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The Ore Deposits in Finland, Norway, and Sweden—a Review

Introduction

DESPITE its relative smallness, Fennoscandia is an area rich in mineral deposits; a number of these have been productive for many hundreds of years, some since the Middle Ages. The main part of Fennoscandia is made up of the Precambrian Baltic Shield, which is the western part of the large Fennosarmatian block. In the east, the Baltic Shield is covered by undisturbed Phanerozoic rocks. The western part of Fennoscandia is made up of the Caledonian mountain chain. Geographically the area is divided between four countries: Finland, Norway, Sweden, and the Soviet Union. In this issue of *Economic Geology* some of the ore deposits and ore types within the first three Nordic countries will be dealt with. Extensive exploration (Fig. 1) and exploitation in the last few decades have led to new discoveries and a better understanding of the origin and the stratigraphic and tectonic positions of the ores. The main purpose of this issue of *Economic Geology* is to present some results of these investigations. This introductory article briefly describes the principal ore-bearing areas and ore types. The metallogeny of the Nordic countries has been discussed in the memoir accompanying the *Metallogenic Map of Europe* (Frietsch, 1979a; Kahma et al., 1979). The ore deposits of Finland are reviewed by Kahma (1973, 1978) and Isokangas (1979), those of Norway by Vokes and Gale (1976) and Vokes (1976), and of Sweden by Frietsch (1975, 1977, 1980).

Finland

Before World War II the mining industry was relatively unimportant in Finland. Since the war and largely owing to the effort put into exploration, the production of mineral commodities has grown rapidly. In 1976, 15 mines were in production, yielding a total of 1.167 million metric tons of iron concentrate (65.8% Fe on average), 494,000 metric tons of pyrite concentrate (47.3% S), 414,000 metric tons of chromite conconcentrate, 191,000 metric tons of cobalt concentrate, 183,000 metric tons of copper concentrate (22.8% Cu), 122,600 metric tons of ilmenite concentrate (45.7% TiO_2), 122,500 metric tons of zinc concentrate, 115,600 metric tons of nickel concentrate, and 3,000 metric tons of lead concentrate. In addition to these main metals the following elements and compounds were also produced: 2,589 metric tons of V_2O_5, 428 metric tons of cadmium, 24,051 kg of silver, 13,186 kg of mercury, 9,931 kg of selenium, and 818 kg of gold. The production of industrial minerals, feldspar for glasswork, and talc for paper mills was quite small.

In 1978 the capacity of the nickel-copper mine at Vammala was increased and the first plans were made for an apatite mine at the Siilinjärvi carbonatite complex. Some of the major research targets in the mining field are the Sokli carbonatite complex, the Kolari iron ore district, and the Pahtavuoma copper ore district in northern Finland (Lapland).

Norway

In Norway, where one of the mines still in operation first went into production 1654, the mining industry has recently been facing considerable difficulty owing to the state of the metal markets. In 1976 fourteen metal mines produced 3.92 million metric tons of iron concentrates and pellets, 0.78 million metric tons of ilmenite concentrate, 0.37 million metric tons of pyrite concentrate, 0.13 million metric tons of copper concentrate, 0.06 million metric tons of zinc concentrate, and 6,500 metric tons of lead concentrate. Production from three other mines comprised 8,300 metric tons of graphite concentrate, 264,600 metric tons of nepheline syenite concentrate, and 410,000 metric tons of olivine products, respectively. Other economic mineral production included over 5 million metric tons of limestone, 0.5 million metric tons of dolomite, 82,500 metric tons of quartz, and 50,000 metric tons of feldspar.

Considerable prospecting activity has taken place in Norway during the last decade or so, though in the last few years a certain slowing down has been evident. This is expected to be only temporary. The main objects of interest in recent years have been

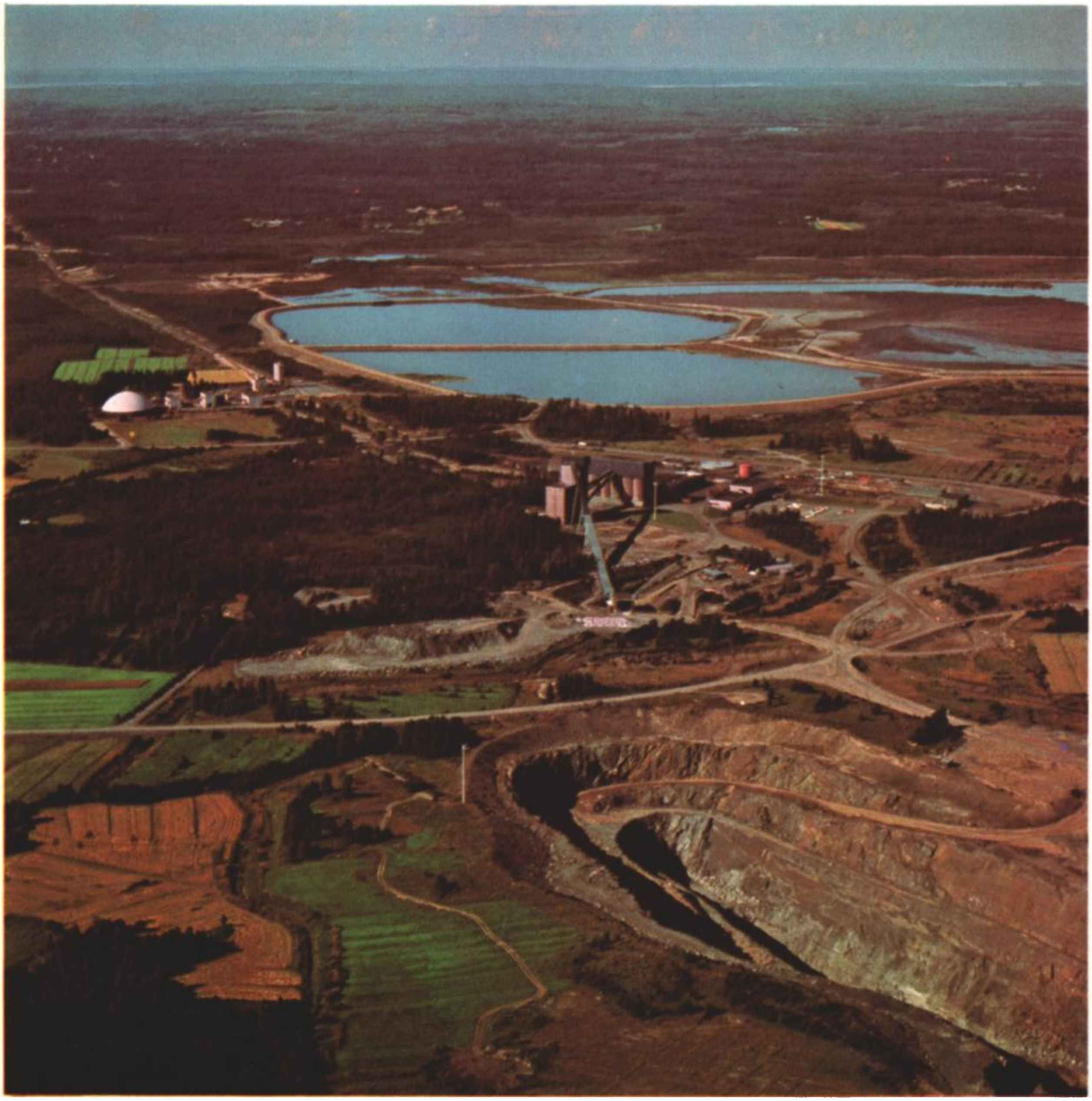

FIG. 1. The Vuonos mine in the Outokumpu district Finland. This blind Cu orebody was found by the lithogeochemical surveys approximately 6 km northeast of Outokumpu. A low-grade nickel ore was mined from 1972 to 1976 in the open pit in foreground of the picture.

nickel and molybdenum in the metallic sector and the utilization of domestic minerals (anorthosite, nepheline) as sources of alumina.

Sweden

In Sweden the mining industry has long traditions. Although Sweden is rich in mineral deposits, many of them are of no economic value and currently only a few types of deposits are mined. During recent years several mines have been closed, in particular iron ore deposits in central Sweden. Of the 53 mines operative in 1976, 30 were extracting iron ores. The production of iron ore was 30.526 million metric tons. The extraction of nonferrous, mainly sulfide, ores gave 958,000 metric tons of concentrate, namely 402,000 metric tons of pyrite concentrate, 180,000

FIG. 2. Special geophysical methods are called for when conventional methods fail. A. A pulse electromagnetic receiver in use in a Finnish forest. B. An electromagnetic ("Slingram") measuring crew at work in northern Sweden. Photo: Å. Hesselbom)

FIG. 3. Geochemical exploration goes on all year. Sampling lake sediments through winter ice in a Finnish lake.

metric tons of copper concentrate, 124,000 metric tons of lead concentrate, and 225,000 metric tons of zinc concentrate. In addition, tungsten (about 400 metric tons), silver (about 200 metric tons), gold (about 3 metric tons), selenium (about 6,000 metric tons), and arsenic oxide (about 6,000 metric tons) concentrates were also produced.

The production of industrial minerals and rocks in Sweden is limited. The principal products are limestone, dolomite, quartz, chalk, kaolin, fireclay, and feldspar. Some apatite, talc, and fluorite are also extracted.

Besides the attempt to expand the ore reserves around known mining areas, great efforts have been, since the 1960s, put into regional exploration work covering the central and northern part of the country. This work traditionally has concentrated on base metals, but during the latest decade the search for ferroalloys, especially nickel, and uranium has been intense.

Exploration

During the Ice Age Fennoscandia was an intensely glaciated area, and thus no more than 3 percent of the bedrock is exposed in Precambrian areas outside the Caledonian mountain range. This has influenced the choice of exploration methods, which are more or less the same in all three countries. The exploration activities largely resort to geophysical, geochemical, and other methods which permit penetration of the overburden.

Exploration is being carried out by the Geological Surveys and a number of state-owned and private mining companies. In each country bedrock mapping, the main requirement for successful exploration, is the responsibility of the Geological Survey. A computer-based input system has been developed for the storage and retrieval of field observations. Geological mapping helps to delineate the areas and zones favorable for ore deposits and these are subsequently submitted to geophysical (Fig. 2) and geochemical surveys.

