Geological Survey of Finland

Bulletin 306

The ore deposits of Sweden

by Rudyard Frietsch

Geologinen tutkimuslaitos · Espoo 1980

Geological Survey of Finland, Bulletin 306

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with one figure in the text

GEOLOGINEN TUTKIMUSLAITOS
ESPOO 1980

Frietsch, R. 1980. The ore deposits of Sweden. *Geological Survey of Finland, Bulletin 306.* 20 pages and one figure.

The metallogenic provinces of Sweden are reviewed. The Precambrian deposits include the iron, sulphide and tungsten ores of Central Sweden, the sulphide ores of the Skellefte district, the molybdenum and uranium mineralizations of the Arjeplog province, and the iron and sulphide ores of the Kiruna district. The main deposits of Palaeozoic age are the lead mineralizations along the eastern margin of the Caledonides, the ores in the inner part of the Caledonides and the low-grade uranium deposits in the Cambrian alum shales of Västergötland.

Key words: economic geology, mineral deposits, metallogeny Precambrian, Palaeozoic, Sweden

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ISBN 951-690-113-1
ISSN 0367-522X

Helsinki 1980. Valtion painatuskeskus

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INTRODUCTION

The mining industry of Sweden has ancient traditions and has been of great importance for the country and its economy. Ever since Middle Ages, the iron and copper ores of central Sweden have been mined. At the beginning of this century the large phosphorus-bearing iron ores in the northern part of the country were exploited and the sulphide deposits of the Skellefte district since 1920's. The mining of the lead ores at the margin of the Caledonides started at the beginning of 1940 and the Aitik copper deposit in the north came into production in 1968.

Even if Sweden is rich in a variety of mineral deposits many of these have at the present no economic value. Nowadays only a few ore types are mined and the main production comprises the following mineral commodities in order of decreasing sales value: iron, copper, zinc, lead, pyrite and tungsten. In 1976 fifty-three mines were operative, of these 30 extracted iron ores. The 1976 production of iron ore products (ore, concentrate, pellets) was 30 526 000 tons with a sales value of 1 141 million kronor. The extractation of non-ferrous, mainly sulphide ores gave 958 000 tons of concentrate with a sales value of 619 million kronor, namely 402 000 tons with pyrite, 180 000 tons with copper, 124 000 tons with lead and 225 000 tons with zinc. In addition there was a small production of tungsten (about 400 tons), silver (about 200 tons), gold (about 3 tons), selenium (about 6 000 tons) and arsenic oxide (about 6 000 tons); the two last figures refer to the 1977 production. In contrast Sweden has a relatively small production of industrial minerals and rocks; in 1974 the sales value was about 258 million kronor. The most important products are limestone, dolomite, quartzite, chalk, kaolin, fireclay and feldspar. In additional small amounts of apatite, talc and fluorite have been extracted. The main mineral commodites exported are iron and zinc, whereas the main commodites imported are ferro-alloys. Sweden is a major producer of special steel but has to import the necessary ferro-alloys.

GEOLOGICAL SETTING

The largest part of the bedrock of Sweden is Precambrian and belongs to the Baltic Shield. The Precambrian rocks have been affected by several periods of folding and deformation and at least three orogenies or cycles can be discerned: the Archean (Pre-Svecokarelian) with an age more than 2600 Ma, the Svecokarelian [1]) in the range 1800—2200 Ma and the Dalslandian about 1000 Ma old.

Archean (Pre-Svecokarelian) formations are only found in restricted areas in the north against the Finnish border. Here gneissose granites and gneisses make up the basement of the Svecokarelian rocks.

The main part of the Precambrian is composed of Svecokarelian rocks, covering large areas in central and northern Sweden and parts of south-

[1]) Svecokarelian (folding) is preferred instead of the previously used terms Svecofennian, Svecofennokarelian fold belt or folding; cf. Rankama and Welin (1972).

eastern Sweden. They are made up of older supracrustals (acid-basic volcanics and different kinds of sediments) and younger acid-basic intrusives about 1800—1900 Ma old. In the southeastern part of the country, but also in restricted areas in central and northern Sweden, mostly close to the Caledonides, there are acid volcanics about 1600—1750 Ma old and granites about 1500—1750 Ma old. Both have generally a post-orogenic or anorogenic appearance in relation to the Svecokarelian. However in northernmost Sweden the rocks have been folded and metamorphosed and thus Post-Svecokarelian orogenic events may have occurred.

Southwestern Sweden is dominated by gneisses, mainly metamorphosed acid-basic granitoids. Their age seems to be comparable to or somewhat lower than that of the Svecokarelian granitoids. This region has been involved in a thermal metamorphism known as the Sveconorwegian regeneration which occurred about 1000 Ma ago. A part of the region has been tectonically deformed by the Dalslandian orogeny, approximately of the same age as the Sveconorwegian metamorphism.

Late Precambrian formations are of restricted extension. In southwestern Sweden there is a minor area with 1050—1100 Ma old (Dalslandian) metasediments which have been affected by the Dalslandian deformation. Unfolded and mostly horizontally inclined arenites of Jotnian age, possibly around 1300 Ma old, occur in limited areas in the central part of the country as a platform cover on the folded and metamorphosed Precambrian. Some of the occurrences are grabens delineated by faults. In southern Sweden quite restricted Eocambrian sediments occur in a similar way.

The Precambrian is covered by Phanerozoic rocks. An unfolded platform cover of Cambro-Silurian metasediments is confined to the southeast along the Baltic sea. Scattered remnants of this cover occur in southern and central Sweden. Cambro-Silurian and Triassic to Cretaceous metasediments are found in Scania in the southernmost part of the country.

