalt mineral is cobaltite, but the paragenesis includes minerals containing Fe, Co, Ni, Cu, Bi and As. The ore had a maximum width of about 30 cm and could be followed for about 90 m along a tectonic zone (Lundqvist 1968). In addition, cobalt mineralisations were found as impregnation in the amphibolite outside the tectonic zone. There is no available information on grade and tonnage of the ore production.

Håkansboda

Håkansboda is located in western Bergslagen about 1.5 km north of Lindesberg. Copper deposits in the area have been known since the 1400s and ore has been mined intermittently from the 16th century to the 1920s (Tegengren et al. 1924, Carlon 1986). Approximately 60,000 tonnes of ore was mined in different periods during 1741–1919. The closed mine has subsequently changed owners a number of times: Store Kopparberg, Gränges AB, SSAB, BP-LKAB and Copperstone Resources AB. The ore occurs as lenses and layers of sulphides in a dolomitic marble. The main minerals are chalcopyrite, pyrrhotite, arsenopyrite, pyrite, magnetite and molybdenite. Cobalt substitutes for iron in pyrrhotite and arsenopyrite and is present in cobaltite and glaucodot.

Tunaberg

Tunaberg is located about 14 km SSW of Nyköping in Södermanland county. The mining in Tunaberg has a medieval history. Information about copper mining is mentioned for the first time by Erik of Pommern in 1420 when he extended the privileges of the miners. The ore field comprises a number of copper-cobalt deposits located in a zone of banded gneisses including pyroxene skarn. The ore comprises chalcopyrite and cobaltite (Tegengren et al. 1924). The most significant mine in the Tunaberg field is Storgruvan. The ore is 3.5–5.5 m wide in the upper parts but decreases to about 1.5–2.5 m in the deeper parts of the mine (about 165 m below the surface). Berkut Minerals currently has exploration permits in Tunaberg (Berkut Minerals 2018b).

Vena

Vena is located approximately 2 km east of Åmmeberg in Örebro county. The mining area extends for more than 2 km and comprises more than a hundred individual mines. Mining of cobalt began in 1770 and continued intermittently until the 1870s. The best mines in the field were the Gamla Vena and the Galt mines. Tegengren et al. (1924) describes the bedrock in the area as consisting of "plagioclase leptite" and "leptitic gneiss" (probably metavolcanics rocks of intermediate to felsic origin) with amphibolite. The ore minerals consist of pyrrhotite, pyrite, chalcopyrite, cobaltite, sphalerite, arsenopyrite, smaltite, galena and bismuthinite. The ore is made up of parallel mineralized zones that are 0.5–5 meters wide and up to 500 meters in length. The cobalt content of the ore was 0.2–0.5 per cent and is not mined out but continues at depth (Tegengren et al. 1924). SGU has recently started a project at Vena that includes new sampling, mapping and collection of geophysical data.

Gladhammar

Production in Gladhammar ore field started in the 1400s and mining was initially focused on production of iron and copper. Cobalt was produced for a short period in the early 1820s to be resumed in 1875, but the mining stopped in 1891. Gladhammar ore field has been Sweden's largest producer of cobalt products and a total of about 4,260 tonnes of ore with a content of 6 percent Co, corresponding to 256 tonnes of cobalt, was extracted here.

Riddarhyttan

The Riddarhytte field is located in Skinnskatteberg municipality in Västmanland. The field is dominated by iron ore, but there is also copper, cobalt, rare earth elements, molybdenum and gold. Mining at Riddarhyttan started in the Middle Ages, and both sulphide and iron ore from a number of mines has intermittently been produced until 1979 when the Bäckegruvan iron mine closed. The bedrock in the Riddarhytte field consists of a sequence of paleoproterozoic (1.8–1.9 Ga) metavolcanic and metasedimentary rocks dominated by altered rhyolites and carbonates and skarn. The supracrustal rocks are intruded by several generations of granite and pegmatite. Compact sulphide mineralisations containing pyrite and pyrrhotite occur (Ihre & Sädbom 1986). The iron ores consist of both magnetite and hematite.

Hematite ore, "Blåkulla type", is fine-grained hematite, often quartz banded with layers of calc-silicates. Magnetite ore is often associated with sulphides and skarn. The sulphides include pyrite, chalcopyrite, cobaltite, pyrrhotite and molybdenite. Rare earth elements (predominantly light rare earth elements) occur in several places, including the cerite mine in the new Bastnäs field.

The company EMX Royalty Corp. currently has exploration permits in the area.

Fluorite

Fluorite is a mineral that is mainly used as a raw material for the production of hydrofluoric acid and as fluxing agent in aluminum and steel production. Fluorite is found in many different geological environments and can occur as hydrothermal veins and fillings together with metal sulphides. World production in 2017 was approximately 6 million tonnes. China is the world's largest producer. The USGS states that the world's reserves are 270 million tonnes. In addition, there are additional resources of approximately 500 million tonnes (USGS, 2018).

Sweden: There is a significant deposit at Storuman in northern Sweden. The company Tertiary Minerals has presented a JORC-compatible resource calculation that yields 27.7 million tonnes with a content of 10.21 percent CaF_2. The Yxsjöberg mine in Bergslagen has been a producer of fluorite.