Airborne geophysical measurement is an important tool for interpretation of the structures and lithology of the bedrock and for indicating ore. Geophysical airborne survey data are recorded on magnetic tape, processed by computer, and partly printed by a computer-controlled color plotter. The three countries are to a varying degree covered by airborne magnetic, electromagnetic, and radiometric measurements. The most promising areas have been covered by low-altitude (30 m; line-spacing 200 m) airborne measurements. In mineralized areas ground-based geophysics include magnetic, gravimetric, and a variety of electrical methods. Electric resistivity, very low frequency, applied potential, spontaneous polarization, radiometric, and magnetic three-component measurements are applied to drill logging. The geophysics

FIG. 4. Prospecting and drilling crew being unloaded in the Sulitjelma area, Norwegian Caledonides. (Photo: T. Soyland Hansen)

instrumentation is largely developed by the laboratories of the Geological Surveys and individual companies. Although geophysics mainly aims at finding ore deposits, the geophysical mapping done by the Geological Surveys is of vital importance in geological interpretation of lithologic and structural features of the bedrock.

Geochemical prospecting is carried out on two scales: regional and local. Regional reconnaissance sampling of organic stream and stream sediments is often the first stage in the location of anomalies. The geochemistry of till is being systematically studied and the results are published as map sheets by the Geological Survey of Finland. Recent studies have disclosed that the till cover is composed of piles of beds that differ in age and direction of glacial transport. Hence, in Finland and in Sweden local geochemical samples are taken from the deepest parts of the till in profiles down to the bedrock. Samples consisting of humus, peat, and living organisms are also collected for explorational purposes. Special sampling and separation methods have been developed in Sweden and Finland and successfully applied to prospecting for certain weather-resistant heavy ore minerals, e.g., scheelite, wolframite, cassiterite, gold, monazite, and apatite.

Lithogeochemical survey usually aims at the direct discovery of an ore deposit, but it also provides basic information applicable to exploration. In Finland and Sweden a comprehensive study has been in progress since the 1960s to establish the features that characterize mafic and ultramafic bodies with special emphasis on factors related to nickel occurrences. The study has disclosed areas and zones preferred by Ni-deposits. A special study on the geochemical characteristics of the Cu-Zn-Co ores of the Outokumpu type in Finland led to the discovery of the Vuonos orebody not far from the Outokumpu deposit (Fig. 1). In Sweden progress is being made in the study of primary halos to find blind orebodies.

Tracing by prospectors of mineralized float boulders in the moraine is an important step at the initial stage of exploration. More recently trained dogs have been used successfully to sniff out sulfide-bearing boulders. The public has its own particular role to play in this boulder exploration. In Finland the system of encouraging laymen to send mineralized samples to the experts was introduced in the 1930s; as a result, most of the Finnish deposits mined today owe their discovery to the initiative of the public. The method is now used in the other Nordic countries as well. Geological Surveys and individual companies encourage anyone interested in exploration to send in samples to regional offices, where they are examined by a geologist. Tens of thousands of sam-

FIG. 5. Norsk Nefelin's operation of Stjernøy, northern Norway. Mine entrance is near the center of photo at an altitude of 100 m. Mine operations continue, inside Nabberen Mountain, to an elevation of 350 m. Administration building and refining plant in center foreground, quay and concentrate silos at left.

ples are received annually and the senders of the best samples are rewarded at an annual ceremony.

Exploration is not interrupted by the long winter (Fig. 3), which in Lapland lasts for more than seven months. On the contrary, diamond drilling, ground geophysics, and till sampling are easier in winter than in summer because moving in areas without permanent roads is facilitated by snowmobiles and skis, and heavy machines can be transported on iced snow-roads.

Prospecting methods employed in the high Caledonian mountains are essentially the same in principle as those used in the flatter Precambrian terrains to the east. However, difficulties of access and transport are often more pronounced and helicopter transport of men and equipment plays an important role. In the Sulitjelma area of northern Norway, for example, surface drilling to discover and delineate continuations of the orebodies at great depths (in access of 1,000 m) and under difficult terrain and climatic conditions has relied heavily on helicopter transport (Fig. 4). Helicopter-borne geophysical surveys are also widely employed in such terrain.

Another recent development has been the use of magneto-telluric methods to detect deep-lying orebodies, and deep reflection seismic prospecting is also being developed. The mountainous terrain often leads to problems during the development and mining of the orebodies after discovery. The highly successful nepheline-syenite mining operation of the nepheline division of Elkem-Spigerverket A/S, on Stjernøy in northern Norway (70° 30′), was earlier very exposed to disruption and damage by snow avalanches down the steep slopes of the arctic island on which the mine is situated (Fig. 5).

Geological Framework

The majority of the ore deposits, including the most important ones, occur in the Precambrian of the Baltic Shield, mostly in formations 2.2 to 1.8 b.y. old (Figs. 6 and 7). The Caledonides contain a

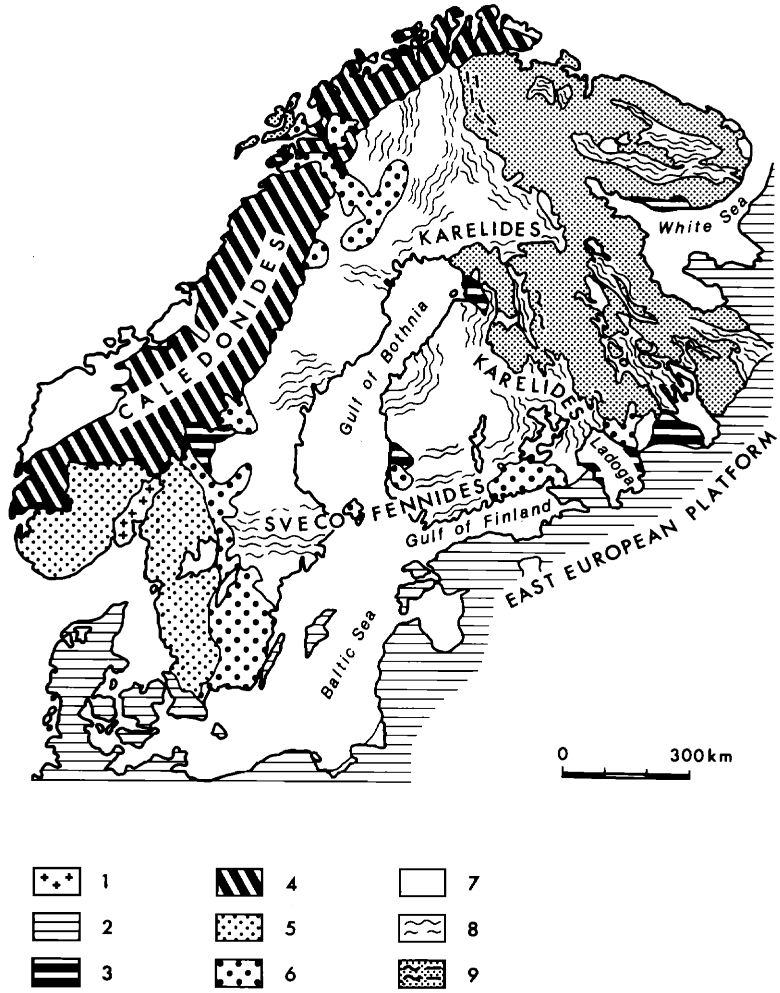

FIG. 6. Main geological units of the Fennoscandian area: (1) Oslo igneous province (age ca. 250 m.y.); (2) Phanerozoic platform cover (younger than 570 m.y.); (3) Jotnian platform cover (ca. 1,300 m.y.); (4) Caledonides (400 to 600 m.y.); (5) region of Sveconorwegian regeneration (ca. 1,000 m.y.); (6) post- and anorogenic, mostly igneous complexes (1,500 to 1,700 m.y.); (7) Svecokarelian igneous rocks, mostly granitoids (1,800 to 1,900 m.y.); (8) Svecokarelian folded supracrustal rocks (1,800 to 2,200 m.y.); (9) Archean folded region and granitoids (older than 2,600 m.y.). Mainly after Kahma (1978).

relatively large number of deposits, some of which are of considerable economic importance. The Paleozoic platform cover is more or less devoid of mineral deposits except for the uranium deposits in Sweden.

The Baltic Shield comprises Precambrian formations 3,500 to 600 m.y. old. They have been involved in at least three orogenies.

The oldest, the Archean, affected rocks more than 2,800 m.y. ago in the eastern and northern parts of the shield. The bulk of the Precambrian rocks in Finland and Sweden were affected by the Svecokarelian orogeny, which began about 2,200 and ended about 1,800 m.y. ago. In Sweden, mainly in the central and southern parts of the country, and in southern Finland there are some formations, mostly igneous complexes, which have a postorogenic or anorogenic appearance in relation to Svecokarelidic folding. About 1,000 m.y. ago southwestern Sweden and southern Norway were involved in thermal metamorphism, the so-called Sveconorwegian regeneration. Southwestern Sweden is dominated by gneissic granitoids; locally, nongneissose supracrustals also occur. A part of southwestern Sweden has been tectonically deformed by the Dalslandian orogeny, of roughly the same age as the Sveconorwegian regeneration. This refers particularly to the 1,050- to 1,000-m.y.-old Dalslandian metasediments. The southern Norwegian Precambrian areas are usually included in the Sveconorwegian (or Dalslandian) province and are characterized by isotopic ages of about 1,600 to 850 m.y.

Despite the paucity of detailed age-relationship

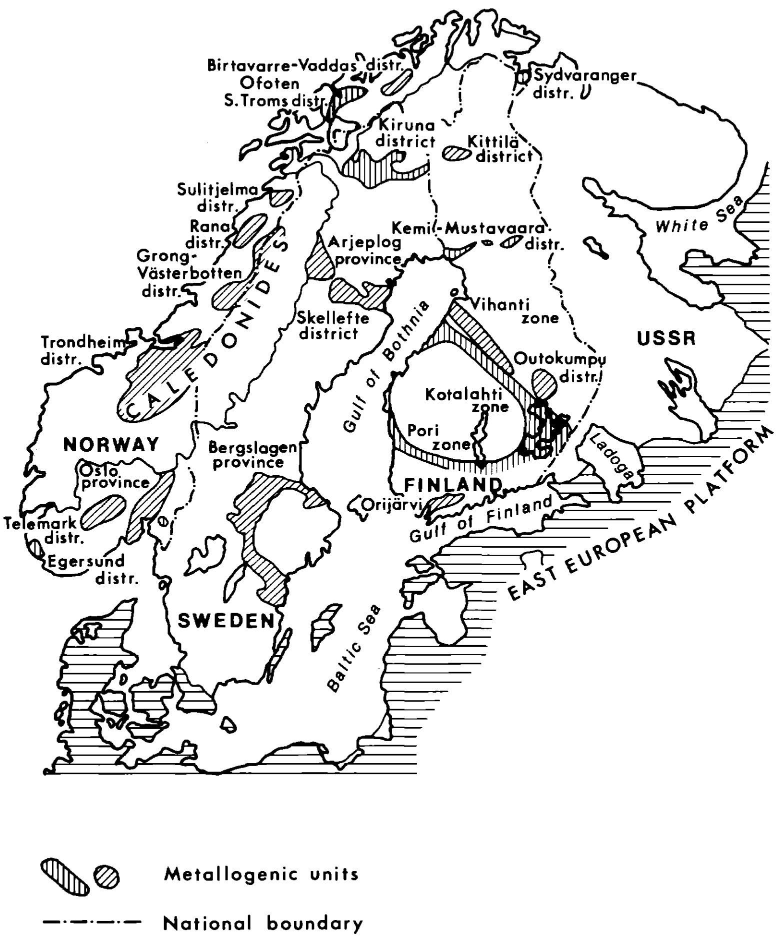

FIG. 7. Main metallogenic units of Finland, Norway, and Sweden.

studies in this Sveconorwegian province, a few points are beginning to emerge (Versteeve, 1975). For example, relict ages of around 1,600 to 1,700 m.y. have been obtained in several places, pointing to the presence of a Svecokarelian basement on which the Sveconorwegian (Telemarkian) orogeny developed. The main stage of the Sveconorwegian metamorphism occurred around 1,200 m.y. ago, and postmetamorphic cooling ages of minerals are usually between 850 and 1,000 m.y. Late- to post-tectonic granite and other plutons intruded between 900 and 950 m.y. ago.

