Economic Potential of Battery Metals and Minerals in Sweden

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Abstract. The potential for battery metal production in Sweden is difficult to predict with the present geological knowledge. The Swedish bedrock are known to contain numerous occurrences of lithium, cobalt, nickel, manganese, vanadium, and graphite, but a waste majority of them have not been studied in any detail recently and data to estimate their potential is therefore limited. However, known alum shales and graphite schists probably constitute world class deposits of vanadium and graphite if extracted and processed in an economically feasible and environmentally responsible manner, while the potential to find significant manganese and cobalt deposits in Sweden is probably low. These metals, as well as vanadium, could rather be extracted from the waste material of active and historic mines. The geology of parts of Sweden also suggests that significant sulphidic nickel deposits might exist, as well as lithium-pegmatites similar to those in the same crustal domain in Finland.

1 Introduction

The transition from vehicles using fossil fuels to EV's and the need for storage of electricity produced from wind and sun to meet the climate challenges has caused an increased demand of certain raw materials, such as lithium, cobalt, nickel, manganese, vanadium, and graphite. These commodities are known from many mineral occurrences in Sweden, but so far only limited production has occurred in the past. Their character, economic potential, and possible contribution as supply to the battery production in EU is so far not well known although significant information exists for most of them in the form of scientific publications and exploration reports (e.g. Eilu et al., 2021; Hallberg & Reginiussen, 2020, Lauri et al., 2018).

Sweden has a long mining history with currently important production of Fe, Cu, Zn, Pb, Ag, Au, and Te. Historic production also includes Mn, Ni, Co, W, Mo, REE, Li, Cs, and Se. Important mining districts are found within the 2.5-2.0 Ga Karelian greenstones in northernmost Sweden and in the 1.9 Ga Svecofennian provinces occupying large areas of the Swedish bedrock (Weihed et al., 2005). Sweden is also one of the leading nations in the discovery of new elements including the important battery metals. Cobalt was discovered by Georg Brandt in 1739, nickel by Axel Fredrik Cronstedt in 1751, manganese by Johan Gottlieb Gahn in 1774, lithium by Johan August Arfwedson in 1818, and vanadium by Nils Gabriel Sefström in 1830. The geology of known occurrences of these metals and of graphite, exploration activities, and the potential for production in Sweden, is presented and discussed in the following sections. There is no production of these battery commodities at present in Sweden, but exploration activities are high with about 70 different actors including a large number of junior companies and the established mining companies in Sweden. The focus is mainly on base and precious metals but among the junior companies also battery metals and graphite are included but in several cases are not the main target. Only a few projects have reached the status to apply for mining concession and only five approved concessions exist (Table 1).

Table 1. Active claims and mining licenses in Sweden.

Commodity	Claims	Mining licenses
Li	14	0
Co	71	0
Ni	52	3
V	24	1
Mn	0	0
Graphite	11	4

2 Character of known occurrences in Sweden

The geological knowledge of the battery commodities in Sweden is rather limited and this overview is largely based on previous exploration activities and reports from the Geological Survey of Sweden and from the database FODD (2020) and all data for grade and tonnage is from those sources and from companies' web pages.

2.1 Lithium

The only lithium occurrences found in Sweden are of the LCT-pegmatite type. Since lithium was first discovered in the mineral petalite from the Utö LCT-pegmatite, lithium minerals have also been found in several other pegmatites. Only the Varuträsk deposit have been investigated in more detail with trial mining during the years 1936-1942 and minor production of petalite, spodumene, and pollucite, and has a reported historic resource of 0.4 Mt @ 0.26% Li_2O. During exploration in the 1980's several LCT-pegmatites were discovered in central Sweden and a few of them were investigated with drilling. The most significant discovery was the Järkvissle spodumene deposit with a historic resource of 0.6 Mt @ 0.97% Li_2O. The most recent discovery is the Bergby spodumene-petalite occurrence with reported drill intercepts of 8.75 m containing 2.63% Li_2O. Drilling indicates the pegmatite to be at least 600 m long, but drill holes are too few for resource estimates.

Most of the known LCT-pegmatites occur within the Svecofennian Bothnian Basin, an area of metasediments intruded by S-type granites. In general, they contain small amounts of tantalum as a possible by-product. Similar deposits are found in the same crustal domain in Finland with the Kaustinen deposits containing combined reserves (proven and probable) from five deposits of 12.3 Mt @ 0.94% Li_2O for open pit and underground mining.