Gallium

Gallium has an average crustal content of 16 ppm. The element does not form its own minerals which are economically recoverable but are extracted as a by-product of aluminum production and (to a lesser extent) from zinc production. Bauxite is the most important source and contains on average about 50 ppm gallium (USGS 2018). Gallium can be recovered from solutions during processing of bauxite for aluminum production by the Bayer process. The USGS reports that there is more than one million tonnes of gallium in the world’s bauxite resources. The supply of gallium is limited not by geological factors, but by industrial capacity for extraction.

China is the country with the greatest production capacity due to large investments in the country's aluminum industry. Global production capacity is approximately 450–600 tonnes of gallium (EU Commission 2017b). Gallium is mainly used as semiconductors in the electronics industry (integrated circuits), LED lighting and solar cells (CIGS).

Sweden: Zinc-dominated massive sulphide deposits can be a potential source.

Germanium

Germanium is a rare element with an average crustal content of 1.3 ppm. There are only a few germanium minerals, the most important being germanite. Germanite was previously a source of production of germanium, but today there are no known economic occurrences. Germanium is currently produced as a by-product of zinc production and from fly ash from coal combustion. It is estimated that about 60 percent comes from zinc production and 40 percent from fly ash (EU Commission 2017b). Germanium is a semiconductor and was important for the development of the transistor industry during the 1950–1970s. Main use today is in fiber optics, IR optics, solar cells and catalyst in the production of polymers (PET plastics). China is the most important producer. Finland was recently a producer of Ge with a production in 2015 of 13 tonnes (from imported concentrate), but has now ended production (Bio 2015, GTK 2018).

Sweden: The potential in Sweden is relatively poorly known, but due to the strong connection between zinc and germanium, Swedish zinc deposits are potential sources.

Graphite

Graphite is an allotrope of carbon that have metallic and non-metallic properties. The material conducts heat and electricity, is chemically inert, has a high melting point and is non-toxic. Because of these properties, graphite has several applications, such as lining in smelting furnaces, lubricants, batteries, flame retardants, neutron moderators in nuclear reactors, electric motors (brushes), friction products (for example, brake bands), pencils and new high-tech materials such as graphene. Three main grades/types of graphite are extracted for commercial purposes: "vein" graphite, microcrystalline graphite and "flake" graphite (Simandl et al. 2015).

Global annual production of natural graphite is approximately 1.1 million tonnes (annual average 2010–2014). China is the largest producer of graphite with about 69 percent of world production (EU Commission 2017b). Norway produces graphite from a mine in Skaland in northern Norway, which accounts for about 1 percent of global production.

Sweden: Sweden has a number of graphite deposits. Below are descriptions of some of these.

Woxna

During exploration for graphite in the county of Gävleborg in the 1980s, an occurrence in Voxnadalen outside Edsbyn, was discovered. Boulders were also found about 10–12 km further south at Kringeltjärn. Graphite mineralisation occurs in Precambrian metasediments and metavolcanics that are intruded by felsic intrusives. The graphite is likely to be formed by contact metamorphism of carbon-rich portions of the metasediments.

The Kringel mine was licensed in 1992 and the company Flinders Resources (now Leading Edge Materials) bought the mine with associated licenses from Woxna Grafit AB in 2012. Today, the Woxna project includes four nearby graphite deposits (Kringelgruvan, Gropabo, Mattsmyra and Månsberg), the most important of which is Kringelgruvan. In total, the three deposits Kringelgruvan, Gropabo and Mattsmyra have an NI 43-101 indicated and measured mineral resource of 7.7 Mt containing 9.3 percent Cg of graphite carbon (Flinders Resources, 2015).

Woxna is a complete mine with a production facility that currently does not produce graphite commercially but is kept in production ready mode. Leading Edge Materials focuses on process development as well as research and development to offer anode materials for lithium-ion batteries. To this end, a demonstration plant is now being built at Woxna (Leading Edge Materials 2018b).

Vittangi (Nuunasvaara)

The graphite deposits in the Vittangi area were discovered in 1916–1918. During the 1970s and early 1980s, the discovery was studied by LKAB and SGU with the purpose of testing the possibility of using graphite as fuel in a future heating plant in Kiruna. In 2012, Talga Resources initiated a drilling program in Nunasvaara that resulted in a modern JORC (2004) compatible estimate. This was supplemented with new drilling as well as test mining for a new JORC (2012) estimate. The latest estimate is an inferred and indicated mineral resource of 12.3 Mt containing 25.5 percent graphite carbon (Talga Resources, 2018a). Talga plans to use graphite from Vittangi as a raw material for graphene and anode material in lithium-ion batteries. Nunasvaara has been designated by SGU as a mineral deposit of national interest.

Jalkunen

The Jalkunen project is located about 15 km southeast of Masugnsbyn in Norrbotten. The area was investigated by LKAB exploration in the 1980s. Further studies by SGAB /NSG demonstrated a graphite mineralisation (NSG 1991). Talga Resources, which now owns the project, has presented an JORC inferred resource of 31.5 Mt containing 14.9 percent graphite carbon.

Raitajärvi

Raitajärvi is located approximately midway between Överkalix and Övertorneå in Norrbotten. SGU performed exploration work on behalf of NSG in Raitajärvi during the years 1974–1978. In the period 1989–1992 graphite mineralisation was investigated by SGAB on behalf of NSG. Talga Resources now owns the project and has presented a JORC compliant indicated + inferred mineral resource of 4.3 Mt with a content of 7.1 percent total graphite carbon (Cg) (Talga Resources 2017). Raitajärvi has been designated by the SGU as mineral deposit of national interest.