Unfolded and mostly horizontal arenites of Jotnian age, possibly ca. 1,300 m.y. old, constitute a platform cover on folded and metamorphic Precambrian rocks in a few confined areas in Sweden and Finland. Some of the occurrences lie in grabens delineated by faults. In southern Sweden some restricted Eocambrian sediments occur in a similar manner.

In the southeast the Precambrian is covered by Phanerozoic rocks, dominantly metasediments of Cambro-Silurian age. Scattered remnants of this platform cover are preserved in southern Norway and in central and southern Sweden; in the latter area Triassic to Cretaceous rocks also occur. In southern Norway magmatic rocks of the Oslo paleorift were formed in Permo-Carboniferous time.

In the east the Caledonides are made up of autochthonous late Precambrian, Cambrian, and Ordovician sediments and cover the Precambrian platform. They are overlain by autochthonous to allochthonous thrust units of Precambrian and Cambro-Silurian age. The nappe structure is characterized by displacements from the west.

Archean Mineral Deposits

The oldest formations of the Baltic Shield are Archean (or early Precambrian), more than 2.6 b.y. in age, and occur in eastern and northern Finland, in northern Norway, and to a small extent in northern Sweden (Fig. 6). Gaál et al. (1978) have subdivided the Finnish Archean rocks into two main lithological units: the granitoid basement and the overlying supracrustal greenstone belt association. Detrital zircons from the supracrustal rocks have

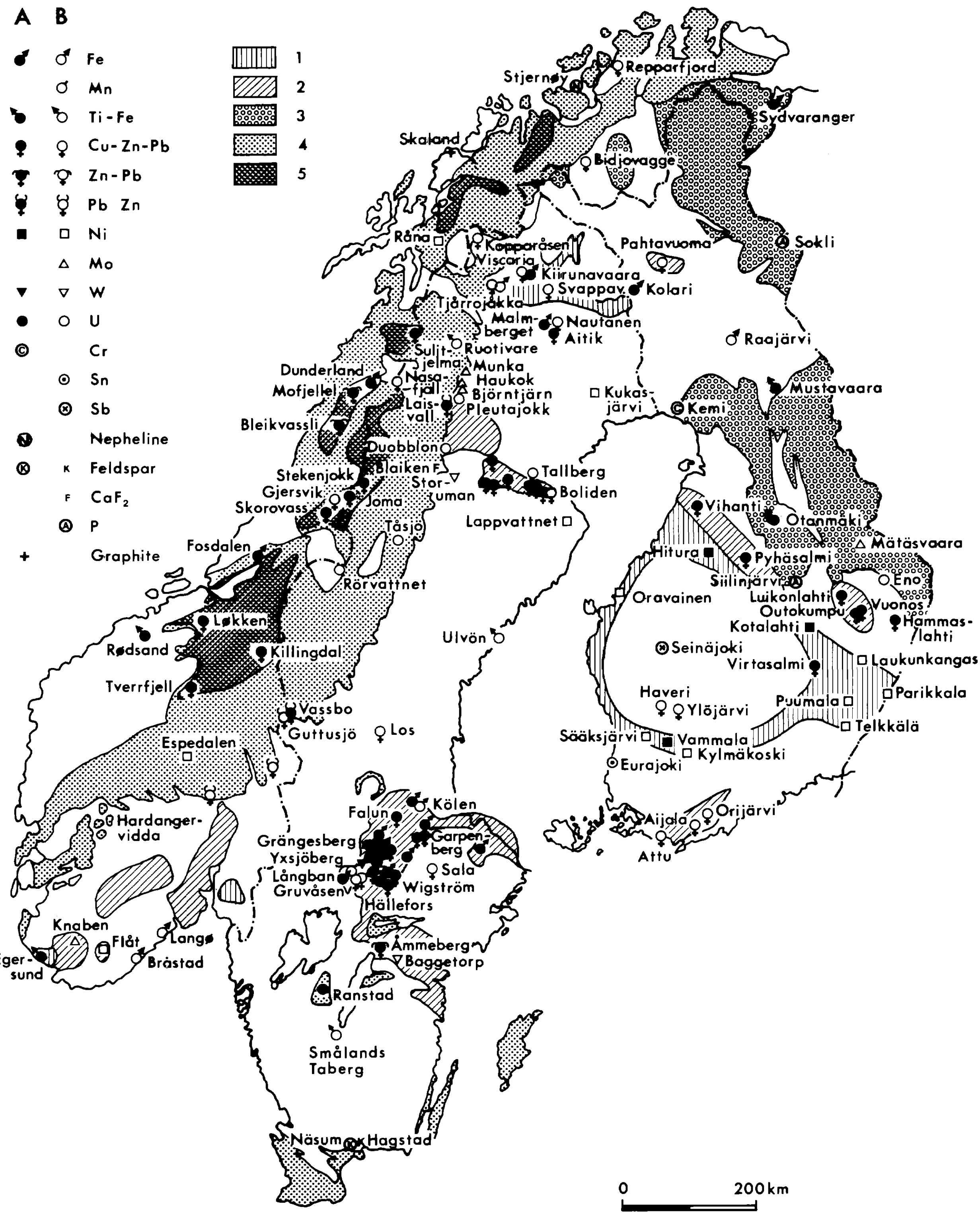

FIG. 8. Mineral deposits of Finland, Norway, and Sweden. A. Operating mines in 1976. B. Occurrences: 1, areas of iron oxide ores and/or copper-nickel sulfide ores; 2, areas of copper, zinc, and lead sulfide ores; 3, Archean rocks; 4, Phanerozoic cover and Caledonides; 5, ore districts in the Caledonides.

yielded U-Pb ages of 3.0 to 2.9 b.y. According to Gaál et al. (1978), the granitoids constituted the basement to the supracrustal rocks but were rejuvenated about 2.8 b.y. ago, at the same time that the Archean trondhjemites and granodiorites were formed. The boundary between the Archean and the Proterozoic Svecokarelian formations in Lapland is a subject of controversy (Gaál et al., 1978), but in eastern Finland the unconformity between these formations is well established owing to the presence of basal conglomerates. The same conditions apply to northern Sweden.

Only a few ore deposits are known in the Archean areas. The Bjørnevann iron ore of the Sydvaranger district in northeastern Norway is a banded iron-formation associated with intermediate to acid metavolcanites (Bugge, 1978). The ore is currently mined by A/S Sydvaranger (see below). In eastern Finland there are some minor occurrences of iron-formations in mafic volcanites; a few are also encountered in clastic lithologies such as the small occurrences at Ilomantsi (Laajoki and Lavikainen, 1977).

The nickel-copper occurrences at Suomussalmi, eastern Finland (Papunen et al., 1979), are associated with carbonatized and tectonized ultramafites of the Kuhmo-Suomussalmi greenstone belt. According to Jahn et al. (1979), the belt comprises both komatiitic and tholeiitic rocks; the latter are the hosts to Ni-Cu sulfides.

The Mätäsvaara molybdenum deposit, which was exploited in 1940–1947, is located in the basement gneissic granitoid of eastern Finland (Fig. 8). The age of the ore, dated by an Re/Os method, is 2.8 b.y. (Kahma, 1973).

Svecokarelian and Other Proterozoic Mineral Deposits

Proterozoic formations dominate the Baltic Shield, both in extent of and with regard to mineral deposits of economic importance. Most of the Proterozoic rocks belong to the Svecokarelian folded belt. Largely on the basis of lithological composition and geographical location, the belt was formerly divided in Finland and Sweden into two distinct orogenic belts —the older Svecofennian belt in southwestern Finland and central Sweden and the younger Karelian belt in eastern and northern Finland, northern Sweden, and northern Norway. Radiometric dating has, however, shown that these are parts of one and the same orogenic cycle, the Svecokarelian orogeny, in which the main phase of folding and metamorphism occurred about 1,900 to 1,800 m.y. ago. The names Svecofennides and Karelides are still used in Finland to distinguish between geographically and lithologically separate units.

In southeastern Sweden and in certain areas in central and northern Sweden, mostly close to the Caledonides, acid volcanics 1,750 to 1,600 m.y. old and granites 1,750 to 1,500 m.y. old are encountered. In southern Finland rapakivi granites intruded 1,700 to 1,540 m.y. ago (Vaasjoki, 1978). These rocks have a postorogenic or anorogenic appearance in relation to Svecokarelian folding. In northern Sweden, however, the rocks of this age group are metamorphosed and folded, indicating that post-Svecokarelian orogenic events also may have occurred.

Finland

The following ore provinces and ore types characterize different areas and formations of the Svecokarelian cycle in Finland.

Between the 2,800-m.y.-old Archean granitoids and the 2,200- to 1,800-m.y.-old Svecokarelian rocks, there is in northern Finland a belt more than 200 km long of mafic plutonic rocks that extends discontinuously from Kemi eastward to the Soviet border. There are several layered, differentiated bodies of ultramafites, gabbros, and anorthosites (Piirainen et al., 1977). The intrusions are 2,450 m.y. old. The large gabbro body of Koitelainen in central Lapland, which is outside the belt proper, is of the same age. The oldest magmatism of the Svecokarelian orogeny shows ages of about 2,200 m.y. Thus, the intrusion of layered gabbros was a pre-Svecokarelidic, probably intracratonic, event.