The Caledonian mountains are in the east made up of autochthonous Eocambrian, Cambrian and Ordovician metasediments, covering the Precambrian basement. They are overriden by autochthonous to allochthonous thrust units of Precambrian, Eocambrian and Cambro-Silurian age. The nappe structure is characterized by displacements from west to east.

A general review of the Precambrian is given by Lundqvist (1979), and of the Caledonides by Gee and Zachrisson (1979).

MINERALIZED FORMATIONS

Several thousand deposits and occurrences of ore are known in Sweden. The bulk of these are confined to Precambrian rocks. A minor parts is found in the Caledonides. The unfolded Phanerozoic cover is barren in mineral deposits, the only exception being the uranium-bearing Cambrian alum shales.

The greatest majority of the economically important ores are found in Middle Precambrian formations which are 1600—2200 Ma old. The main part of the Precambrian ores occurs in three separate regions, each with a large number of deposits (Fig. 1). Historically the oldest and formerly most important is the Bergslagen province in Central Sweden with occurrences of iron and base metal ores. To the north, in the Norrbotten county, there is the iron ore district of Kiruna which also contains some copper deposits and, situated between Bergslagen and Norrbotten, is the Skellefte district with considerable base metal ores. West of Skellefteå is the recently discovered Arjeplog province with mineralizations of iron, molybdenum and uranium. Elsewhere in the Precambrian are several scattered

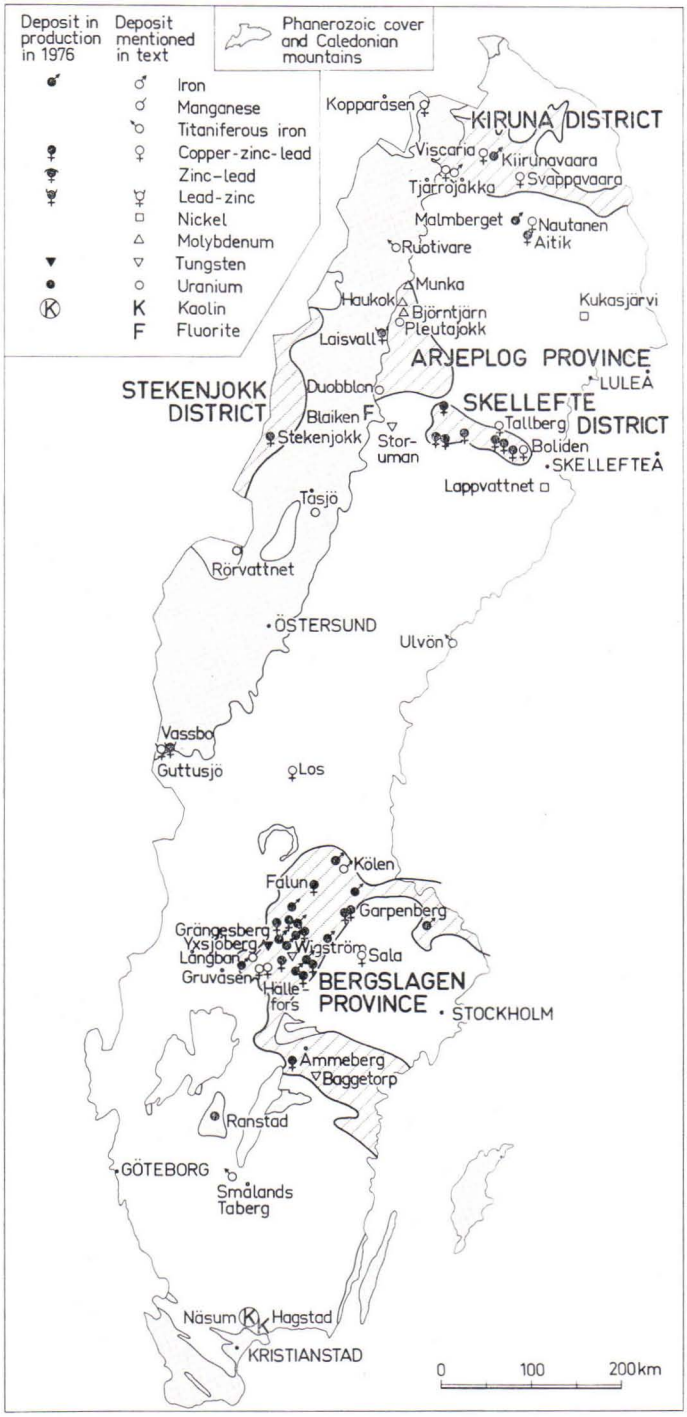

Fig. 1. The main ore-bearing areas in Sweden and some single deposits mentioned in the text.

occurrences of base metals, titanium, manganese, tungsten etc. which are mostly not workable. In the Caledonian mountains base metal ores occur in the inner (western) part and at the eastern margins.

General reviews of the ores of Sweden are given by Tegengren (1924), Geijer and Magnusson (1944), Magnusson (1970, 1973), Grip and Frietsch (1973), Frietsch (1975, 1977, 1979) and Grip (1978).

Middle Precambrian ores

Bergslagen province

The Svecokarelian rocks of Central Sweden are composed of acid volcanics (leptites) ranging in composition from sodic to potassic. Limestone and dolomite intercalations are common and in many areas detrital sediments and basic volcanics occur. The rocks have been folded and metamorphosed in connection with the intrusion of syn-kinematic, acid-basic igneous rocks about 1900 Ma old (Rb/Sr age determination; Åberg 1978). In the final phase of the orogeny regional migmatization and intrusion of late-kinematic granites accompanied by pegmatites took place. The age of the pegmatites is about 1810 Ma (U/Pb age determination; Welin and Blomqvist 1964).