Hafnium

In nature, hafnium always occurs together with zirconium and is produced as a by-product of zirconium extraction. The main source is the mineral zircon and baddeleyite. The average content of hafnium in the earth's crust is 3.7 ppm, while that of zirconium is 132 ppm (Rudnick & Gao 2003). Annual production of hafnium, as a by-product of zirconium refining, averaged about 70 tonnes in the years 2010–2014 (EU Commission 2017b). The main producer countries are France and USA. Superalloys are an important area of application. Hafnium and zirconium are also used by the nuclear industry in the reactor control rods.

Indium

Indium occurs in the same concentration in the earth's crust as silver, about 0.05 ppm (Rudnick & Gao, 2003). By comparison, zinc is about 1,440 times more common and copper about 540 times more common. Indium can form compounds with copper, iron and sulphur to indium minerals such as roquesite and indite. These indium minerals, however, lack economic interest today. Indium can substitute in sphalerite, chalcopyrite and cassiterite which are important sources for commercial zinc, copper and tin production (Werner et al. 2015). The indium content in zinc ores is variable, but usually low (1–50 ppm). Even in zinc concentrates, the content of indium is low, typical contents can be 70–200 ppm (Polinares 2012). 95 percent of global indium production today is as a by-product of zinc smelters, while <5 percent comes from copper and tin production.

Demand for indium has grown dramatically in recent years mainly due to use in solar panels (including in thin film solar cells; CIGC) and flat screens. Primary production of indium increased by approximately 1,890 percent from 1975 to 2014. (Kelly & Matos, 2014). Unlike indium, primary zinc production increased only by about 230 percent during the same period (Kelly & Matos, 2014), indicating that the recovery of indium from zinc production has increased. Global indium production is dominated by China, South Korea and Japan. In Europe, Belgium and France are the largest producers. World production amounted to 881 tonnes in 2014 (Kelly & Matos, 2014).

Sweden: Swedish sulphide deposits, mainly zinc and copper ores, contain low levels of indium.

Lithium

Lithium has an average crustal content of about 16 ppm (Rudnick & Gao 2003). Lithium is extracted from two main sources. One source is salt lakes (brines), which are found in the Andes in the border region between Chile, Bolivia and Argentina (an example is Salar de Atacama in Chile). The other source is hard-rock deposits e.g. rare element granites and complex granitic pegmatites (Greenbushes in Australia is an example). The most common economic lithium minerals are spodumene, lepidolite and petalite.

Electric vehicles and many electronic products require batteries and there is currently an increased demand for lithium and other battery metals. Global production in 2017 was approximately 43,000 tonnes of Li (USGS 2018). Australia was the largest producer followed by Chile. To meet the high demand for Li-ion batteries, many new mining projects are under development globally, including Argentina, Australia, Bolivia, Chile, Finland, Portugal, Canada, China, Spain, Serbia and the USA.

Sweden: Swedish lithium deposits are associated with fractionated pegmatites. The first discovery of the element lithium was made in 1818 by J.A. Arfwedson from petalite in a pegmatite on Utö in the Stockholm archipelago. So-called rare-element pegmatites can be grouped into two types based on the content of characteristic elements: LCT (lithium-cesium-tantalum) and NYF (niobium-yttrium fluorine). Several of these occur in areas of low to medium degree of marine-origin metasedimentary rocks associated with S-type granites in the Bothnian basin.

Järkvissle

The Järkvissle deposit was discovered in 1982 in connection with tin and tungsten exploration. At Järkvissle there are several pegmatite dykes and swarms with lithium, tantalum and tin mineralisations that occur in an area of about 7 × 2 km. One of the mineralisations was considered to be particularly interesting and a total of 17 boreholes were drilled along a distance of 1,200 meters in 1982–1985. A resource estimate yielded 600,000 tonnes of "spodumene ore" with 0.45 percent Li, 0.07 percent Sn and 80 ppm Ta (Tuuri & Ek, 1986)). It is emphasized that the resource estimate is of a historical nature and is not compatible with modern international reporting standards. Tests at LKAB's research laboratory in Malmberget with flotation and magnetic purification yielded a spodumene concentrate with up to 6 percent LiO_2 (Bida, 1983).

Varuträsk

In 1933, a lithium-caesium pegmatite was discovered at the village of Varuträsk, about 10 kilometers west of Skellefteå in Västerbotten. The Pegmatite is a famous geological site because of its mineralogy and has been the subject of several scientific studies. The mining company Boliden mined the pegmatite during the years 1936–1946. So far, about 90.5 tonnes of Li and 63.3 tonnes of Cs have been mined (Gustafsson 1989).

Bergby

In 2007, a spodumene-mineralized boulder was found near Bergby, about 25 km north of Gävle. The company Leading Edge Materials obtained an exploration permit in the area in 2016 and has demonstrated spodumene and petalite-bearing pegmatites of the LCT type (Leading Edge Materials 2018a). Since exploration is still at an early stage, it is not possible at this stage to draw any certain conclusions regarding the size of the deposit.