2.2 Cobalt

Cobalt has historically been produced in Sweden in small scale during the years 1739-1891 from several different Co-bearing deposits containing mainly cobaltite, glaucodot, and minor smaltite and linnaeite. Several of these deposits occur in the Bergslagen area and generally in association to chalcopyrite and pyrrhotite forming stratabound to discordant bodies. The only exception is the vein-style Los deposit which also contains Ni-minerals. Grades are locally up to several % but the average grade is mostly <0.2%. The only deposit in Bergslagen of the stratabound type with a historic resource calculation is Såggården containing 0.7 Mt with 0.06% Co, with cobalt mainly occurring in pyrite and pyrrhotite. Higher grades (0.2-0.5% Co) is supposed to have been produced from the Vena Co-deposit in historic time.

Minor contents of cobalt also occur in association with orthomagmatic sulphidic Ni-Cu deposits. Of those, the highest content is found in the Lainejaure deposit containing an inferred resource of 0.46 Mt @ 2.2% Ni, 0.93% Cu and 0.15% Co while most others have contents <0.05%. The large tonnage but low grade Rönnbäcken Ni-deposit, with a resource (indicated+measured) of 320 Mt, contains 0.10% Ni and 0.003% Co.

Co-bearing pyrite with up to 3.6% Co is related to several types of Cu-deposits and Fe-deposits in northern Sweden. The largest occurrence is the Kiskamavaara deposit of IOCG type containing an historic resource of 2.87 Mt @ 0.09% Co, 0.6% Cu and some Au. A JORC compatible inferred resource based on recent investigations is 7.67 Mt @ 0.25% Cu and 0.04% Co. Metallurgical results from Kiskamavaaara shows up to 91% recovery of Co to concentrate and 99% to solution by a hydrometallurgical process. Ahmavuoma is a similar but less studied deposit with drill core intercepts of 73.1m @ 0.16% Co and 0.24% Cu**.** Co-bearing pyrite is also found in the Aitik Cu-deposit of porphyry type and the Kiirunavaara Fe-deposit of AIO type with grades up to 2.6% Co and an average grade of <0.5% Co.

No systematic exploration for Co-deposits have been made in Sweden and sulphide occurrences have not always been analyzed for Co. However, several active claims for base metals and sulphidic Ni-Cu deposits also includes Co as a potential commodity in Bergslagen and northern Sweden and a few with Co as main commodity.

2.3 Nickel

Nickel has historically been mined in small scale during the years 1845-1942 in south Sweden from orthomagmatic Ni-Cu deposits related to gabbroic intrusions. Total production is 0.10 Mt at a grade of 0.7 to 2% Ni. However, the most significant production has been in northern Sweden from the Lainejaure deposit during World War II with a total of 0.11 Mt @ 2.2% Ni and 0.93% Cu. By recent drilling at the Lainejaure deposit an inferred resource of 0.46 Mt @ 2.2% Ni, 0.7% Cu and 0.15% Co has been established.

In the second half of the 1900’s several exploration campaigns were done by state financed projects and by Boliden AB resulting in the discovery of several subeconomic deposits related to mafic/ultramafic intrusions. Most important was the Ni-belt in Västerbotten with several deposits hosted by small ultramafic intrusions with grades of 0.4 to 1% Ni and tonnage up to 6 Mt. The last 10-20 years several companies have re-investigated some of these discoveries further but not added much more economic potential to them except for a few cases where also PGE have been detected. Several deposits related to mafic/ultramafic intrusions were also discovered in southeastern Norrbotten with Ni-contents up to 0.44%.

The Rönnbäcken deposit is different in character and was discovered and investigated in the 1970´s. More recently it has been investigated further by drilling, metallurgical tests and resource calculations. It is a low-grade disseminated deposit hosted by a serpentine-altered dunite with heazlewoodite as the main Ni mineral formed in response to serpentinization. It comprises three separate ore bodies with a combined (indicated+measured) resource of 320 Mt @ 0.10% Ni. Mining licenses are granted for all three ore bodies that could be mined at low cost by large scale open pit operations with a low strip ratio. As heazlewoodite is the only sulphide mineral, a high-grade concentrate with a Ni-content of 25 to 30% could be produced by flotation.

Alum shale could be a potential source for Ni as by-product if mined for its content of other metals (e.g., V, see next section). Grades are generally low, and Ni has to be extracted by hydrometallurgical processes similar to the other metal contained in this rock.

2.4 Vanadium

Vanadium has never been mined in Sweden, but several types of deposits are known and might have economic potential. The metal was discovered in ore from the iron deposit Taberg in south Sweden. It is an orthomagmatic deposit of Ti-V rich magnetite in a mafic intrusion. Several other occurrences of Ti-V rich magnetite in gabbroic to anorthositic intrusions have been known for a long time in Sweden and investigated mainly as a source for iron. The only significant iron production was between 1939-1960 from Taberg with 1.2 Mt ore mined, containing 30% Fe and 6% TiO_2. Minor production was also from magnetite-rich cumulates in a mafic sill at Ulvön during 1939-1950 with ore containing 25% Fe and 8% TiO_2. The apatite iron ores in Bergslagen and northern Sweden are mostly enriched in vanadium with magnetite containing up to several thousands of ppm V but have so far not been considered as a resource for vanadium.