The layered intrusions contain some ore occurrences of interest. Low-grade nickel-copper showings are encountered close to the basal contact of the Portivaara intrusion, in the eastern part of the mafic belt. The Mustavaara vanadium deposit (Juopperi, 1977) is in a magnetite gabbro in the upper part of a layered intrusion. The deposit has been mined since 1975 in an open pit by Rautaruukki Oy; in 1977 the ore output was 984,000 metric tons. The chromite ore of Kemi occurs in an ultrabasic basal cumulate layer of a layered complex at the western end of the intrusion belt. In 1977 the deposit, owned and mined by Outokumpu Oy, yielded 837,000 metric tons of ore, from which 602,000 metric tons of chromite concentrate were extracted.

The lowest part of the Karelian sequence in eastern Finland is composed of basal weathered sediments resting on the Archean basement. These are followed upward by the epicontinental lithosome of quartzites and some basic volcanites known as the Jatulian sequence. The overlying Kalevian is a flyschoid lithosome composed of geosynclinal metasediments, phyllites, mica schists, and mica gneisses. In northern Finland the oldest section of the Karelides has been given the name of Lapponium; it is composed of basic volcanites and metasediments and is unconformably overlain by an arkosite conglomerate of the Kumpu formation. Zircon and titanium datings by the Pb/U method indicate ages from 2,050 to 2,160 m.y. for Jatulian volcanism (Sakko, 1971; Sakko and Laajoki, 1975).

The Svecofennian sequence in southwestern Finland has been subdivided by Simonen (1960) into three successions: lower, middle, and upper Svecofennian. The supracrustal rocks of southwestern Finland are described here by Latvalahti (1979). The silicic volcanites (leptites) of the lower Svecofennian group seem to be favorable for base metal mineralization. The supracrustal Svecofennian rocks have been intruded by synkinematic and late kinematic plutonic rocks. Owing to intense migmatization and high-grade metamorphism, the primary structures of the supracrustal rocks have only survived in certain belts and places. The age of the Svecofennian syntectonic intrusions is between 1,900 and 1,860 m.y. and that of the late orogenic intrusions, from 1,860 to 1,800 m.y.

The basement of the Svecofennides is a controversial subject. Basal formations as in the Karelides are lacking. Some gneissic granites, like that at Kettuperä described by Helovuori (1979) from the Pyhäsalmi area, yield ages slightly higher than 1,900 m.y., which is the upper age limit of syntectonic intrusives. According to Helovuori (1979), the volcanites of the Pyhäsalmi area belong to the same age group as the syntectonic granodiorites. This supports the interpretation (Marttila, 1976; Huhtala, 1979) that the Svecofennidic geosynclinal lithosome, composed of metavolcanites and metasediments, was deposited on the sialic basement which was rejuvenated during metamorphism and intruded the overlying sequence as syntectonic bodies.

In some parts of north Karelia, eastern Finland, the epicontinental Jatulian quartzites contain low-grade stratabound uranium occurrences (Piirainen, 1968). In places the uranium was enriched at the contacts of intersecting metadiabase dikes. A deposit of this type, exploited in Paukkajanvaara from 1960 to 1961, produced a total of 52,000 metric tons of ore. In addition to the uranium occurrences, some minor stratabound iron oxide ores occur in the Jatulian metasediments; in general, however, the deposits have no economic significance (Laajoki and Saikkonen, 1977).

Hammaslahti is a copper deposit in the lowermost Kalevian metasediments (metaarkose). This chalcopyrite-pyrrhotite ore is in the form of disseminations or quartz veins and breccia. According to Hyvärinen et al. (1977), the sulfides were originally synsedimentary but later remobilized during regional metamorphism and concentrated in transversal shear zones. In 1976 the mine produced 407,500 metric tons of ore.

The low-grade manganiferous iron-formations of the Kittilä district in the central Finnish Lapland volcanite area (Lapponium) have long been known (Paakkola, 1971). During the last 10 years the Pahtavuoma area, which is not far from the iron-formations mentioned, has been the target of intensive exploration. The Kittilä district includes several small deposits of iron-, copper-, zinc-, cobalt-, and arsenic-sulfides and locally some uranium oxides. The Pahtavuoma deposit (Mäkelä, 1977; Inkinen, 1979) is the most important. The ore minerals occur as breccia in quartz veins or as stratabound disseminations in sedimentogeneous schists. The Kittilä district is part of a greenstone complex, which comprises metavolcanites of spilitic composition interlayered with clastic sediments.

The Kolari iron ore district, which lies southeast of Pahtavuoma, contains several oxide iron ores, mainly of skarn type (Hiltunen and Tontti, 1976). The district is a continuation of the Kaunisvaara iron ore area of northern Sweden. The most important of the deposits is Rautuvaara, where a mine has been operated since 1975 by Rautaruukki Oy. In 1976 the mine produced 812,000 metric tons of ore.

The ore deposits of the Outokumpu district in eastern Finland have been the backbone of the Finnish mining industry. At present three mines are in operation: Outokumpu, Vuonos, and Luikonlahti. The Outokumpu deposit, which was discovered in 1910, contained 28 million metric tons of ore averaging 3.8 percent Cu, 1 percent Zn, 0.24 percent Co, 0.12 percent Ni, 0.08 ppm Au, 9 ppm Ag, and 0.005 percent Pb. The ore is associated with a rock complex in which serpentinite forms the core and is enveloped by carbonate rocks, skarn, cherty quartzites, and graphite-rich black schists. The rock complex forms a sinuous strip more than 200 km long, in the Kalevian flyschoid metasediments. The deposits contain platy bodies composed of massive ore comprising iron sulfides, chalcopyrite, and sphalerite with several rare minerals. The massive copper-cobalt-zinc ores are embedded in cherty quartzite. At Vuonos a low-grade disseminated nickel ore has been encountered above the massive orebody. From 1972 to 1976 the nickel ore was exploited from an open pit.

The unique features of the ores of the Outokumpu district led Peltola (1978) to speak of a special Outokumpu ore type. The origin of the ores has been the subject of continuing controversy. At one time it was considered that the ores were epigenetic and derived from intrusive rocks or, through selective remobilization, from sulfide-bearing black schists. More recently, the similarities with volcanic-exhalative deposits have been stressed (Mäkelä, 1974; Peltola, 1978). Gaál et al. (1975) and Gaál (1977) have pointed out the polyphase metamorphic history of the Outokumpu deposit and the effect of deformation on the present shape of the orebody.

The lead model age of the galena in the Outokumpu ore is about 2,100 m.y. (Helovuori, 1979), but the uraninite of the ore yielded an age of 1,900 m.y. (Kouvo and Tilton, 1966). The Outokumpu complex, which is characterized by serpentinites, has not been dated directly; the age of the complex has, however, been correlated with that of Jatulian basic volcanism, which is 2,200 ± 50 m.y. (Peltola, 1978).

The Vihanti sulfide ore zone, northwest of the Outokumpu district, is located at the margin of the Archean craton. The principal ore deposits of the zone are the pyrite-copper-zinc-lead ores at Vihanti and Pyhäsalmi (Rouhunkoski, 1968; Kahma, 1973; Helovuori, 1979; Huhtala, 1979). In 1976, 903,700 metric tons of ore were produced at the Vihanti mine and 811,400 metric tons of ore at Pyhäsalmi. There are also several minor deposits in the Vihanti ore zone, which are described by Huhtala (1979). The host rocks of the ores are metasediments and metavolcanites, particularly silicic volcanites. The rocks of the zone are so intensely metamorphosed that locally they have turned into migmatites, and the primary structures are rarely recognizable.

Huhtala (1979) and Helovuori (1979) suggested that the ores in the Vihanti zone are volcanic exhalative in origin. They give several reasons for their proposal: the occurrence of the ores in silicic metavolcanites, the zonality of their composition, the platy shape of the orebodies, the alteration zones of the wall rocks, and the fact that the ores are frequently composed of massive pyrite with Cu-Zn sulfides. Rehtijärvi et al. (1979) describe a uranium-bearing phosphatic horizon associated regionally with ore deposits of the Vihanti type, the origin of which was interpreted to be due to submarine volcanic-exhalative mechanism. Huhtala suggests an island-arclike environment during the deposition of the metavolcanites and metasediments in the zone. The lead isotopic composition of the Pyhäsalmi area presented by Helovuori (1979) indicates that the age of the volcanic rocks is slightly above 1,900 m.y. and, within limits of experimental uncertainty, the same as that obtained from the isotopic composition of the galena lead in the Pyhäsalmi ore. There are many similarities between the ores of the Vihanti zone and the Skellefte area in Sweden.

In lithology and ore types the Orijärvi district in southwest Finland correlates with the Bergslagen province in central Sweden. Characteristic rocks of the Orijärvi district are the acid volcanites or volcanic-sedimentary rocks (leptites), which form an ore-bearing zone. Numerous small showings have been exploited during the last 200 years, but only three of them, Orijärvi, Aijala, and Metsämonttu, have been mined in the present century. The belt includes both oxide and sulfide deposits. The iron ores can be classified as skarn deposits, banded iron-formations, and Ti-Fe deposits in gabbroic intrusions. The sulfide deposits are complex Cu-Pb-Zn ores in either skarn rocks or acid metavolcanites. The sulfide ores are often associated with cordierite-anthophyllite rocks, which Latvalahti (1979) regards as the metamorphic equivalent of the alteration pipes of volcanic-exhalative deposits. In his classic study of the area, Eskola (1914) described the deposits as epigenetic, the ore constituents being derived from granodioritic intrusions whose hydrothermal fluids induced magnesia metasomatism around the intrusive bodies. According to the data presented by Helovuori (1979) the lead isotope composition of galena from the Svecofennidic deposits suggests an age of about 1,800 m.y. They are thus younger than the sulfide deposits of the Vihanti-Pyhäsalmi district (about 1,900 m.y.) and the ore deposits of the Outokumpu type (probably 2,200 m.y.). The plumbotectonic model suggests a crustal origin for lead in Svecofennidic sulfides.

The Otanmäki Fe-Ti-V deposit is associated with Svecokarelian plutonic rocks. The ore occurs in gabbro-anorthosite bodies, whose age, determined by the U-Pb method from zircon, is 2,050 m.y. The ore lenses, several hundred in all, form belts in the mafic intrusions. The oxide minerals display banded structures that Lindholm and Anttonen (1978) consider to be primary magmatic layering. The ore deposit is held to be magmatic in origin, but the intrusive body bears marks of regional metamorphism.

In central Finland a large area is covered by synkinematic Svecokarelian igneous rocks, commonly called the granitoid of central Finland. Different types of sulfide ore deposits and occurrences surround and are associated with the granitoid. Gaál and Isohanni (1979) describe copper-molybdenum showings that resemble porphyry-type deposits from the northwestern part of the area. The copper-tungsten ore of Ylöjärvi, described by Himmi et al. (1979), is a tourmaline breccia pipe in the contact zone of a granitoid. The Virtasalmi (Hällinmäki) Cu ore is the most prominent of the skarn-type deposits that occur in the eastern contact area of the granitoid. According to Hyvärinen (1969), the ores are genetically related to the intrusion of a synorogenic quartz-diorite body and represent a deposit of the contact pneumatolytic type.