In the acid volcanics occur, more or less intimately associated with limestones and dolomites, quartz-banded iron ores and skarn iron ores. The quartz-banded ores consist of hematite, magnetite, quartz and small amounts of Ca-Mg-Fe-silicates. The ores are considered as volcanic-sedimentary by Geijer and Magnusson (1944, 1952 a and b). Reserves exist of about 290 million tons of which 2.1 million tons were mined in 1976. The skarn iron ores, which consist of magnetite and skarn silicates, are divided into a non-manganiferous type (< 1 % Mn) and manganiferous type (> 1 % Mn). The non-manganiferous ores with skarn silicates rich in magnesium, or in calcium and magnesium, are considered to be either volcano-sedimentary deposits later affected by the older Svecokarelian granitoids (Magnusson 1970, 1973) or true pyrometasomatic deposits formed by emanations from the latter (Geijer and Magnusson 1952 a and b). The reserves are about 110 million tons of ore of which 1.1 million tons were mined in 1976. About 70 million tons of the reserves are found in the Kölen ore, NE of Falun, discovered in 1970 by Stora Kopparberg AB (Carlsson 1979). The Kölen ore is one of the largest non-phosphorus iron ore deposits in Sweden. The manganiferous skarn ores contain manganese-rich silicates and are considered to be of volcano-sedimentary origin. The reserves are about 250 million tons of ore of which 0.9 million tons were mined in 1976.

From both an economic and size viewpoint, the most important iron ores of central Sweden are the apatite-bearing magnetite-hematite ores. Only a few deposits are known, the largest being Grängesberg. The reserves are about 280 million tons of ore of which 3.4 million tons were mined in 1976. The ores have an intrusive appearance, occurring as lens-shaped bodies in the volcanics, and are considered as a late differentiation phase genetically related to the volcanics (Geijer 1931 b, Magnusson 1938, 1970, Geijer and Magnusson 1944). However, according to Landergren (1948) the iron is sedimentary and later mobilized and injected into the volcanics during palingenesis. Near the Grängesberg deposit, hematite impregnations poor in apatite represent a late metasomatic phase in the same process that resulted in the apatite-bearing ores.

Within the volcanics and in part connected with carbonate rocks occur some bedded manganese-oxide-silicate ores associated with ores of jaspilitic hematite and magnetite. The Långban mine is famous for its mineral wealth, there

being a great number of minerals rich in barium, lead and antimony. Most common among the oxides are braunite and hausmannite with spessartine, rhodonite and richterite representing the major silicates. The ores are of volcano-sedimentary origin (Koark 1970). According to Magnusson (1930, 1970, 1973) the ore material was deposited at low temperatures near the surface or at the surface itself by volcanic processes, however, a metasomatic provenance was also postulated. Boström *et al.* (1979) also consider the Långban ore as exhalative-sedimentary but compare it with more recent manganese ores being formed at a spreading centre or at a subduction zone. The lead in the galena and other lead-bearing minerals gives a model age of 1840—1950 Ma (Wickman *et al.* 1963).

The sulphide ores in Central Sweden, including the well-known deposits at Falun and Sala, occur partly in the volcanics and partly in the limestones and dolomites. In some cases the sulphides are intermingled with quartz-banded iron ores and skarn iron ores. The sulphide ores contain on an average 4.5 % Zn, 2.5 % Pb and 0.5 % Cu with reserves of about 30 million tons of which 0.8 million tons were mined in 1976. The main ore minerals are pyrite, pyrrhotite, chalcopyrite, sphalerite and galena. Small amounts of silver minerals (dyscrasite, pyrargyrite and fahlerz) are sometimes present, and the Garpenberg Norra ore is mined for its silver content (about 200 g/t). The main sulphide minerals are present as weak disseminations and massive ore bodies. The limestones which are usually altered to dolomites or skarns with Ca-Mg and Mg-rich silicates, contain galena and sphalerite as the dominant ore minerals. In the volcanics mainly chalcopyrite with subordinate pyrite, sphalerite and galena are encountered. The volcanics are commonly altered to micaschists and »quartzites» both with Mg-rich minerals. In these rocks also some zinc-lead-copper ores occur.

The emplacement of the ores is thought to be at least partly controlled by tectonic structures. The sulphides are considered to be formed by a magnesia-rich metasomatism in connection with the folding of the volcanic complex and the intrusion of the older Svecokarelian intrusives (Geijer 1917, 1964; Magnusson 1936, 1948, 1960 b). It has also been proposed that the ores are pre-metamorphic (syngenetic) in the volcanics and that their formation is due to exhalative-sedimentary processes (Koark 1962, 1973). The model lead age in galena is about 1700—1900 Ma (Wickman *et al.* 1963).

In central and southeastern Sweden zinc-lead-iron sulphides occur as long, narrow layered disseminations at the boundary of the volcano-sedimentary complex with the Late Svecokarelian migmatites. The ores appear in the acid volcanics or in the limestone-dolomite intercalations. The only deposit of importance is Åmmeberg from which 250 000 tons of ore (10—14 % Zn and 1—3 % Pb) were mined in 1976. The dominant ore minerals are sphalerite and galena with small amounts of tetrahedrite, pyrrhotite, pyrite and arsenopyrite. The ores are considered to be epigenetic resulting from the Late Svecokarelian migmatization (Geijer and Magnusson 1944, Magnusson 1948, 1970). According to Henriques (1964) the Åmmeberg ore is syngenetic and formed by submarine hydrothermal solutions. The lead model of the galena at Åmmeberg is about 1910 Ma; in the other deposits 1760 and 1850 Ma (Wickman *et al.* 1963).