During the second half of the 1900's several exploration programs have been directed specifically to orthomagmatic Fe-Ti-V deposits in mafic intrusions. These rocks have the character of gabbroic-anorthositic plutons, gabbroic sills, and layered gabbroic-anorthositic complexes. In general, these deposits contain 20-40% Fe, 5-10% TiO_2 and 0.1-0.3% V_2O_5 with titanomagnetite and some ilmenite as most important ore minerals.

In northern Sweden the anorthosite-hosted Ruoutevare deposit is the most important discovery with an inferred resource of 140 Mt @ 39.1% Fe, 5.7% Ti and 0.2% V established by a more recent re-investigation. Metallurgical tests have been done in the 1970's and more recently with the focus to produce a high-grade magnetite concentrate.

In other deposits, vanadium has been the main target and several deposits in central Sweden previously known as Fe-deposits have been reinvestigated. But new discoveries have also been made in Norrbotten and Bergslagen. The Airikurkkio deposit is a fractionated mafic sill within the Karelian greenstones in northern Sweden. Only a few holes have been drilled and the best section contains 18 m with 28% Fe, 5.1% TiO_2 and 0.58% V_2O_5. In Bergslagen, the Vanberget deposit is hosted by metamorphosed mafic intrusions enriched in magnetite. It is investigated with drilling and sections with up to 30% magnetite exists and with a content of 0.8 to 1.3% V in magnetite.

The only deposit that has a mining license is the Bricka mine. It is one of several gabbroic intrusions in central Sweden containing accumulations of titanomagnetite and are previously known as iron deposits. The Bricka mine has a historic resource of 12 Mt containing 0.23% V and a magnetite content of 25%. By magnetic methods a magnetite concentrate with 64% Fe and 0.92% V have been produced in metallurgical tests using magnetic separation in several steps.

Several active claims have vanadium as the main commodity and most of these are focused on orthomagmatic titanomagnetite deposits. But some claims target another type of vanadium deposits that are related to alum shale with examples in southernmost and central Sweden. These deposits are large tonnage containing 0.3-0.4% V_2O_5. These deposits also contain Ni, Mo, U, and mined metals will be extracted by hydrometallurgical processes. In Skåne, a smaller part of the alum shale unit has a mineral resource (inferred+indicated) of 116.9Mt @ 0.39% V_2O_5 and the Häggån deposit in central Sweden has a mineral resource (inferred+indicated) of 124 Mt @ 0.43% V_2O_5 making them both potential world class deposits.

2.5 Manganese

Like vanadium, manganese could be used in batteries for large scale stationary storing of electricity and demand is expected to increase with increased production of wind and solar energy. Only very limited production of manganese has occurred in Sweden, from Mn-oxide deposits related to iron deposits in Bergslagen. They contain hausmannite, braunite and jacobsite as important Mn-minerals but are also enriched in elements like Ba, As, Sb, Pb and Be. Most important was the Långban deposit with 0.4 Mt ore containing 15-40% Mn produced between1880-1955.

Several carbonate-hosted Fe-oxide deposits in Bergslagen also have elevated Mn-contents (2-10%) with most of the manganese occurring in carbonate and/or silicate minerals (knebelite, rhodonite, spessartine) and total tonnage is typically <10 Mt with Dannemora as an exception (probable ore reserve resource 25.4 Mt @ 33.4% Fe and 1.8% Mn). Also, some of the base metal deposits in Bergslagen are hosted by Mn-rich skarn and Mn-rich carbonates.

There are also BIF-type deposits with Fe-oxides and a high content of Mn-silicates resulting in 10-20% Mn but deposits are mostly of small size (< 1 Mt). Similar Mn-rich iron formations of Svecofennian age occur in northwestern Sweden with contents up to 7% MnO.

Small vein-style deposits occur in southwest Sweden and a few of them have been mined in small scale for manganese occurring as hausmannite, rodochrosite and rodhonite. More important are hydrothermal breccia-type deposits consisting of manganite, braunite and secondary pyrolusite (Bölet and Spexeryd) with a combined historic production of 0.2 Mt with 20-50% Mn.

No systematic exploration has been done for manganese and there are no active claims for this metal at present. The only exploration for manganese in northern Sweden was initiated by the discovery of a manganese-rich boulder in 1935 which resulted in the discovery of the Mn-oxide occurrences in Ultevis in 1943. It is a BIF-type hematite deposit with up to 2 cm thick layers of piedmontite, Mn-garnet, bixbyite, hollandite, and braunite. Also, Mn-occurrences of epigenetic character are found in the same area and occurs as breccia infill, veins and replacement bodies of hollandite and bixbyite.