The Haveri pyrrhotite-chalcopyrite-Au deposit, not far from Ylöjärvi, is composed of a sulfide breccia and fracture-filling veins in a basic metavolcanite. Between 1942 and 1960 a total of 1.5 million metric tons of ore was mined from the deposit. The origin of the sulfides has not been established. At Seinäjoki native antimony occurs as a dissemination in gneisses and schists. According to Pääkkönen (1966) the mineralizing hydrothermal fluids originated from nearby porphyrite. The exhausted galena deposit at Korsnäs was associated with a coarse-grained pegmatite, but it also contained appreciable amounts of carbonates, apatite, and other phosphates as well as rare earth elements, indicating that the mineralizing fluids had a carbonatitic origin.

The nickel-copper sulfide occurrences of southern Finland are distributed in a roughly circular pattern around the granitoid of central Finland (Papunen et al., 1979). Three mines, Hitura, Kotalahti, and Vammala, are in production; in 1976 they produced 115,600 metric tons of Ni concentrate, with an average of 5.5 percent Ni. The deposits are associated with ultramafic bodies that intruded about 1,900 m.y. ago during the early stage of orogenesis. At Vammala, which is described by Häkli et al. (1979), the ultramafic magma intruded unconsolidated sediments close to or at the bottom of the sea. The apparent linearity in the distribution of the occurrences in the Kotalahti nickel belt has been explained by Gaál (1972) to be the result of a deep-seated wrench fault system that transects Finland in a northwest-southeast direction over a distance of 430 km; fractures control the intrusion of ultramafic magma. A negative gravity anomaly parallels the belt.

The youngest intrusive phases of some postorogenic rapakivi granites contain tin, tungsten, and beryllium mineralizations. According to Haapala (1977) disseminated cassiterite and other ore minerals occur in the granites, pegmatite veins, greisen, and quartz veins or in the skarn rocks surrounding the intrusive body. Haapala and Kinnunen (1979) describe fluid inclusions in a greisen occurrence of this type.

Sweden

In Sweden most of the Precambrian ores occur in three regions, each containing a large number of deposits. The historically oldest, and formerly the most important, is the Bergslagen province in central Sweden, which has iron ores and base metal ores. The Kiruna district with its iron ores and some copper ores is in the north of the country. Between these two is the Skellefte base metal district. West of it is the Arjeplog province, which has only recently been discovered, containing iron, molybdenum, and uranium mineralizations. Outside these regions, but still in the Precambrian, there are some subeconomic occurrences of base metals, titanium, manganese, tungsten, etc.

Bergslagen province: The Svecokarelian rocks of central Sweden are composed mainly of acid volcanics (leptites) and locally of detrital sediments. They were metamorphosed during the intrusion of synkinematic granitoids, about 1,900 m.y. ago, and of late-kinematic granites about 1,800 m.y. ago. The supracrustal rocks contain different types of ore. The quartz-banded iron ores are volcanic-sedimentary in origin (Geijer and Magnusson, 1944, 1952a and b). The reserves are about 290 million metric tons of ore and in 1976 2.1 million metric tons were mined. The skarn iron ores are either volcanic-sedimentary deposits later metamorphosed by older granitoids (Magnusson, 1970, 1973) or pyrometasomatic deposits formed by emanations from granitoids (Geijer and Magnusson, 1952a and b). The reserves are about 390 million metric tons of ore and in 1976 2 million metric tons of ore were mined. Grängesberg is the largest of the apatite-bearing iron ores that are intrusive in appearance and which are considered as late magmatic (Geijer, 1931b; Magnusson, 1938, 1970; Geijer and Magnusson, 1944). According to Landergren (1948), the iron is sedimentary in origin and was later mobilized and injected during palingenesis. The reserves are about 280 million metric tons of ore and in 1976 3.4 million metric tons of ore were mined. Some bedded manganese-oxide-silicate ores, including the famous Långban deposit, have been described as volcano-sedimentary (Koark, 1970) or volcano-metasomatic (Magnusson, 1930, 1970, 1973). In the opinion of Boström et al. (1979), Långban is an exhalative-sedimentary deposit that formed at a spreading center or above a subduction zone. The lead model ages of the Långban type are 1,840 m.y. (Wickman et al., 1963). The copper-zinc-lead sulfide ores of the Falu type, which occur in magnesia-altered limestones and acid volcanics, were formed by metasomatic processes connected with the intrusion of the older granitoids (Geijer, 1917, 1964; Magnusson, 1936, 1950, 1960) or they are of premetamorphic (syngenetic) origin formed by exhalative-sedimentary processes (Koark, 1962, 1973). The lead model ages are from 1,900 to 1,700 m.y. The ores contain on an average 4.5 percent Zn, 2.5 percent Pb, and 0.5 percent Cu. The reserves are about 20 million metric tons of ore and in 1976 0.8 million metric tons of ore were mined. Some layered zinc-lead-sulfide ores occur at the boundary between the volcanic-sedimentary complex and the late Svecokarelian migmatites. The only deposit of importance is Åmmeberg where in 1976 250,000 metric tons of ore were mined. The ore contains 10 to 14 percent Zn and 1 to 3 percent Pb. The ore is epigenetic and the result of migmatization (Geijer and Magnusson, 1944; Magnusson, 1948, 1970) or syngenetic and formed by submarine, hydrothermal solutions (Henriques, 1964). The lead model age is 1,910 to 1,760 m.y. Several scheelite-bearing skarns occur in limestones and dolomites in association with late Svecokarelian granites (Hübner, 1971; Ohlsson, 1979). Mined at present are Yxsjöberg (production 135,000 metric tons of ore annually; the reserves are about 1.5 million metric tons of ore with 0.3–0.4% WO_3) and Wigström (production 35,000 metric tons of ore annually). The Baggetorp deposit in aplite contains wolframite and molybdenite.

Skellefte district: The sulfide ores of the Skellefte district account for an important part of the base metals produced in Sweden. In 1976 nine mines were in operation. Boliden Metall AB extracted 1.8 million metric tons of ore. The ore reserves are about 100 million metric tons. The famous Boliden mine was exhausted in 1967. The ores occur in a Svecokarelian volcanic-sedimentary complex in which the oldest unit is composed of acid-intermediate volcanics with intercalations of tuffs and sediments. They were intruded by the synkinematic Jörn granite (about 1,900 m.y. old), which was followed by the formation of schists (phyllites) with abundant basic volcanics. The late kinematic Revsund granite with an age of 1,785 m.y. (Welin et al., 1971b) was formed in connection with regional folding and migmatization. The ores are found in acid-intermediate volcanics, mainly in the immediate proximity of the overlying schists. The ores, which occur mostly as disc- or lens-shaped bodies, are pyritic with subordinate amounts of pyrrhotite, chalcopyrite, sphalerite, and galena. Arsenopyrite is a common constituent. The wall rock is often metasomatically altered and contains sericite and chlorite. The ores average 0.8 percent Cu, 2.3 percent Zn, 0.2 percent Pb, 1.5 g/metric ton Au, 39 g/metric ton Ag, and 0.8 percent As (Grip and Frietsch, 1973). The lead model ages for the sulfides are around 2,000 m.y. (Wickman et al., 1963). Sulfur isotope composition of the barite-bearing Åsen pyrite deposit is described by Rickard et al. (1979a).

Gavelin (1955, 1976) and Grip and Frietsch (1973) consider that the ores are epigenetic and genetically related to the Revsund granite. The ores represent secondary mobilizations of the original metal content of the sedimentary rocks, particularly the schist. Rickard and Zweifel (1975, 1976) have proposed a syngenetic origin by volcanic-sedimentary processes.

The Tallberg copper deposit, northwest of Boliden, occurs in granodiorite and quartz diorite that are associated with the Jörn granite. The rocks are metasomatically altered and contain sericite, chlorite, epidote, calcite, and quartz veins. Pyrite and chalcopyrite form veins, fracture fillings, and impregnations; there are also small amounts of molybdenite and sphalerite.

In 1975 to 1976, scheelite-bearing skarns in Svecokarelian metasediments and metavolcanites were discovered at several localities northeast of Storuman, west of Skellefteå. The mineralization is possibly related to the Revsund granite. The area is still being explored.

In 1971 to 1973 a nickel-bearing belt was discovered south of Skellefteå (Nilsson, 1973). The belt is at least 10 km long and contains three discrete orebodies (Lappvattnet, Brännorna, and Mjövattnet). The ore is of a type not previously encountered in Sweden. It is associated with ultrabasic rocks (peridotites and minor pyroxenites) that occur as elongate parallel bodies in migmatites and locally graphite-bearing metasediments. The sulfides, which occur in the ultrabasites and gneisses, form disseminations, veinlets, and breccia fillings. The ore minerals are pyrrhotite, pentlandite, and chalcopyrite. The age of the nickel belt is unknown, but it is older than the 1,785-m.y.-old Revsund granite that migmatized the host rocks. Breccia zones interconnecting the deposits indicate that the ultrabasites probably were emplaced along a system of fault lines. Somewhat similar is the Kukasjärvi deposit north of Luleå. This mineralization is associated with altered ultrabasic, sill-like intrusions in Svecokarelian sediments.

Kiruna district: In northern Norrbotten, skarn iron ores and quartz-banded iron ores, both with magnetite and iron sulfides, are encountered in a Svecokarelian volcanic-sedimentary complex composed of basic volcanites with intercalations of phyllites, tuffs, tuffites, graphite-bearing schists, limestones, dolomites, and marls. The complex, comparable to the Lapponium of the Karelides in northern Finland, may be from 2,200 to 2,000 m.y. old. North of Kiruna the complex rests on an Archean basement about 2,800 to 2,750 m.y. in age (Welin et al., 1971b). The complex is intruded by granodiorites and gabbros about 1,880 m.y. old (Welin et al., 1971a).

The quartz-banded iron ores rich in Mg-Fe silicates are of volcanogenic origin (Frietsch, 1973a, 1977). The skarn ores rich in Ca-Mg-silicates are considered to have a pyrometasomatic (Geijer, 1931a; Geijer and Magnusson, 1952a) or a volcanic-sedimentary origin and to have formed simultaneously with the host rock (Frietsch, 1973a, 1977). The reserves are about 500 million metric tons of ore.

The Viscaria copper mineralization, west of Kiruna, was discovered in 1973 (Godin, 1976). The basic volcanites ("Kiruna greenstones") reveal horizons, several kilometers long, of weakly metamorphosed and only slightly folded sediments composed of graphite-bearing schists, basic tuffs and tuffites, magnetite-bearing carbonates, and banded albite rocks. The ore minerals, mainly chalcopyrite and pyrrhotite, occur in the sediment as fine banding, impregnations, and veinlets. The reserves are estimated to be about 30 million metric tons of ore with 1.1 percent Cu.