Spodumenberget / Dyngselet

In 2017, the company Novo Litio investigated a previously known mineralisation in Dyngselet west of Örnsköldsvik. No drilling has been done by Novo Litio so far, but new samples analysed in 2017 indicate elevated levels of Sn, Li, Ta, Nb and Cs (Novo Litio 2018).

Orrvik

A small spodumene bearing pegmatite occurs in the village of Orrvik. A 6-hole diamond drilling program in 4 profiles demonstrated scattered, small and weak mineralisations (Gustafsson 1989).

Magnesium

Magnesium is common in both the earth's crust and in seawater. In seawater, Mg is the third most common element, in the earth's crust the eighth most common. Magnesium is a metal and is found in a variety of minerals (for example in dolomite, magnesite and silicates). In the past, magnesium was largely extracted from seawater, but mineral extraction dominates today. Magnesium is also extracted from magnesium-rich salts (brines). Magnesium is a very light metal used in aluminum alloys in the transport sector and the automotive industry, construction and packaging. Magnesium is also used as a desulphurising agent in steel production. There is currently no production of pure magnesium in the EU. The manufacturing industry is completely dependent on imports from China and a few other countries outside the EU (Israel, Turkey and Russia). On average, approximately 118,000 tonnes of magnesium per year were imported into the EU in the period 2010–2014 (EU Commission 2017b).

Nickel

Nickel is not listed as a critical raw material by EU but is an important metal that is widely used as an additive in stainless steel and in many other alloys. Sweden has previously mined small tonnages of nickel at Kleva, Kuså, Slättberg and Lainejaur. However, a large number of nickel deposits have been detected in Sweden, for example through exploration by SGU and SGAB (Åkerman 1987). Many of these are associated with layered mafic intrusions. Many nickel deposits are polymetallic and are associated with copper and cobalt. Some contain anomalous concentrations of platinum group metals.

Kleva

Kleva in Småland was discovered in 1691 and was first mined for copper. Mining of nickel started in 1845. During the years 1845–1878, 1882–1889 and 1914–1919, 54,400 tonnes of ore was produced with 1.9 percent Ni, 0.8 percent Cu and 0.2 percent Co. The mineralisation consists of massive sulphides and breccia that are associated with a gabbronoritic intrusion.

Lainejaur

Lainejaur is located about 10 km northeast of Malå in Västerbotten. The deposit was discovered in 1941 and the mineralisation is in a gabbrodioritic intrusion. During the Second World War, the Boliden company mined about 100,000 tonnes of ore with a content of 2.2 percent Ni, 0.93 percent Cu and 0.1 percent Co. At the base of the intrusion is a massive sulphide ore with a thickness of about 1–3 meters. The sulphides consist of pyrrhotite, chalcopyrite and pentlandite. Above the massive ore is disseminated ore (up to 11 meters wide) with impregnations of pyrrhotite, pentlandite and chalcopyrite. Veins of nickel-copper arsenides are found in the lower parts of the basal sulphide ore and in the metasediments below it (Grip & Frietsch 1973, Blackstone Ventures 2009, Berkut Minerals 2018a).

The exploration company Blackstone Ventures published in 2009 a NI-43-101 compliant inferred mineral resource of 645,000 tonnes with 1.33 percent Ni, 0.66 percent Cu and 0.09 percent Co (Blackstone Ventures 2009). Berkut Minerals is the current owner of the project and recently reporetd an updated JORC compliant mineral resource (460,000 tonnes) with 2.2 percent Ni, 0.7 percent Cu and 0.15 percent Co (Berkut Minerals 2018).

Slättberg

Slättberg is located 25 km north of Falun. The area comprises a 2 km long zone of mineralisation and historic mining areas. The deposits in Slättberg were mined for copper in the beginning of the 19th century and mining for nickel started during 1815–1820. In 1876 about 5,000 tonnes of ore was mined, but mining was subsequently closed due to declining nickel prices. Sulphide minerals are magnetite, chalcopyrite, pentlandite, pyrite, linnerite, bravoite and millerite. Remaining ore in Slättberg are estimated at about 300,000 tonnes with 0.6 percent Ni, 0.5 percent Cu and 0.06 percent Co (Flood 1979). However, this estimate is uncertain and does not comply with modern reporting standards. The company Sienna Resources currently has exploration permit in Slättberg and has started a drilling program to investigate the deposit in more detail (Sienna Resources 2018).

Kuså

Kuså is located 12 km north of Borlänge. The mineralisation in Kuså is related to a differentiated mafic intrusion. Mining in Kuså has occurred during different periods in the 1800s–1900s, including during the Second World War when 3,500 tonnes with 0.9 percent Ni and 1.0 percent Cu were mined (Lehto et al. 1984)

The nickel line

During nickel exploration by SGU and SGAB in the 1970s–1980s, several interesting nickel deposits were found in east-northeast oriented zone south of the Skellefte field. This so-called nickel line contains several Ni-Cu deposits associated with ultramafic rocks. The deposits in the nickel line are magmatic sulphide mineralisations that have many similarities to known large

Ni-Cu deposits in other parts of the world. As a group, magmatic Ni-Cu sulphide deposits, together with laterites, are the most important global source of nickel. Possible mechanisms for forming these deposits involve partial melting of the upper mantle with subsequent fractionation, magma mixing and contamination.