During exploration for iron deposits in the Karelian greenstones, Mn-enriched BIF deposits of mainly silicate facies was found. They could be more than 100 m thick units containing 2-6% Mn occurring as knebelite, Mn-rich pyroxene, and amphibole. Low grade Mn-Fe deposits are locally also found in metasedimentary rocks with Bygdsiljum in central Sweden as a typical example containing 4.5% MnO. The main minerals are fayalite, garnet, hedenbergite, antophyllite and pyrrhotite.

Mn-nodules are known to occur in the Bothnian Basin, the Bothnian Sea, and the Baltic Sea and contains 14-46% MnO. So far, their economic potential has not been evaluated since technical, economic and environmental aspects of sea-floor mining have not been studied.

2.6 Graphite

Graphite occurs in many metasedimentary domains in Sweden and was formed by metamorphose of carbonaceous sediment deposited in anoxic environments. Small-scale mining has occurred in the past in deposits containing flaky graphite. Industrial scale production of graphite has only occurred in central Sweden during 1996-2001 in Kringeltjärn containing flaky graphite in highly metamorphosed metasediments. There are plans for reopening the mine and indicated+measured resources were recently calculated to 2.5 Mt @ 9.3% graphite. Kringeltjärn was discovered 1983 in relation to a systematic exploration program for graphite covering most of Swedens metasedimentary domains. Besides reinvestigating known occurrences, also several new objects were identified and studied in more detail to evaluate economic potential. Three more deposits of flaky graphite were found close to Kringeltjärn and have valid mining licenses but are so far not exploited.

Several known graphite deposits in northern Sweden have also been claimed recently. Some of them containing flaky graphite, as Raitajärvi with an inferred and indicated resource of 4.3 Mt @ 7.1% graphite. However, the largest deposits are mainly classified as amorphous graphite and are known from investigations in the early 1900's. They belong to a 15-20 m thick graphite schist containing 15-40% graphite that form an extensive stratigraphic unit within the Karelian greenstones in northernmost Sweden. The recently claimed Nunasvaara deposit with a resource of 10.7 Mt@ 25.7% graphite (inferred+indicated) is part of that unit and have been subjected for metallurgical studies and is planned for production of graphite electrodes to electrical car batteries. Next step in this advanced project is to get all necessary permits to develop a mine and start production.

3 Economic potential of known occurrences in Sweden

If the alum shale deposits of vanadium could be mined considering economic, technical, environmental, and legal aspects they constitute world class deposits. The orthomagmatic Fe-Ti-V deposits are smaller in size but some of them could also have potential to contribute to a Swedish vanadium production. This is also the case with the apatite iron ores as the magnetite used in steel production will give a slag containing several percent of vanadium that could be recovered from this waste material.

Also for graphite there is a good potential for significant production. If the Nunasvaara project is successful, the potential resources of graphite could be very large as the deposit is part of a very extensive stratigraphic unit of graphite schist that outcrops for combined distances of at least 30 km within the Karelian greenstones in northernmost Sweden. With a thickness of 15-20 m and a graphite content of 15-40% they constitute giant world class deposits of graphite.

At present the potential for significant nickel production is limited as known deposits are mostly rather low grade and of small size. However, many occurrences of sulphidic nickel deposits are known and although rather extensive exploration has occurred, potential for new and more significant deposits exists. The Rönnbäcken deposit is an exception with possibility of low cost and large-scale production in open pits. It could also produce a very high-grade Ni-concentrate, but the very low Ni-grade of the ore will generate large volumes of tailings.

The potential for Li-production is less obvious as only limited exploration has occurred and only a few junior companies are presently focusing on lithium. However, the Kaustinen Li-project in Finland indicates a possibility to find economic Li-deposits in the Swedish part of the Bothnian Basin. These deposits are expected to be small to moderate in size based on the present knowledge.

Although several active claims include Co as a possible commodity only a few projects have this metal as the main target. This might partly depend on the limited geological knowledge of cobalt occurrences in Sweden, but also that most of the known deposits seem to be small and of low grade. However, in some of them Cu±Au could add some value. Several sulphidic deposits also contain pyrite with elevated contents of Co with the potential of Co to be a by-product if metallurgical methods are developed. Especially Co-bearing pyrite could have the potential to a minor supply of cobalt.

Manganese is often associated to iron deposits and although very limited exploration for manganese has occurred in Sweden in the past, considerable knowledge has been accumulated in relation to iron exploration and mining. Even if high-grade Mn-deposits have been mined in the past, the potential to find economically significant Mn-deposits in Sweden is probably low. The only contribution to the supply of manganese could possibly be as by-product from Mn-rich iron deposits and some of the base metal deposits in Bergslagen.

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