In Central Sweden there are tungsten-molybdenum deposits which are related to the Late Svecokarelian granites and palingenetic processes (about 1800 Ma ago). The granites themselves contain some economically unimportant quartz veins and pegmatites with molybdenite. In the Ludvika area several tungsten mineralizations occur in limestones and dolomites which are skarn-altered and rich in pegmatitic minerals (Ohlsson 1979). They contain some scheelite in association with fluorite, calcite, molybdenite, pyrrhotite and chalcopyrite. In the Yxsjöberg deposit with 0.3—0.4 % WO_3 and 0.25 % Cu, small amounts of magnetite, apatite, sphene, bismuthinite and native bismuth occur (Hübner

1971, Lindroth 1922). Deposits presently mined are at Yxsjöberg (production 135 000 tons of ore annually; reserves estimated to about 1.5 million tons of ore) and at Wigström (production 35 000 tons of ore annually) which was discovered in 1976 by the Geological Survey. The Baggetorp deposit, farther south, is associated with a quartz-aplite intruding veined gneisses. The ore minerals are wolframite and subordinate molybdenite, pyrite and chalcopyrite (Magnusson 1953, Grip 1978).

Central Sweden represents the only area in Sweden in which an enhanced tin content is found, but no deposits of economical interest occur. Some of the sulphide ores of the Falu type (e.g. the Silver mine at Hällefors and Gruvåsen mine) contained within dolomite and limestone have a small content of cassiterite in skarn. The tin content is 0.01—0.04 % Sn (Sundius *et al.* 1966 a and b, Eriksson 1973). In the Grängesberg apatite iron ore tin is also present (about 0.01 % Sn) as cassiterite and in part within the magnetite (Björkstedt 1972).

Skellefte district

North of the metallogenic province of Bergslagen is a large area virtually barren of mineral deposits. It is covered by Svecokarelian gneisses of sedimentary derivation and late-kinematic granites (about 1800 Ma old). North of this »Central Norrland geosyncline» (Magnusson 1960 a) the Skellefte district is situated. The sulphide ores of the Skellefte district account for an important part of the production of base metals in Sweden with nine mines operating in 1976. The famous Boliden mine has been abandoned since 1967. The ores occur in a Svecokarelian volcano-sedimentary complex in which the oldest units are composed of acid-intermediate volcanics with intercalations of tuffs and sediments. They are intruded by the syn-kinematic Jörn »granite» suite (about 1900 Ma old) and subsequently succeeded by the formation of schists (phyllites) with abundant basic volcanics. In connection with a regional folding and migmatization the late-kinematic Revsund granite with an age of 1785 Ma (Rb/Sr radiometric age determination, Welin *et al.* 1971) was intruded. The ores are found in the acid-intermediate volcanics, mostly in the immediate proximity to the overlying schists. The ores which occur mostly as disc- or lens-formed bodies, are pyritic with subordinate amounts of pyrrhotite, chalcopyrite, sphalerite and galena; arsenopyrite is a common constituent. The wall rock is often metasomatically altered with the formation of sericite and chlorite. On an average the ores contain 0.8 % Cu, 2.3 % Zn, 0.2 % Pb, 1.5 g/t Au, 39 g/t Ag and 0.8 % As (Grip and Frietsch 1973). The reserves are about 100 million tons of ore of which 1.8 million tons of ore were mined in 1976.

Gavelin (1955, 1976) and Grip and Frietsch (1973) considered the ores as epigenetic and genetically related to the Revsund granite. The ores represent secondary mobilizations of the original metal content of the sedimentary rocks, particularly the schists. A syngenetic origin by volcano-sedimentary processes has been proposed by Rickard and Zweifel (1975, 1976). The lead model ages for the sulphides indicate an age of about 2000 Ma (Wickman *et al.* 1963).

Potentially economic ore reserves are still being discovered in the Skellefte area, for example, 35 km NW of Boliden the Tallberg copper occurrence was recently found by Boliden Metall AB. The host rocks are granodiorite and quartz diorite associated with the Jörn »granite» suite. These rocks are altered with the formation of sericite, epidote and calcite, in addition vein quartz occurs. Pyrite and chalcopyrite form veins, fracture fillings and impregnations; small amounts of molybdenite and sphalerite are also present.

At several localities NE of Storuman, west of the Skellefte district, scheelit-bearing skarns were discovered in 1975—76 by the Geological Survey of Sweden. The amphibole-pyroxene skarns appear as intercalations in schistose graywackes,

associated with black schists and basic volcanics, all of Svecokarelian age. The mineralization is associated with intrusions of Revsund granite.

During the period 1971—73 a nickel-bearing belt 25 km S of Skellefteå was also discovered by the Geological Survey of Sweden (Nilsson 1973). Within the belt, having a ENE direction and length of at least 10 km, three separate ore bodies have been found, namely Lappvattnet, Brännorna and Mjövattnet. The ore type, not formerly known in Sweden, is associated with ultrabasite (peridotites and minor pyroxenites) forming elongate, parallel bodies in veined gneisses (migmatites and metasediments which to some extent are graphite-bearing). The mineralizations which occur in the ultrabasites as well in the gneisses, appear as disseminations, veinlets and breccia fillings. The dominant ore minerals are pyrrhotite, pentlandite and chalcopyrite in association with small amounts of magnetite, graphite and sporadic pyrite; accessories include gersdorfite, nickelin, maucherite and ilmenite. The age of the mineralization is unknown, but is believed to have formed prior to the Revsund granite (1785 Ma old) and the closely related migmatization of the host rocks. Breccia zones interconnecting the deposits indicate that the ultrabasites probably were emplaced along a system of fault lines.