Lappvattnet

At Lappvattnet, which is one of the largest nickel deposits in the nickel line, mineralisation occurs as dissemination and massive ore in metamorphosed mafic to ultramafic sills and intrusives (metaperidotite and metapyroxenite) as well as fragments and breccia in the enveloping paragneiss. The mineralisation is 620 meters long and 1–20 meters wide (Åkerman 1987, SGU 2007). The sulphides are dominated by pyrrhotite, pentlandite and chalcopyrite. The deposit was mined by NSG during the years 1978–1982. Blackstone Ventures published in 2009 an NI-43-101 compliant inferred mineral resource of 1.14 Mt with 0.91 percent Ni, 0.19 percent Cu and 0.02 percent Co (Blackstone Ventures 2009).

Rörmyrberget

Mineralisation at Rörmyrberget occurs in a differentiated ultramafic sill that is 1.7 km long and 320 meters wide (Åkerman1987, SGU 2007). The mineralisation was investigated and drilled by SGU and NSG during 1979–1983. Outokumpu performed additional drilling as well as mineralogical studies in the 1990s. Nickel mineralisations are detected along the entire length of sill, but only the western part of the intrusion appears to have interesting grades. Blackstone Ventures published in 2007 a NI-43-101 compliant inferred mineral resource (6.37 Mt) with 0.35 percent Ni, 0.04 percent Cu and 0.01 percent Co (Blackstone Ventures 2007).

Njuggträskliden

Several Ni-mineralized ultramafic bodies appear along a 5 km long zone at Njuggträskliden. Ni-Cu mineralisations occur in four (A – D) lenses and with metapyroxenite and serpentinite. Of these, the A, C and D lenses are the most important. In total, it is estimated that the mineralised bodies contain 0.57 Mt with 0.71 percent Ni, 0.26 percent Cu and 0.04 percent Co (Åkerman, 1987). The D lens is the largest and it also contain anomalous levels of PGE (Åkerman 1983).

Gårkälen

Several ultramafic bodies consisting of metaperidotite and metapyroxenite occur in the Gårkälen area. Two of these are mineralised, of which the largest has a length of 90 meters and a maximum width of about 20 meters (Filén & Johansson 1981). Diamond drilling indicates that the vertical extent of the mineralisation is 15–20 meters. The tonnage is calculated at 35,000 tonnes with 0.4 percent Ni, 0.18 percent Cu and 0.04 percent Co (Åkerman 1987). Further, smaller intrusions were discovered by Outokumpu during the 1990s, but no interesting mineralisation was found.

Rönnbäcken

Rönnbäcken includes the three individual nickel deposits Rönnbäcksnäset, Sundsberget and Vinliden, which are located about 20 km south of Tärnaby in Västerbotten. Rönnbäcken was investigated by Boliden in the 1970s. In 2012, Nickel Mountain Resources published a modern NI-43-101 compatible estimate for the largest of the three deposits (Rönnbäcksnäset) with an indicated mineral resource of 319.9 Mt with 0.103 percent Ni and 0.003 percent Co, as well as an inferred mineral resource of 12.2 Mt with 0.085 percent Ni and 0.004 percent Co. The mineralisation occurs in serpentinite and consists mainly of nickel sulphides which were formed epigenetically upon serpentinization of Ni-rich olivine. A separate magnetite phase is also produced in this reaction. Dominant nickel sulphides are heazlewoodite, pentlandite and millerite. The most common cobalt minerals are pentlandite, millerite and cobaltite. Pyrrhotite and chalcopyrite are subordinate. Nickel also occurs in olivine, serpentine, magnetite and brucite (Nickel Mountain 2012).

Detritic serpentinites

Ultramafic rocks occur in several of the major tectonic units in the Swedish Caledonides and analyses performed in the 1970s initially indicated that the so-called detritic serpentinites contained higher nickel and cobalt contents than "normal" peridotites and massive serpentinites. The extraction potential of these rock types was therefore investigated (Zachrisson & Stigh, 1981; Stigh et al. 1981a, b). However, control analyzes showed that the elevated levels of nickel and cobalt in detritic serpentinites could be explained by analytical errors. In addition, enrichment experiments showed that it was more difficult to extract nickel concentrates from the dedritic serpentinites, and these were therefore not considered to offer any advantages from the extraction point of view (Zachrisson 1983). Three deposits of dedritic serpentinites are described below.

Njeretjakke

Njeretjakke is located about 800 meters above sea level in the Vardofjäll area in Västerbotten and is the single largest known body of detritic serpentinite (Stigh et al. 1981). Although the area has not been studied in detail with diamond drilling and lacks a proper resource estimate, an initial calculation (Stigh et al. 1981a, b) indicated that the levels and tonnage of nickel and cobalt were so high that it could provide a basis for large-scale mining. Later analytical results which show that Ni and Co levels probably were overestimated by about one third due to analytical errors (Zachrisson 1983) makes the basis for these estimates very uncertain. However, the fact remains that the tonnage in Njeretjakke is very large.

Kroksjön

Kroksjön is located south of the Rönnbäcken river and a few km east of Lake Virisen in Västerbotten. Kroksjön probably has the highest cobalt concentrations of the detritic serpentinites (Stigh et al. 1981), although the absolute levels are probably about one third lower than the analytical values initially reported (Zachrisson 1983).

Njuonajaure

Njuonajaure is located about 10 km southwest of Klimpfjäll and about 11 km southeast of Stekenjokk. Compared to other detritic serpentinites, the object has relatively high nickel levels (Stigh et al. 1981b).