A similar deposit occurs farther north at Kopparåsen in sediments interlayered in basic volcanites. According to Adamek (1975) this uranium-bearing polymetallic impregnation is a volcanic-sedimentary deposit, but, according to Grip and Frietsch (1973), it is genetically related to tectonic zones.

The basic volcanites of the Kiruna district are overlain by trachytic or rhyolitic volcanites that often occur as porphyries. The age of the volcanites in and southwest of the Kiruna area is 1,605 to 1,635 m.y. (Welin et al., 1971b). These rocks, which are restricted to western and central Norrbotten, contain apatite-bearing magnetite-hematite ores like those at Kiirunavaara and Malmberget. The reserves amount to 3,400 million metric tons of ore and in 1976 25.5 million metric tons of ore were mined by Luossavaara-Kiirunavaara AB. Networks of ore veinlets ("ore-breccia") are associated with elongated and tabular bodies of massive ore. According to Geijer (1910, 1931b, 1935), Geijer and Ödman (1974), and Frietsch (1973b, 1977, 1978, 1979b), the ore originated by magmatic differentiation, that is, it was injected as a late phase in the host rock. Lundberg and Smellie (1979) advocate the assimilation of iron-rich material by the volcanic host rocks; in other words the ores were formed by immiscibility aided by high volatile content. The importance of magnetite-filled globules is emphasized. This is in accordance with the concept by Geijer (1931a, 1960), that the ores and the globules are similar formations, 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 (1975a and b).

In northern Norrbotten there are a number of deposits where copper sulfides occur as veins and impregnations in basic to intermediate volcanites and metasediments. The economic mineral is chalcopyrite. The mineralizations are related to metasomatic alteration that gave rise to the formation of scapolite, tourmaline, and sericite. The only deposit of importance is Aitik, east-southeast of Gällivare. It is the largest single copper deposit in Sweden and has been mined since 1968. In 1976, 6.8 million metric tons of ore were mined. The reserves are about 150 million metric tons of ore with an average of 0.4 percent Cu and 0.22 percent Cu cut off. The country rocks are metasomatically altered sediments. The ore minerals, chalcopyrite, pyrite, magnetite, and pyrrhotite, occur as veins and disseminations accompanied by quartz, barite, calcite, and fluorite. The deposits at Svappavaara (in intermediate porphyries about 1,600 m.y. old) and Nautanen (in the same metasediments as Aitik) are similar but economically unimportant. According to Geijer (1918, 1924) and Frietsch (1966), the mineralizations are related to the intrusion of the Lina granite about 1,565 m.y. ago. In the opinion of Zweifel (1972, 1976), the ore constituents at Aitik are syngenetic in the sediments: in connection with the intrusion of the Lina granite the ore material was remobilized at the same time that the metasomatic alterations occurred.

Close to the apatite-bearing iron ore at Tjärrojåkka, west-southwest of Kiruna, a stratabound chalcopyrite-bornite ore occurs in tuff-tuffite intercalations in acid to intermediate lavas that may be about 1,600 m.y. old.

The Arjeplog province, northwest of the Skellefte district, contains different kind of ore deposits in Svecokarelian rocks. North of Arjeplog, some low-grade, quartz-banded ores occur in acid volcanic and sedimentary rocks. The ores are volcanic-sedimentary in origin (Frietsch, 1977). The reserves are about 100 million metric tons.

Molybdenite occurrences were discovered north of Arjeplog in 1967 to 1968. They are all related to granites similar to the 1,565-m.y.-old Lina granite. Fissure fillings and disseminations of molybdenite with some pyrite and chalcopyrite are encountered in a sericite-altered porphyry at Haukok and Skarjaviken. Economically more interesting are the Björntjärn and Munka deposits of disseminated molybdenite in aplite or quartz veins, and to some extent, in surrounding tuffitic sediments. Scheelite-bearing skarns are also included in the association.

Since 1969 several uranium deposits have been discovered around Arjeplog. The uranium potential of the area is estimated to be about 20,000 metric tons of uranium, half of which is in the Pleutajokk deposit. More than 20 occurrences with similar characteristics have been met with in acid volcanics older than 1,900 m.y.; a few have also been encountered in granitoids about 1,900 m.y. old (Jörn granites). The deposits are made up of fissure-fillings and disseminations with pitchblende, quartz, chlorite, and some calcite and fluorite (Adamek and Wilson, 1977, 1978; Gustafsson and Minell, 1977). The host rocks are metasomatically altered and contain albite and some riebeckite. The pitchblende crystallized between 1,850 and 1,740 m.y. ago. According to Adamek and Wilson (1977), the uranium province is located at the southern margin of a protocontinental landmass immediately north of an island arc (the Skellefte district). The uranium deposits were formed at the culmination of the Svecokarelian orogeny about 1,750 m.y. ago. Even so, it seems more likely that the ore-forming solutions have a metamorphic origin. A clear relation is displayed with joints and fault zones, especially west of Arvidsjaur.

The supracrustals and granitoids in the Duobblon area are overlain by a basal (weathering) breccia, which in turn is overlain by acid volcanics (ignimbrites) with intercalations of red-bed sedimentary deposits. The ignimbrites, about 1,725 m.y. old, contain a unit with stratabound uranium mineralization (Lindroos and Smellie, 1979).

Only scattered occurrences of ore deposits are found in the Precambrian formations of other parts of Sweden; none are exploited at present.

Uraninite mineralizations occur in the Hotagen area (Rörvattnet) within the Olden window in the Caledonides. The area is covered by Svecokarelian granites and volcanics. The mineralization appears in tectonic zones and in connection with basic dikes. The breccia zones are chloritized and albititized and contain some fluorite.

Hydrothermal copper-iron-sulfide veins bound to zones of brecciation and tectonization occur in Svecokarelian rocks in southeastern Sweden and to a minor extent in central Sweden. Age determinations show that some of the deposits in central Sweden were formed between 1,785 and 1,585 m.y. ago (Wickman et al., 1963).

Some of the Svecokarelian and younger Precambrian gabbros contain titaniferous iron ore and nickel-bearing sulfides. The only deposit of importance is Taberg in Småland, a magnetite-olivinite in a hyperite about 1,600 m.y. old (Klingspor, 1976). The deposit contains 150 million metric tons of ore. The minor (20 million metric tons) Jotnian titaniferous iron ore of Ulvön is in an olivine dolerite about 1,245 m.y. old (Welin and Lundqvist, 1975).

Mineral deposits in late Precambrian formations are rare and without economic value. Hydrothermal veins with copper-lead sulfides and manganese oxides occur in Dalslandian rocks of southwestern Sweden. The lead model age of the sulfides is from 1,200 to 740 m.y. (Wickman et al., 1963). In the same area the Dalslandian sediments contain stratabound chalcopyrite impregnations. At Lake Vättern in southern Sweden there are occurrences of copper sulfides in Eocambrian sandstones.

Norway

The Norwegian share of the Baltic Shield is by and large much less richly endowed with ore deposits of economic importance than are the corresponding areas in Sweden and Finland.

Deposits in the Archean and Proterozoic areas of the northern Norwegian shield region in the county of Finnmark have been briefly mentioned in the foregoing account. By far the most important single group of ores in this region is that of the Sydvaranger iron ore district, where upward of 2 million metric tons of magnetite concentrates are recovered annually from metataconites of the Archean Bjørnevann group. Total ore reserves are reckoned to be on the order of 200 million metric tons.

Operations at the Proterozoic, deformed and metamorphosed volcanic-sedimentary copper-(gold) deposit at Bidjovagge in central Finnmark were recently suspended after an operational period of some 6 to 7 years. The ore reserves were originally estimated to be on the order of 3.5 million metric tons at 1.8 percent Cu. In 1974, the last full year of operation, 100,000 metric tons of ore were milled to yield 4,600 metric tons of concentrates.

The Precambrian areas of southern Norway are divided unequally by the Paleorift zone of the Oslo region (see below). Ore deposits of a considerable diversity of types abound in both the southeastern and southwestern parts of this area, but very few have given rise to lasting mining operations in this country.

The main Precambrian mineral deposit provinces of the southern Norwegian Precambrian have been discussed by several authors (Vokes, 1958; Torske, 1976; Bugge, 1979). The more common and more widely spread types of deposits are magmatic segregation deposits of iron-titanium and nickel-copper; metamorphosed sedimentary (skarn-type) iron deposits; epigenetic, mainly vein-type, deposits of copper, copper-molybdenum, and molybdenum sulfides (the latter in places associated with tungsten minerals); vein and breccia deposits of fluorite; and, less commonly, vein-type lead-zinc, gold-bismuth, and copper-silver deposits.

Economically by far the most important operation in the region is the mining of ilmenite-magnetite ores at the Tellnes deposit of A/S Titania in the Egersund area. This deposit is a large (+300 million metric tons) body of ilmenite-bearing norite enclosed in an anorthosite complex, probably having an intrusion age of about 950 m.y. In 1976 the deposit yielded nearly 760,000 metric tons of ilmenite concentrate, 47,000 metric tons of vanadium-bearing magnetite concentrate, and 12,500 metric tons of a copper-nickel sulfide concentrate from about 2.5 million metric tons of ore.

Until 1973 the region could boast that it contained the only producer of Mo concentrates in western Europe, which was also the oldest continuous primary Mo producer in the world. This was the Knaben mine in the southwest of the area, which until 1973 had produced some hundreds of metric tons of concentrates annually from an ore with a grade of 0.2 to 0.15 percent MoS_2. The deposit has traditionally been considered to be of the hydrothermal, epigenetic, quartz vein-set type, though in recent years emphasis has been placed on the role of sedimentary volcanic processes in the original localization of the molybdenum (e.g., Urban, 1974). Konnerup-Madsen (1979) presents the results of a study of fluid inclusions in quartz from gneissic host rock of the Flottorp deposit, which is similar to the Knaben deposit.

Other production of comparatively recent date from the southern Norwegian Precambrian includes copper and nickel concentrates from the Flåt mine, near Evje (Bjørlykke, 1947), and minor amounts of iron from deposits at Søftestad, Bråstad, and Langø. Mention should also be made of the production of niobium (columbium) concentrates in the form of pyrochlore from the carbonatite zones of the Fen alkaline-carbonatite complex of latest Precambrian (550 to 600 m.y.) age, which cuts the shield rocks just to the west of the Permian Oslo province.