Of somewhat similar type is Kukasjärvi, 70 km N of Luleå, a deposit recently discovered by Boliden Metall AB. The mineralization is associated with ultrabasic, sill-like intrusions in Svecokarelian sediments, partly graphite-bearing. The ultrabasites are strongly altered with the formation of serpentine, amphibole, biotite and talc. The ore minerals are pyrrhotite, chalcopyrite and pentlandite, while pyrite, marcasite and magnetite are found sporadically. The mineralization also occurs in the adjacent sediments.

Arjeplog province

Northwest of the Skellefte district is situated the Arjeplog province bordered to the west by the Caledonian mountains. North of Arjeplog there occur some low-grade, quartz-banded iron ores in acid volcanics and sedimentary rocks of Svecokarelian age. The ores which have a volcano-sedimentary origin (Frietsch 1977), comprise reserves of about 100 million tons.

In 1967—68 molybdenite mineralizations also north of Arjeplog were discovered by the Geological Survey of Sweden. They are all related to granites, probably equivalents to the Lina granite dated to about 1565 Ma old. At Haukok (and Skarjaviken) there are fissure fillings and disseminations of molybdenite with some pyrite and chalcopyrite in a sericite-altered porphyry of Svecokarelian age. More interesting economically are the Björntjärn and Munka deposits with molybdenite disseminated in aplite or quartz veins, and to some extent in the surrounding tuffitic Svecokarelian sediments. Scheelite-bearing skarns also belong to the association.

Since 1969 several uranium deposits around Arjeplog have been discovered by the Geological Survey of Sweden. There are more than twenty occurrences with similar characteristics. The mineralizations which occur in Svecokarelian acid volcanics more than 1900 Ma old, and to a lesser extent in granitoids about 1900 Ma old (e.g. Jörn granites), are made up of fissure fillings and disseminated impregnations with pitchblende, quartz, chlorite and occasionally calcite and fluorite (Adamek and Wilson 1977, 1978, Gustafsson and Minell 1977). In the host rocks there is a metasomatic alteration with the formation of albite and some riebeckite. U/Pb isotopic determinations show that the pitchblende precipitated 1740—1850 Ma ago. The uranium potential of the area is estimated to about 20 000 tons of uranium, half of which is located within the Pleutajokk deposit with a stockwork at least 4.5 km long.

According to Adamek and Wilson (1977) the uranium mineralizations in this region are located at the southern margin of a protocontinental land mass immediately north of an island arc environment (the Skellefte district). The uranium

deposits were formed at the culmination of the Svecokarelian orogenesis about 1750 Ma ago. There is, however, a clear relationship to joints and fault zones, expecially in the area west of Arvidsjaur. Dolerite dykes always occur in the vicinity of the vein mineralizations but are apparently much younger. A metamorphic origin to the ore-forming solutions would appear the most likely mechanism.

The above described supracrustals and granitoids are at Duobblon (in the southwestern part of the Arjeplog province), overlain by a basal weathering breccia which is in turn overlain by acid volcanics (ignimbrites) with intercalations of red-bed sedimentary deposits. The ignimbrites, which are about 1725 Ma old, contain a prominent unit with a stratabound uranium mineralization (Lindroos and Smellie 1979). The primary uranium mineralization is syngenetic or at least of syn-devitrification in origin. The uranium is present as complex uranotitanates, uranium-rich mica components in the rock matrix and finely dispersed pitchblende in microfractures.

Kiruna district

In the northern part of the county of Norrbotten skarn iron ores and quartz-banded iron ores occur in a Svecokarelian volcanic-sedimentary complex of basic volcanics with intercalations of phyllites, tuffs, tuffites, graphite-bearing schists, limestone-dolomites and marls, possibly 2000—2200 Ma old. North of Kiruna the complex rests on an Archean basement of gneissose granite with a U/Pb radiometric age of about 2750—2800 Ma (Welin *et al.* 1971). The complex is intruded by granitoids (mostly granodiorites and gabbros) with a Rb/Sr radiometric age of about 1880 Ma (Welin 1970, Welin *et al.* 1970).

The quartz-banded ores contain quartz, magnetite, Mg-Fe-silicates and small amounts of pyrite and pyrrhotite. The ores, which are considered to be volcanogenic (Frietsch 1973 a, 1977), have total reserves of about 120 million tons. The skarn ores occur directly in the basic volcanics, or more often in association with the sediments, as limestones-dolomites and marls. All the larger deposits are associated with a sedimentary sequence. The ores are composed of magnetite and Ca-Mg or Mg-silicates, often interlayered with calcite; some pyrite, pyrrhotite and minor amounts of chalcopyrite are typical. The ores (reserves about 500 million tons) have been considered as pyrometasomatic (Geijer 1931 a, Geijer and Magnusson 1952 a), the iron emanating from the older (1880 Ma) granitoids, or, as volcano-sedimentary formed simultaneously with the host rocks (Frietsch 1973 a, 1977).

Within the basic volcanics and associated sediments there are local intercalations of graphite-bearing schists which form a large potential reserve of graphite. The graphite is very finely crystalline (»amorphous») with a content of carbon mostly between 25 and 35 % (Eriksson and Hallgren 1975, Svensson and Wester 1974).

In 1973 the LKAB company discovered the Viscaria copper mineralization 5 km west of Kiruna (Godin 1976). In the basic volcanics (»Kiruna greenstones») there are horizons, several kilometers long, of relatively unmetamorphosed and only slightly folded sediments consisting of graphite-bearing schists, basic tuffs and tuffites, magnetite-bearing carbonates and banded albite rocks. The copper mineralization occurs in the metasediments as a fine banding, even impregnation and veinlets. The ore minerals are chalcopyrite and pyrrhotite: magnetite is subordinate and accessories are sphalerite, pyrite and galena. The reserves are about 30 million tons of ore with about 1.1 % Cu.