Niobium

Niobium has an average crustal content of 8 ppm (Rudnick & Gao 2003). Niobium deposits are often associated with peralkaline granites, syenites and carbonatites. At present, almost all niobium is extracted from carbonatites which are magmatic rocks with a high content of primary carbonate minerals. They are found almost exclusively in areas with continental extension and rifting. Brazil is the dominant producer with around 95 percent of global niobium production. The world largest niobium mine is in Araxa in the Minas Gerais province. The other significant niobium producer is Canada, which accounts for about 5 percent of the world production. The most important niobium minerals are pyrochlore and columbite. Niobium is used in HSLA ("high-strength, low-alloy") steel and in superalloys. Niobium is not traded as ore or concentrate, but as processed products such as ferroniobium or niobium metal. During the period 2010–2014, world production of ferroniobium averaged 51,000 tonnes per year (EU Commission 2017b).

Sweden: There are no known economic niobium deposits in Sweden. LCT pegmatites, carbonatites and alkaline intrusions are potential sources.

Phosphate

Phosphate rocks are the most important source of phosphorus. Phosphorus is fundamental to all biological life and 95 percent of all phosphate extracted globally is used as fertilizer and animal feed. The remaining 5 percent is used in industry in a variety of products, chemicals and processes, including cleaning products, food additives, matches, toothpaste, and flame retardants. The mineral apatite is most important for commercial extraction. Average global production (2010–2014) was 217 million tonnes per year. China is the world's largest producer country with 44 percent, followed by the US and Morocco, each accounting for 13 percent (EU Commission 2017b).

Sweden: Apatite iron ores in, for example, Kiruna, Malmberget and Grängesberg are potential sources of phosphate. In addition, there are significant occurrences of phosphorites in the Tåsjö area.

Platinum group metals

The platinum group metals (PGM) consist of the six elements ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). PGM is regarded as precious metals and is very rare in the earth's crust with average levels at ppb level. Platinum, palladium and rhodium are the most commercially important PGEs. The main areas of application are in catalysts for exhaust gas purification, petroleum refining and the chemical industry as well as in jewelry and electronics (EU Commission 2017b, Thorman et al. 2017). PGE often occurs together with nickel and copper sulphides, for example in Norilsk-Talnakh in Russia and Sudbury in Canada. Another important deposit type is the so-called "reef-type" where thin, but laterally continuous, layers rich in PGE occur in layered mafic-ultramafic intrusions. Examples are Merensky Reef in the Bushveld complex in South Africa and Great Dyke in Zimbabwe (Thorman et al. 2017). South Africa is the world's largest producer of PGE followed by Russia. Largest reserves are also found in South Africa.

Sweden: Layered mafic intrusions, including some of the deposits in the nickel line southwest of Skellefteå, may have potential.

Rare Earth Elements

Rare Earth Elements (REE) is a group of 17 chemical elements including the lanthanides and yttrium. Scandium is also often included in the REEs, but this element is described separately below. It is common to divide the REEs into two groups, light rare earths (LREE) comprising lanthanum to samarium and heavy rare earths (HREE) comprising europium to lutetium and yttrium. Deposits containing HREE are generally scarcer than deposits dominated by LREE. The REEs does not occur naturally as metallic elements, but in mineral groups such as halides, carbonates, oxides and phosphates. About 200 REE-bearing minerals exist, but only a few are commercially interesting. Important REE minerals are bastnäsite, xenotime, monazite, eudialyte and loparite. The commercially most important deposits are hosted by alkaline magmatic rocks, carbonatites (including secondary weathered carbonatites), placers and REE-rich clays (so-called ion adsorption clays). The average annual production of Rare Earth Oxides (REO) for the period 2010–2014 was approximately 135,000 tonnes (EU Commission 2017b). The largest producer country is China, with 95 percent of world production. The Bayan Obo mine is the world's largest REE producer. REEs are important components of electronic, optical, magnetic and metallurgical products and have become indispensable in modern society and increasingly important in the high-tech industry and green technologies.

Sweden: Sweden has significant REE deposits. The Swedish deposits include alkaline intrusives, carbonatite, apatite iron ore, granite and pegmatite, Bastnäs type (skarn), phosphorite and paleo-placer type. Below are descriptions of some of these.

Norra kärr

The deposit in Norra Kärr was discovered in 1906 by SGU in connection with regional bedrock mapping. Norra Kärr is an agpaitic peralkaline nepheline syenite that has many similarities to other peralkaline complexes, for example, in southern Greenland and on the Kola Peninsula. The intrusion covers an area of approximately 450 × 1,500 meters and extends from the surface to a depth of more than 350 meters. The Canadian company Tasman Metals (now Leading Edge Materials) began investigating the discovery in 2009. An extensive drilling program has been implemented and the company has made a modern resource calculation (NI-43-101) which has shown a probable mineral reserve with 23.57 Mt with 0.59 percent TREO (Tasman Metals 2015). Norra kärr has been designated as mineral deposit of national interest by SGU and represents one of the most significant deposits of REE in the EU. The most important REE mineral at Norra kärr is eudialyte. The deposit is relatively enriched in HREE (including neodymium and dysprosium), which are economically valuable and important raw materials in permanent magnets. In addition to be a source of REE, Norra Kärr also contains significant amounts of zirconium, hafnium and the industrial mineral nepheline. The content of radioactive substances in the deposit is relatively low.