Caledonian Mineral Deposits

Geological framework

The deformed and often highly metamorphosed rocks of the northwest European Caledonian orogenic zone are hosts to a number of important ore districts in both Norway and Sweden. They occupy almost the whole of the western edge of the Scandinavian land mass in a belt about 1,700 km long and up to 250 km wide. The Scandinavian Caledonides show a sharp eastern and southeastern margin, with a series of often highly metamorphic, far-travelled, nappes overlying a narrow belt of autochthonous sedimentary rocks which range in age from latest Precambrian (Vendian) to Silurian. These autochthonous rocks in turn lie unconformably on the Precambrian rocks forming the Baltic or Fennoscandian Shield. Precambrian rocks form, wholly or partly, thrust slices within the Caledonian orogenic belt, whereas tectonic windows of these rocks, often with an anticlinal or domal structure, have been exposed by erosion within the belt, especially along the international border. Along the Atlantic coast of Norway, Precambrian rocks also form part of the northwestern foreland zone of the Caledonides and have in places themselves been involved in the Caledonian deformation and metamorphism.

The Caledonides of Norway comprise rocks deposited in both mio- and eugeosynclinal environments. Sedimentation began with conglomerates on the Precambrian peneplain, continuing with pelites, sandstones, and arkoses (sparagmites). This sedimentation took place in Eocambrian to Cambrian time and was followed by development of the eugeosyncline, with flysch deposition, submarine volcanism, and shore line conglomerates. The extrusion of mainly basaltic lavas took place in Ordovician time, but volcanism as a whole persisted over a long interval from the Cambrian to the Silurian. The amount of volcanic rocks along the orogenic belt varies greatly, submarine lava extrusions reaching their greatest thickness in the Trondheim region (see map, Fig. 8). The thickness of the sedimentary pile also varies along the Caledonides, with the sediments in each sedimentary basin having different characteristics. After their deposition the sediments were metamorphosed and tectonized during the Caledonian orogeny, while intrusion of syn- and late orogenic granite and gabbro was prominent in many areas.

The Swedish Caledonides form the easternmost zone of the Caledonian belt in Scandinavia. Three principal geological and structural units can be distinguished. Farthest to the east, a thin, generally badly exposed zone, a few kilometers wide, is formed by autochthonous late Precambrian, Cambrian, and Ordovician sediments (arkose, sandstone, siltstone, gray shale, alum shale, and limestone). Similar rocks, although in a more highly deformed state, occur around the Precambrian windows, mainly in the antiformal zone along the international boundary already mentioned.

In the Caledonian front, the autochthonous zone is overridden by parautochthonous to allochthonous units with Eocambrian and lower Paleozoic sequences corresponding to those of the autochthon. The uppermost units are probably of Wenlockian age. There are, however, changes in facies and, especially in the Ordovician, limestone and shale in the east are replaced by shale and graywacke farther west. The rocks lack volcanic intercalations (apart from some bentonite horizons) and intrusions and have been designated as miogeosynclinal, although facies and rate of sedimentation do not generally show geosynclinal characteristics.

The major part of the Swedish Caledonides is formed by the metamorphic allochthon, a complicated nappe complex in greenschist to upper amphibolite facies, which has been thrust for hundreds of kilometers from the west-northwest. The lower units are mainly composed of Precambrian igneous rocks and meta-arkoses of the Offerdal nappe and associated units and of heavily dolerite-intruded meta-arkoses of the Särv nappe. The strictly eugeosynclinal sequences form the Seve-Köli nappe complex, composed of a lower, high-grade (amphibolite facies) part, Seve, and an upper, low-grade (greenschist facies) part, Köli.

Mineral deposits of the Caledonides

The exposed Caledonides in Scandinavia carry economically important mineralization, mainly as stratabound deposition in rocks of sedimentary and/or volcanic origin. Mineralization with other characteristics, including clearly epigenetic vein-type deposits, is present in parts of the belt but with few exceptions has not been of any great economic significance. The age of this latter mineralization is often unknown.

The generally stratabound mineralization is comprised of three principal types: (1) deposits of lead and minor zinc-sulfide in arenaceous sediments ranging in age from latest Precambrian to Lower Cambrian; (2) deposits of massive and disseminated polymetallic iron, zinc, copper, and, less frequently, lead and sulfides of general stratabound character in volcanic, volcanic-sedimentary, and sedimentary sequences of lower Paleozoic (mainly Ordovician) age; and (3) stratabound deposits of iron oxides (magnetite and/or hematite) in mainly sedimentary rocks, previously considered to be of lower Paleozoic age but which may prove to be, in fact, Precambrian.

These stratabound mineralizations, especially those of groups 2 and 3, have been involved in most, if not all, of the metamorphic and deformational events of the orogenic stage of development of the Caledonides. The orogenic effects on the ore deposits have included recrystallization, deformation, and the remobilization of certain elements, the latter especially in the massive sulfide deposits. It is thus often difficult to determine the true nature of the ores beyond the fact that they are metamorphic (metamorphosed) deposits. However, modern consensus would class them as originally syngenetic sedimentogene of volcanic exhalative deposits. General reviews of the Caledonian metallogenies have recently been published by Grip and Frietsch (1973), Vokes and Gale (1976), and Vokes (1976, 1979). The reader is also referred to Chapter 2 of the *Memoir* accompanying the *Metallogenetic Map of Europe* and to the *Review of Caledonian Stratabound Sulfides* to be published as Project 60 of the International Geological Correlation Programme.

The Precambrian areas involved or included in the Scandinavian Caledonides show a variety of deposit types, the majority of which appear to be themselves of Precambrian age, though exact dating has in most cases not been attempted. There would appear to be a general increase in abundance of these deposits in a northeasterly direction along the orogenic zone.

The Precambrian areas of west-central Norway are characterized mainly by vanadium-bearing magnetite-ilmenite deposits associated with metabasic rocks. For the present, production comes from the large deposit at Rødsand, though the nearby deposits at Meisingset are currently being readied for production. These northwestern gneiss areas are also well-endowed with large bodies of fresh dunite which are exploited on a considerable scale for olivine sand and rock.

On the island of Senja, off the coast of Troms at about 69° N, the small metasedimentary graphite deposit of Skaland has been in production for some years. In 1976 this mine produced nearly 8,700 metric tons of concentrate from 35,000 metric tons of ore. The general area of Lofoten-Vesterålen-Troms is characterized by Fe-Ti deposits, with lesser Fe, Ni, Mo, and Cu deposits, none of which has yielded production of any significance.

The tectonic windows exposing the low metamorphic Proterozoic Raipas Group rocks in the coastal districts of Finnmark are characterized mainly by copper deposits of different types. Until recently copper concentrates were produced from the low-grade (0.7% Cu) deposit at Repparfjord where chalcopyrite, bornite, and other sulfides occur as disseminations in arenites.

In the eastern Caledonides, at Ruotevare in Sweden, Fe-Ti oxides are associated with an anorthosite-gabbro complex of probable Precambrian age.

The first phase of ore deposition which can be ascribed to the early development of the Caledonian geosyncline in late Precambrian (Vendian) times is represented by deposits of predominantly lead sulfides in the latest Precambrian to Cambrian sandstones overlying the peneplaned surface of the Baltic Shield. Deposits of this type are distributed along practically the whole length of the eastern margin of the Caledonides, from Hardangervidda in central Norway, northward through central and northern Sweden, to the Porsanger area of Finnmark in the north of Norway, a distance of some 1,200 to 1,300 km.

The mineral associations of the deposits are dominated by galena occurring as interstitial, often poikilitic, fillings between the clastic grains of the arenites or as coatings on the fractures in these rocks. Sphalerite is generally present in small amounts and is a prominent constituent only in some deposits. Minor amounts of pyrite, calcite, barite, and fluorite occur. Investigations of possibly economic stratabound fluorite deposits have been carried out in an area about 100 km south of Laisvall.

Several of these deposits in Sweden are of actual or potential economic interest, two of them having been in production for some time. These are at Laisvall at 66° N latitude, where about 80 million metric tons of 4 percent Pb ore were originally present, and at Vassbo at 62° N latitude, where the original reserves were about 3 million metric tons grading 5.7 percent Pb, 0.3 percent Zn, and 18 g/metric ton Ag. In 1976 these deposits produced together 1.6 million metric tons of ore. The recently (1972) discovered deposit at Guttujaur is now being prepared for mining.

In Norway, deposits of this type have been the object of increasing prospecting activity in recent years, though as yet no potential orebody has been indicated (Bjørlykke et al., 1973).

The Swedish representatives of the class are the subjects of an extensive literature. Reference may be made to the previously published works of Grip (1954, 1960, 1967), Tegengren (1962), and Grip and Frietsch (1973) and to present articles by Rickard et al. (1979b) and Christofferson et al. (1979) for details regarding the deposits.

Relatively little has so far been published regarding the occurrences of this type on the Norwegian side of the international border. The deposits which have been discovered are on the whole small, though numerous and widespread.

The stratabound lead-zinc deposits of the Caledonian front zone occur in both latest Precambrian (Eocambrian) and Lower Cambrian arenites as well as allochthonous units. Localization of the mineralization in relation to clay-rich impounding layers, as well as to joints and other structures, has been the main argument for an epigenetic interpretation, whereby either the mineralizing solutions were derived from the inner parts of the Caledonides during palingenesis (Grip, 1954, 1960) or the lead was perhaps partly leached from the overlying alum shales (Grip, 1967). A hypothesis relating mineralization to deep hinge zone fracturing at the western margin of the Baltic Shield during Ordovician or possibly Silurian deposition has been forwarded by Gee (1972).

Barkey (1964) and Carlson (1970) advocated a preorogenic, possibly diagenetic, origin, and a similar view has been presented by Bjørlykke et al. (1973) who considered the deposits to be of the red-bed type. Grip and Frietsch (1973) have presented a hypothesis for the genesis of the deposits which presupposes initial, sedimentary accumulation of lead, derived from the weathering of rocks on the Precambrian peneplane, followed by mobilization and transport eastward during the Caledonian orogeny and redeposition in structurally favorable localities along the Caledonian front. That the question of the genesis of these important and interesting deposits is still the subject of considerable discussion will be clear from the articles on specific deposits in the present volume (Rickard et al., 1979b; and Christofferson et al., 1979). The discussion will obviously not be terminated for some time to come.

Vein deposits with similar parageneses occur both in the Precambrian east of the Caledonian front, in the Precambrian windows in the west, and in the allochthonous units. At Nasafjäll extensive quartz veining in a zone associated with probable Eocambrian-Cambrian quartzites and dark schists contains pyrrhotite, galena, and sphalerite. The Alkavare and Silpatjåkkå vein deposits are also generally regarded as belonging to the lead-zinc-fluorite province, although they clearly crosscut the rocks of the Seve-Køli nappe complex. There is a general tendency for vein deposits in the west to show much higher Ag contents than the stratabound lead-zinc deposits of the Caledonian front (Grip, 1967; Grip and Frietsch, 1973). Investigations of the isotopic composition of the ore lead have been made by Wickman et al. (1963) and Moorbath and Vokes (1963) from deposits in both Sweden and Norway. Practically all the samples investigated showed considerable excess of radiogenic lead, giving anomalous, negative model ages for the galenas.