A similar, but economically unimportant, deposit is found at Kopparåsen, farther to the north, which is a polymetallic sulphide impregnation containing uranium in metasediments within basic volcanics. This deposit is by Adamek (1975) considered as volcano-sedimentary, whereas Grip and Frietsch (1973) considered it as

bound to zones of tectonization. Similar are also Pahtavuoma in northern Finland and Bidjovagge in northern Norway.

The basic volcanics of the Kiruna area are overlain by volcanics of trachytic or rhyolitic composition which in many cases occur as porphyries. The age of the volcanics in the Kiruna area and southwest of Kiruna is 1605—1635 Ma (Rb/Sr age determination, Welin *et al.* 1971). In these rocks, which are restricted to the western part of the Norrbotten county, apatite-bearing iron ores, as Kiirunavaara and Malmberget, occur. The reserves amount to 3400 million tons of ore of which 25.5 million tons of ore were mined in 1976. The ores which consist of of magnetite and hematite with subordinate amounts of apatite, actinolite-tremolite and diopside, occur as elongated, tabular bodies or in part as network-forming veinlets (»ore breccia»). The average content of phosphorus is mostly around 1 %. The ores originated by a magmatic differentiation within the same process that resulted in the enclosing volcanics; the ore was injected as a late phase in the host rock (Geijer 1910, 1931 b, 1935, Geijer and Ödman 1974, Frietsch 1973 b, 1977, 1978, 1980). Lundberg and Smellie (1979) anticipate assimilation of iron-rich material by the volcanic host rocks; the ores were formed by immiscibility aided by a high volatile content. The importance of the magnetite filled globules is emphasized. This is in accordance with Geijer (1931 a, 1960) in that the ores and the globules are genetically related, volatiles being active in both. A palingenetic-sedimentary origin has been postulated by Landergren (1948) and an exhalative-sedimentary origin by Oelsner (1961) and Parák (1975 a and b). According to the latter author the ores in the Kiruna area were deposited in a volcano-marine environment. The ores formed as a result of chemical and minor mechanical sedimentation in connection with the volcanism. This hypothesis of formation is supported by various observations, for example, the apatite-bearing ores occur as fragments in the wall rock indicating that the ore is older than part of the volcanics and, thus, not of intrusive origin.

In the vicinity of Kiruna some apatite-rich ores containing 2—5 % phosphorus occur. They represent, according to the magmatic theory, a low temperature phase in the ore forming activity. In addition, there occur apatite-free hematite impregnations which were deposited hydrothermally during the final stage of ore formation.

In the northern part of the Norrbotten county there are a number of deposits where copper sulphides (mainly chalcopyrite) occur as veins and disseminations in basic to intermediate volcanics and metasediments. The mineralizations are associated with metasomatic alterations which resulted in the formation of scapolite, tourmaline and sericite. The only deposit of importance is Aitik, about 15 km ESE of Gällivare, which is the largest single copper deposit in Sweden and has been mined since 1968. About 5 km east of Aitik a similar but smaller mineralization occurs called Liikavaara E. The outcrop area of Aitik is 380 000 m² with an average grade of 0.4 % Cu, 1.5 % S, 0.3 g/t Au and 5 g/t Ag; the cut-off grade is 0.22 % Cu (Zweifel 1972, 1976). The reserves are about 300 millions tons of ore of which 6.8 million tons were mined in 1976. The country rocks are sediments which have been metasomatically altered forming sericite, tourmaline, scapolite and skarn minerals. The metasediments are probably older than the apatite iron ore-bearing porphyries, but younger than the basic volcanics. The ore minerals occurring as veins and disseminations, are chalcopyrite, pyrite, magnetite and pyrrhotite and are in association with quartz, barite, calcite and fluorite. The deposits at Svappavaara (in intermediate volcanics probably about 1600 Ma old) and Nautanen (in the same sediments as Aitik) are similar but economically unimportant. According to Geijer (1918, 1924) and Frietsch (1966) the mineralizations are related to the intrusion of the late-kinematic Lina granite (about 1565 Ma old, Rb/Sr age determination, Welin *et al.* 1971). Zweifel (1972, 1976) con-

sidered the ore at Aitik to be syngenetic within the sediments; in connection with the intrusion of the Lina granite the ore material was mobilized and metasomatic alterations occurred.

In 1963 an apatite-bearing iron ore (with reserves about 65 million tons) was discovered by the Geological Survey of Sweden at Tjårrojåkka, 50 kilometers WSW of Kiruna. The wall rocks are acid to intermediate lavas with intercalations of tuffs and tuffites; these are possibly about 1600 Ma old. Adjacent to the iron ore a copper mineralization associated with the tuffite intercalations occurs. The ore minerals are chalcopyrite, bornite and magnetite.

Other parts of Sweden

Outside the main ore-bearing areas there exist within the Middle Precambrian scattered ore deposits, many of which have in older times been mined but are at present without importance.

Within Svecokarelian rocks in southeastern Sweden and to a lesser extent in central Sweden, hydrothermal copper-iron sulphide veins bound to zones of brecciation and tectonization are present. Age determinations show that some deposits in central Sweden have been formed 1585—1785 Ma ago (Welin 1961, 1964 a and b, 1966).

Some gabbros of Svecokarelian or Post-Svecokarelian age contain titaniferous iron ore and nickel sulphides. There are about twenty deposits of gabbroic rocks with associated pentlandite-bearing pyrrhotite, mostly occurring at the contact of the igneous bodies. The titaniferous iron ores are few and the only deposit of importance is at Smålands Taberg in southern Sweden, made up of a magnetite-olivinite in a hyperite about 1600 Ma old (Rb/Sr age determination, Klingspor 1976). The deposit contains 150 million tons of ore with 28—32 % Fe, 5—10 % TiO_2 and 0.12—0.17 % V. Of Jotnian age is the minor (20 million tons) titaniferous iron ore Ulvön in northern central Sweden lying in an olivine dolerite about 1245 Ma old (K/Ar age determination, Welin and Lundqvist 1975).