Olserum

A uranium mineralisation NV of Västervik was discovered during exploration in the 1950s. Subsequent surveys by SGU in the 1970s and follow up investigations in 1990 led to the discovery of REE mineralisation in Olserum. Tasman Metals has published an NI 43-101 compliant Indicated Mineral Resource of 4.5 Mt with 0.60 percent TREO and a NI 43-101 Inferred Mineral Resource of 3.3 Mt with 0.63 percent TREO (Tasman Metals 2013).

The REE line in Bergslagen

Along a distance of about 100 km from Norberg in the northeast via Riddarhyttan-Bastnäs to Nora in the southwest, a number of magnetite-related REE mineralisations of the Bastnäs type occur (Andersson, 2004, Jonsson et al. 2014). Important REE minerals include cerite, allanite and bastnäsite.

Tåsjö

A uranium and phosphorus-bearing shale that was investigated by SGU in the 1970s occurs in the Tåsjö area. A very pure phosphorite concentrate from this deposit contained 0.68 percent REE.

Apatite iron ore

Several of the Swedish apatite iron ore deposits (for example, Kirunavaara, Malmberget and Grängesberg) contain considerable quantities of REE and constitute a considerable resource (Frietsch & Perdahl 1995, Peelman et al. 2018). REE occurs in the mineral apatite, which also contains phosphorus. Phosphorus is not desirable in LKAB's pellet products and the ore from LKAB's mines therefore undergoes a process where apatite is separated from the magnetite. The phosphorus content in Swedish apatite iron ore varies and may contain 1–5 percent phosphorus (Pålson et al. 2014). In Kirunavaara, which is the largest Swedish apatite iron ore, the phosphorus content shows a bimodal distribution.

Apatite was extracted as a by-product from Malmberget and from the Rektorngruvan mine in Kiruna during the Second World War (Grip & Frietsch 1973). The recently completed EU project REEcover has, among other things, been aimed at developing methods for extracting REEs, with the main focus on neodymium and dysprosium, from tailings from Kirunavaara (REEcover report summary 2017). LKAB reported that the company together with the recycling company Ragn-Sells, will invest in pilot plants that will process mining waste from LKAB's iron ore production. In the long term, the goal is to build full-scale plants with the extraction of REE and phosphorus from tailings (LKAB 2018).

Scandium

Although scandium is not very rare, the average concentration in the earth's crust is about 22 ppm (Rudnick & Gao 2003), it is rare to find concentrations of more than about 100 ppm in nature. This is because scandium, due to a small ion radius, rarely forms its own minerals and is only to a limited extent selectively incorporated into other minerals (the exception is scandium-yttrium silicate Thortveitite). The market for scandium is small; the global production in 2010–2014 was about 15 tonnes (EU Commission 2017b). There is little data on commercial use of scandium in the EU, but much is used in research and development. The most important areas of use are in solid oxide fuel cells (SOFCs) and aluminum scandium alloys. Aluminum scandium alloys are among the lightest alloys available and can help increase energy efficiency in the transport sector (EU Commission 2017b). Other applications are ceramics, electronics, lasers, lighting and radioactive isotopes.

Sweden: A dolomite in Vuolep Räskavare in Norrbotten contains high levels (about 100 ppm) of scandium (Holmqvist & Nordström 1986 and analyses in this project). The source of the scandium is not known.

Silicon metal

An important use for silicon is as semiconductor in solar cells and microelectronics. Quartz which is the most important source of silicon, is the second most common mineral in the earth's crust after feldspar. Although quartz is common, the requirement for high purity means that few deposits can deliver the quality and volume that is required by the semiconductor industry. Some pegmatites and hydrothermal quartz are used as raw material for this purpose. Silicon is also used in the metallurgical industry in aluminum alloys and in the chemical industry as raw material for silicone. These applications do not have the same purity requirements as the semiconductor industry. China is the world's largest producer (61 percent) followed by Brazil (10 percent) and Norway (7 percent).

Sweden: Large hydrothermal quartz veins occur along the Caledonian front in northern Sweden. These can be up to 10–20 meters wide and several hundred meters in length. Examples of quartz deposits that have been investigated for high purity quartz include Pajeb Muitunisjaure, Själbmatjäkkä and Vuolep Räskavare in Norrbotten (Holmqvist 1986, Holmqvist & Nordström 1986). Quartz-rich granite pegmatites occur in several locations within the Svekokarelian and Svekonorvegian orogens.

Tantalum

Tantalum is a relatively rare element with an average content of 0.7 ppm in the earth's crust (Rudnick & Gao 2003.). The element often occurs together with niobium in minerals such as columbite-tantalite and pyrochlore-microlite. Some of the world's tantalum production is related to illegal, small-scale extraction of columbite-tantalite, "coltan", in Central Africa (Democratic Republic of Congo, Rwanda and Burundi). This mining can involve child labor and is partly controlled by armed groups and local warlords. This has led the US and, more recently, the EU to define tantalum as a conflict mineral (EU Commission 2017b). Tantalum is used in a variety of products, for example in capacitors, superalloys and in special cutting tools. The USGS states that primary mining production of Ta was approximately 1,300 tonnes in 2017 (USGS 2018).

Sweden: There are several known tantalum occurrences in Sweden, but none have been in production yet. These are mainly pegmatites of LCT type. One of the most important Swedish deposits is Järkvissle (see tables 5 and 6 and description under the section "lithium" in this appendix).

Tungsten

The average content of tungsten in the earth's crust is 1 ppm (Rudnick & Gao, 2003). Tungsten has high density (19.3) and the highest melting point of all elements. Because of these unique properties, the metal has many uses, including super alloys and special steels. The most economically important tungsten minerals are wolframite and scheelite. Tungsten is found in several different deposit types, including skarn, breccia, porphyry, greisen, strata-bound, "vein-type" and pegmatite. The world's largest tungsten deposits are found in China, Canada and Russia. The USGS reports that primary world production in 2017 amounted to approximately 95,000 tonnes, with China being the world's largest producer (USGS 2018). In Europe, tungsten is produced from mines in Portugal, Spain, the United Kingdom and Austria (EU Commission 2017b, USGS 2018). However, this domestic production relatively modest and does not cover demand from European industry (EU Commission 2017b.

Sweden: The majority of all tungsten produced in Sweden in modern times comes from a number of skarn deposits located in an area around Ludvika in Bergslagen. The largest producer was the mine in Yxsjöberg.

Yxsjöberg

Yxsjöberg is by far the largest tungsten deposit in Sweden and accounts for more than 90 percent of tungsten ore produced in Sweden. Yxsjöberg was known as a copper deposit as early as the 18th century. Mining of tungsten took place during the years 1917–1920, 1935–1963 and 1973–1989. In total, 5.17 Mt of ore was mined with a content of 0.27 percent W (FODD 2018).

The Yxsjöberg deposit consists of the three separate ore bodies Kvarnåsen, Nävergruvan and Finngruvan, which are hosted by a deformed and skarn-altered limestone. The ore consists of scheelite. Other economically significant minerals are chalcopyrite and fluorspar. Pyrrhotite is common and locally magnetite occurs. Other less common minerals include molybdenite, wolframite, sphalerite, bismuth sulphides, apatite and titanite (Ohlsson 1979, SGU 2008).

Wigström

The Wigström mine is located about 15 km southeast of Yxsjöberg and was in operation from 1978 to 1981. Both molybdenum rich and molybdenum poor scheelite are found in the ore. The skarn zone containing the tungsten mineralisation is about 1–25 meters thick. During the three years the mine was in operation, 130,000 tonnes of ore were mined with an average content of 0.3 percent W (FODD 2018).

Sandudden

Sandudden tungsten deposit was found in the mid-1970s. The deposit, located about 7 km northeast of Yxsjöberg, consists of three mineralized zones, of which only the middle one has interesting tungsten contents. The mined tonnage is not known. The ore production was probably included in the production of Yxsjöberg.

Baggetorp

At Baggetorp in Östergötland, mining took place during 1944–1958. More than 275,000 tonnes of ore was produced here (Hübner 1971, FODD 2018). Baggetorp is the only Swedish mine outside the Ludvika area that has produced tungsten. The mineralisation consists of wolframite and scheelite in a pegmatite. Wolframite is sometimes completely replaced by or surrounded by scheelite. Molybdenite occurs as scattered flakes. Pyrite, chalcopyrite and bismuth minerals occur as later mineralisations.

Svärtträsk

The tungsten deposit at Svärtträsk in Storuman municipality in Västerbotten County was discovered in the late 1970s. The deposit consists of scheelite mineralisation and occurs in a 150 meter long and 5–12 meter wide belt of coarse to medium-grained hornblendite. Ore estimates (incompatible with modern standards) show that down to a depth of 50–100 meters there are 250,000 tonnes with a content of 0.17 percent W (FODD 2018).

Storträsket

The mineralisation was found by boulder hunting in 1979–1980. Nine tungsten-mineralised quartz veins have been identified (Fors et al. 1981). In addition to wolframite, scheelite and molybdenite, arsenopyrite, pyrite, pyrrhotite, chalcopyrite, galena, tourmaline and fluorspar occurs.

Rostberget

The mineralisation at Rostberget consists of a zone of wolframite-bearing greisen altered quartz veins in a granite (Gerdin & Triumf 1984). No estimation of tonnage or grade is available.

Vanadium

Vanadium is a relatively common element in the earth's crust with an average concentration of 138 ppm (Rudnick & Gao 2003). Vanadium deposits occur in phosphate rocks, magmatic Fe-Ti-V deposits, and in some sandstones and shales (including alum shales). Significant quantities are also found in bauxite as well as in fossil fuels such as coal, crude oil, oil shale and oil sands. World production of vanadium in 2017 was approximately 80,000 tonnes (USGS 2018). China is the largest producer with a share of 53 percent. Vanadium can be produced as a co-product of slag. Other sources are fly ash, vanadium-containing magnetite concentrate and other vanadium-containing raw materials. Vanadium is used in special steels, stainless steel, superalloys, HSLA steels, energy storage and as a catalyst in the chemical industry.

Sweden: There are a number of well-known vanadium deposits in Sweden. Examples of Fe-Ti-V mineralisations are Sumåssjön, Routevare and Smålands Taberg. Alum shale, including the deposit at Häggån in Jämtland, contains a large tonnage with low-grade vanadium, nickel, uranium, zinc and molybdenum (Aura Energy 2018).