In the Olden »window» situated in the southern part of the Caledonides, uranium mineralizations have recently been found by the Geological Survey, mainly around Rörvattnet in the Hotagen area. The bedrock consists of Svecokarelian granites and volcanics which are cataclastically deformed, fractured and traversed by doleritic dykes. The uranium mineralizations, of which uraninite is the dominant phase, are located in tectonic zones often in association with the basic dykes. The breccia zones are characteristically chloritized and albitized, with fluorite sometimes as a constituent.

In central Sweden some polymetallic uranium mineralizations occur. The Los cobalt-nickel-iron-copper-bismuth sulphide deposit with pitchblende lies in a tectonic zone and is about 1690 Ma old (Welin 1966). In addition, within some of the iron ores of Central Sweden there are fissure fillings with sulphides and pitchblende related to breccia and shear zones. The fissure fillings suggest two episodes of mineralization, namely 1785 Ma and 1585 Ma ago (Welin 1961, 1964 a and b).

The uranium mineralizations in the Precambrian, including those in the Arjeplog province, are thus mainly vein deposits which in most cases are bound to tectonic zones and formed in the interval 1600—1850 Ma ago.

Late Precambrian and Eocambrian ores

Mineral deposits in Late Precambrian formations are few and generally without economical interest. Hydrothermal veins with copper-lead sulphides and manganese oxides occur in southwestern Sweden in rocks of Dalslandian (1050—1100 Ma) and older age. The lead-model age of

the sulphides is 740—1200 Ma (Wickman *et al.* 1963). In the same area Dalslandian sediments contain stratabound chalcopyrite impregnations. In addition, Eocambrian sandstones at Lake Vättern in southern Sweden contain mineralizations of copper sulphides similar to »Red bed» ores.

Phanerozoic ores

Caledonian mountains

The eastern margins of the Caledonides are made up of autochthonous Eocambrian, Cambrian and Ordovician sediments. These sediments, which cover the Precambrian platform, are overriden by parautochthonous to allochthonous thrust units of which the lower, parautochthonous unit, comprises Precambrian, Eocambrian and Cambro-Silurian rocks. Above this lies the Seve-Köli Nappe Complex, comprising metamorphic rocks which have been thrusted far from the west. Although the rocks are dominantly sedimentary and volcanics are probably absent in the older rocks, the Ordovician is partly composed of volcanics with agglomerates and tuffs of varying degrees of basicity. In the inner (western) part of the Caledonides, minor bodies and massifs of ultrabasic, gabbroic and granitic intrusives are encountered.

Mineralizations occurring along the eastern margin of the Caledonides, in autochthonous sandstones and quartzites of Late Precambrian (Eocambrian) and Lower Cambrian age, are in the form of impregnations and fissure fillings of galena with subordinate sphalerite and minor pyrite and chalcopyrite. The mineralizations contain 2.4—5.7 % Pb, 0.1—0.3 % Zn and 10—20 g/t Ag. The gangue is made up of fluorite, barite and calcite. Sericite is a common alteration product of the wall rock. There are several deposits of which Laisvall and Vassbo are mined; Guttujaur, the latest (1972) discovered deposit by Boliden Metall AB, is now about to be exploited. The reserves are more than 50 million tons of ore of which 1.6 million tons were mined in 1976.

The lead mineralizations are stratabound but can locally cut the sedimentary structures. The occurrence in both Late Precambrian and Lower Cambrian rocks excludes a syngenetic origin. The ores are confined by over- and underlying layers of shale and at least in part controlled by joints and other tectonic structures (Tegengren 1962). Christoffersson *et al.* (1979) and Rickard *et al.* (1979) showed the important relation between the thickness and the structures of the sedimentary host rocks. The ore solutions are considered to have been derived from the inner part of the Caledonides in connection with palingenetic processes (Grip 1954, 1960). A portion of the lead has been leached from the overlying Cambrian shales (Grip 1967). Grip and Frietsch (1973) postulated a weathering of the Precambrian peneplain as a source of the lead. The lead is thought to have been deposited in the basins at the western part of the Precambrian peneplain during the Eocambrian and Lower Cambrian. During the Caledonian orogeny the lead was mobilized and transported to tectonically favourable structures at the border of the Caledonides. According to Gee (1972) the mineralizing solutions came directly through the underlying Precambrian basement and are related to a hinge-zone fracturing during Ordovician or possibly Silurian times. Fluid inclusion studies indicate that the ore-solutions were highly saline brines at 150° C (Roedder 1968, Rickard *et al.* 1979). The Laisvall ore is considered to have been formed by the interaction of metal-bearing and sulphide-bearing brines; the age of the mineralization is shortly before the arrival of the Caledonian nappes (Rickard *et al.* 1979). Most of the deposits

contain an excess of radiogenic lead resulting in anomalous »negative» isotopic ages (Wickman *et al.* 1963). NW of Storuman, within the same arenites of the Caledonian front, a subeconomic fluorite deposit (Blaiken) was discovered in 1969 by Gränges AB. The reserves are estimated to 23 million tons with 14 % CaF_2.

Concentrations of uranium in calcareous sandstones-siltstones of Lower Ordovician age occur at Tåsjö, near Strömsund. These rocks have a parautochthonous position at the Caledonian front. The uranium is bound to a carbonate-fluor-apatite of marine origin and the uranium content in the sediment is 200—500 g/t (Andersson 1971). The origin of the uranium is related to the erosion of underlying (Cambrian) alum shale (Armands 1970). According to Gee (1972) the apatite was precipitated at the edge of the Baltic Shield where upwelling currents of cold, phosphate-rich water met warm water with a higher basicity.

In the inner part of the Caledonides, within the metamorphic allochthon which forms the major Seve-Köli Nappe complex, stratabound sulphide ores occur. Most of the important ores lie in the Köli lowgrade metamorphic rocks which consist dominantly of metasediments with intercalations of basic and acid volcanics. The rocks are Silurian or Ordovician, possibly also in part Cambrian (Zachrisson 1969). All the large deposits are to be found in the Silurian where the ores are stratiform but may occur at several levels within one stratigraphic unit. Massive ore bodies are most common, often with associated impregnations, consisting of pyrite and pyrrhotite with varying amounts of chalcopyrite, sphalerite and galena. In many cases there is a metasomatic alteration of the wall rock with the formation of sericite, chlorite and quartz. The deposits contain some 25 million tons of ore with an average of 1.3 % Cu, 3.2 % Zn, 0.3 % Pb, 20 % S, 0.2 g/t Au and 44 g/t Ag (Grip and Frietsch 1973). The largest deposit situated at Stekenjokk was opened in 1976 and produced that year 420 000 tons of ore.

According to Kautsky (1948, 1953), the ores are related both to the late Caledonian palingenetic processes and to the basic volcanics adjacent to the ore bodies. The emplacement of the ores occurred later than the thrusting of the Caledonides. Juve (1974, 1977) considered the (Stekenjokk) ores to be of pre-tectonic age and formed contemporaneously with the volcano-sedimentary host rocks. During the Caledonian orogeny the ore material was mobilized, reworked and concentrated with the present distribution influenced by the major fold phases (Zachrisson 1971).

The titaniferous iron ore of Ruotivare occurs in anorthosite and minor gabbro in thrust units below the Seve-Köli Nappe complex. The age and provenance of the mafic rocks is not known but may represent a dislocated and overthrust part of the Precambrian. The ore consists of magnetite, ilmenite and spinel (Tegengren 1911, Magnusson 1953) and it is the only titaniferous iron ore in Sweden with greater amounts of free ilmenite. The deposit contains 50 million tons of ore with about 40 % Fe, 10 % TiO_2 and 0.18 % V.

In the Seve-Köli Nappe complex there are intrusions of dunite and peridotite of Middle Ordovician age which have been serpentinized and altered to soapstones. They contain small concentrations of chromite of the podiform (Alpine) type. The peridotites also contain small amounts of nickel (0.2 %) and cobalt (0.02 %) which is bound to magnesium silicates and to sulphides such as heazlewoodite, pentlandite, and to some extent breithauptit (Du Rietz 1956).

Palaeozoic cover

The alum shales within the Palaeozoic cover in central and southern Sweden are of economic interest as an important source of energy. The shales which are of Middle and Upper Cambrian age are horizontally inclined, mostly up to some tens of metres thick and tectonically undisturbed. They contain uranium mainly in the *Peltura*

scarabaeoides zones within the Upper Cambrian. The uranium is present as finely dispersed uranium oxide or to a smaller extent bound directly to phosphorite and organic materials (Armands 1972). The uranium-bearing horizon covers large areas in Billingen, Västergötland, where the economically most important deposit Ranstad is situated. The aerial extent is more than 500 km^2 and the uranium-bearing seam is 2.5—4.0 m thick. The grade is 0.025—0.32 % uranium and technically the recoverable quantity of uranium is at least 300 000 tons. Ranstad is thus one of the largest low-grade uranium deposits in the world. Since the beginning of the decade the aim of the mining has been a total extraction of all the recoverable constituents. The shales contain locally (especially in Närke) high amounts of organic material and some hydrocarbons; in addition relatively high contents of vanadium, molybdenum, magnesium, sulphur, nickel and chromium can be recovered together with such elements as aluminium and potassium.

Mesozoic cover

In southern Sweden (Scania) chamosite-goethite-siderite ores are present within arenaceous rocks of Middle or Upper Jurassic (Dogger or Malm) age (Hadding 1933). They are of marine-sedimentary origin and similar to Jurassic Minette ores elsewhere in the world.

Preglacial weathering

Some of the ore deposits in Sweden have been affected by Preglacial weathering which can locally penetrate deeply, in many cases this is greatly facilitated by tectonic disturbances. In Central Sweden some of the skarn iron ores are weathered, mainly those rich in limestone and of the manganiferous type (Geijer 1936, Geijer and Magnusson 1926, Ljunggren 1958). New minerals formed include limonite, martite and siderite and the wall rock is commonly kaolinized. At one mine a diabase of Jotnian age (about 1300 Ma old) has been affected indicating that the weathering is Jotnian or later at this locality. In addition, weathering of the lead-zinc-sulphide ores of the Falu type has resulted in alteration minerals as sulphates, carbonates and hydroxides. A Preglacial alteration of magnetite to hematite is also known from some apatite-bearing iron ores and skarn iron ores in Northern Sweden (Geijer and Magnusson 1926, Frietsch 1960).

Scania, in southern Sweden, contains several kaolin deposits (Byström-Asklund 1969). Of economic interest are those where the kaolinite is formed by a pre-Senonian weathering of Precambrian rocks. For example, mining occurs at Näsum, NE of Kristianstad, were the parent rock is the Vånga granite (about 1500 Ma old) and the kaolin cover is up to 40 m thick. In 1976 about 17 000 tons were taken out. Another important deposit, recently discovered, is Hagstad, E of Näsum. Here the parent rock is a mica-schist belonging to the Svecokarelian Västanå formation with reserves estimated to be 40 million tons.

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ISBN 951-690-113-1
ISSN 0367-522X