Stratabound deposits of uranium have in recent years been investigated in the parautochthonous Caledonides at Tåsjø in central Sweden. The host rock is here a phosphatic, calcareous sandstone-siltstone of upper Tremadocian to lower Arenig age, overlying alum shale of Upper Cambrian and probably lower Tremadocian age. The uraniferous layers in northwest Tåsjö, now strongly folded, are up to 6 m thick and contain 250 to 500 ppm uranium concentrated in apatite (Andersson, 1971). The mineralization is considered to be of sedimentary origin (Armands, 1970).

Polymetallic, massive to disseminated sulfide deposits of the Kieslagerstätten type are present in large numbers in the inner parts of the Scandinavian Caledonides. Especially in Norway these have been historically of considerable economic importance and even today are the basis of important copper, zinc, and lead production.

As can be seen from the map (Fig. 8) deposits of the polymetallic sulfide type are found at intervals over a distance of some 1,400 km and define what is in effect a single metallogenic belt or zone of considerable significance.

The majority of the deposits are spatially related to volcanic and mixed sedimentary and volcanic rocks deposited during the geosynclinal stages of the developing Caledonian orogen. The volcanic rocks are the results of extrusive activity, beginning in the Late Cambrian and reaching a maximum activity in Lower Ordovician times, though it continued intermittently at least into Silurian times. In the Trondheim district of Norway, massive sulfide deposits are found in the Early Ordovician Støren mafic volcanites and their supposed equivalents, whereas in the south central part of this district, minor volcanic units, both older and younger than the Støren rocks, exhibit associated deposits (Nilsen and Mukherjee, 1972). There is evidence of minor volcanic activity in rocks of supposed Silurian age in Norway (Rui, 1972), and in Sweden important sections with acid and mixed volcanic rocks are considered to belong to this period. According to Zachrisson (1969, 1971) the important Swedish deposit of Stekenjokk lies in quartz keratophyres of Silurian age.

The ores are generally of the stratabound type. Sometimes they can be shown to be stratiform and wholly concordant with their country rocks, though in the majority of cases, the orebody morphology has been determined by later events so that the original relations are difficult to decipher. The majority of the orebodies have been described variously as plates, lenses, pencils, rulers, etc., and most are elongated to varying degrees along axes which may or may not coincide with a fold-axial, or other linear, direction in the country rocks.

Figure 8 also shows that these sulfide deposits are disposed in a series of geographic groupings along the length of the orogen. The groupings are probably partly due to original favorable depositional environments and partly to the accidents of later deformation and erosion. The groupings, or districts, vary considerably in importance, measured by the number of deposits present and their aggregate tonnages, and their relative importance has varied with time. The most important districts at the present time are the Trondheim district of Norway, the Grong-Västerbotten district in Norway and Sweden, the Rana district, mainly in Norway, and the Sulitjelma district of Norway.

The Trondheim district has a history of mining dating back to the 17th century and has yielded large quantities of pyritic ores and concentrates. At present only three of the numerous known deposits are in production. The largest of these, that of Løkken, where the total quantity of sulfide (massive pyrite with almost equal amounts of Cu and Zn) was probably of the order of 25 million metric tons, has been worked since 1654. In 1976, 26,500 metric tons of Cu concentrate were produced from this deposit, which occurs in metabasaltic, often pillowed lavas of Lower Ordovician age. The Tverrfjell deposit at Hjerkinn in the southwest extremity of the district is probably almost as big as the Løkken deposit but has a production history dating from only 1968. The 1976 production amounted to nearly 25,000 metric tons of Cu and 10,000 metric tons of Zn concentrates. The deposit consists of steeply dipping lenses of massive sulfide in a metavolcanic-sedimentary succession now comprising amphibolites and schists of various types. At Killingdal, north of Røros, a highly elongated body of Zn-rich sulfides having an original tonnage of some 3 to 4 millions has been worked on a small scale for many years (Rui, 1973). The present yearly production is of the order of 39,000 metric tons of ore yielding 1,900 metric tons of Cu and 2,800 metric tons of Zn concentrates.

The Grong-Västerbotten district contains a number of significant massive sulfides bodies which have, relatively speaking, only recently been put into production. In Norway the main ores are those at Skorovas, Joma (Grong), and Gjersvik, of which the first two are currently being worked. The older mine, Skorovas, began production in 1952 and up to 1975 had produced 3.3 million metric tons of Cu- and Zn-bearing pyritic lump ore. In 1976 this mine produced 7,500 metric tons of Cu and 3,500 metric tons of Zn concentrate from 260,000 metric tons of ore. Due to lack of economic reserves the mine is expected to be closed in the course of the next 2 to 3 years. The deposit occurs as flat-lying lenses in a tholeiitic-calc alkaline greenstone sequence of possibly Middle Ordovician age (Halls et al., 1977). The Joma deposit was put into production in 1972 with economic ore reserves of some 7 million metric tons of mainly copper-bearing sulfides. The orebody is a massive, stratiform, deformed layer in basaltic greenstones of tholeiitic character, probably of comparable age to the Skorovas volcanics but contained in a lower nappe unit. Joma's production in 1976 amounted to 330,000 metric tons of ore yielding 26,400 metric tons of Cu and 4,700 metric tons of Zn concentrate.

Situated in an even lower nappe unit in the Swedish Caledonides of Västerbotten, the Stekenjokk Zn-Cu sulfide orebody reached production stage as late as 1976 with an annual production amounting to 420,000 metric tons of ore. The main Stekenjokk ore contains reserves of the order of 15 million metric tons at 1.5 percent Cu and 3 percent Zn, in the form of a highly elongated body several kilometers in length (Juve, 1974, 1977).

The Sulitjelma district of northern Norway has been a major producer of copper concentrates since the beginning of the present century. Present production (1976) is of the order of 6,580 metric tons of blister Cu from 412,000 metric tons of ore. Altogether some ten separate orebodies have been worked at various times. They are in the form of thin plates of sulfide with large areal extents located at different stratigraphic-structural levels in greenstones, greenschists, and amphibolites and underlying pelitic metasediments most probably of lower Paleozoic age.

The sulfide deposits of the Rana district show considerable dissimilarities to those of the districts just reviewed. Their lithological settings are mainly high-grade schists and gneisses, probably of sedimentary origin with very little obvious evidence of volcanic components, at least of mafic character. The main ores, including the two producing deposits of Bleikvassli (Vokes, 1963, 1966) and Mofjell (Saager, 1966, 1967), are predominantly Zn-Pb ores, with relatively minor amounts of Cu. Recent age dating by A. Råheim (pers. commun.) would also indicate that the host rocks to these ores are not of lower Paleozoic age, as are the majority of the Scandinavian Caledonian sulfides, but of Proterozoic age.

Stratabound, most probably syngenetic, deposits of oxide iron and lesser manganese ores are reported from several localities in the assumed lower Paleozoic sequences of the Caledonides. The deposits appear to show two lithological associations, a sedimentary and a volcanic. Deposits of both associations are economically important in Norway. The main iron ore deposits occur in three separate districts, two showing mainly sedimentary lithologies, the third mainly volcanic. The important ores of the Rana district just south of the Arctic Circle are regarded as of sedimentary origin, being originally deposited in silicate and oxide facies (Bugge, 1948). The main deposits are at Storforshei in Dunderlandsdal, though smaller deposits occur both to the north and the south, in the Salten and Mosjøen districts, respectively.

In the Dunderlandsdal deposits, at present being worked on a large scale by A/S Norsk Jernverk, Rana Gruber, the ore minerals are both magnetite and hematite (specularite). Bugge (1948) suggested that the magnetite in the ores is the result of the partial reduction during metamorphism of a previously homogeneous hematite orebody. According to this authority, iron deposition took place in the form of ferric hydroxide and hematite was produced during diagenesis. The source of the iron was considered to have been a weathering surface, while deposition took place subsequently in shallow water (Bugge, 1948). In 1976 Rana mines milled 3.32 million metric tons of ore to yield 1.18 million metric tons of concentrates.

In the Ofoten-South Troms district to the north the typical ore mineral is magnetite, whereas in the Rana district magnetite and hematite commonly occur together. The deposits are found in a belt extending from Ofoten northeastward toward Tromsø. The orebodies are of limited thickness and have no economic importance today. The previously mentioned age determinations of A. Råheim (pers. commun.) also apply to the host lithologies of the Rana and Ofoten iron ores. Thus they may prove to be, not of lower Paleozoic, but of Proterozoic age.

Iron ore deposits showing volcanic associations occur in the Fosen district of Trøndelag, north of Trondheimsfjord. According to Carstens (1955) the deposits of this district represent a transitional type between the dominantly sulfide iron deposits of the central parts of the geosyncline and purely oxidic iron deposits, since they contain a small percentage of pyrite in mainly magnetite mineralization. They may perhaps be compared with the Lahn-Dill type of iron deposition, though they have undergone metamorphic deformation and recrystallization subsequent to their initial formation. The only economic deposit of this type is that at Fosdalen (Malm), northeast of Trondheim (Fig. 8), from which almost 25 million metric tons of ore have been mined to yield about 12 million metric tons of concentrates since production started 1912. The orebodies comprise thin layers of dominant magnetite together with about 5 percent pyrite and small amounts of chalcopyrite, which are enclosed concordantly in metavolcanic rocks (lavas, tuffites, and agglomerates) and geosynclinal metasediments.

Deposits of nickel-(copper-iron) sulfides associated with syntectonic ultramafic to mafic intrusive bodies have been found at several localities along the Caledonian orogenic belt. On the whole they have so far not proved to be of any great economic importance, but investigations are still continuing at several localities where small-scale production was recorded in the past century.

In the Råna area of the Ofoten metallogenic district, several deposits occur in connection with ultramafic bodies in a large syntectonic norite intrusion. Both impregnations and more massive sulfide concentrations can be found and at least one deposit holds a promise of containing economic quantities. Investigations are still proceeding (Boyd and Mathiesen, 1979).

In central Norway, near the eastern margin of the Jotunheimen complex at Espedalen, nickel-copper sulfides were known and worked as early as the 17th century and are the subject of a detailed reassessment at the present time. They are spatially related to mafic and ultramafic bodies in a large, allochthonous anorthositic complex.

A Caledonian intrusive rock of great economic importance in itself is the body of nepheline syenite on the island of Stjernøy off the coast of west Finnmark at about 70° N latitude. This body is being worked

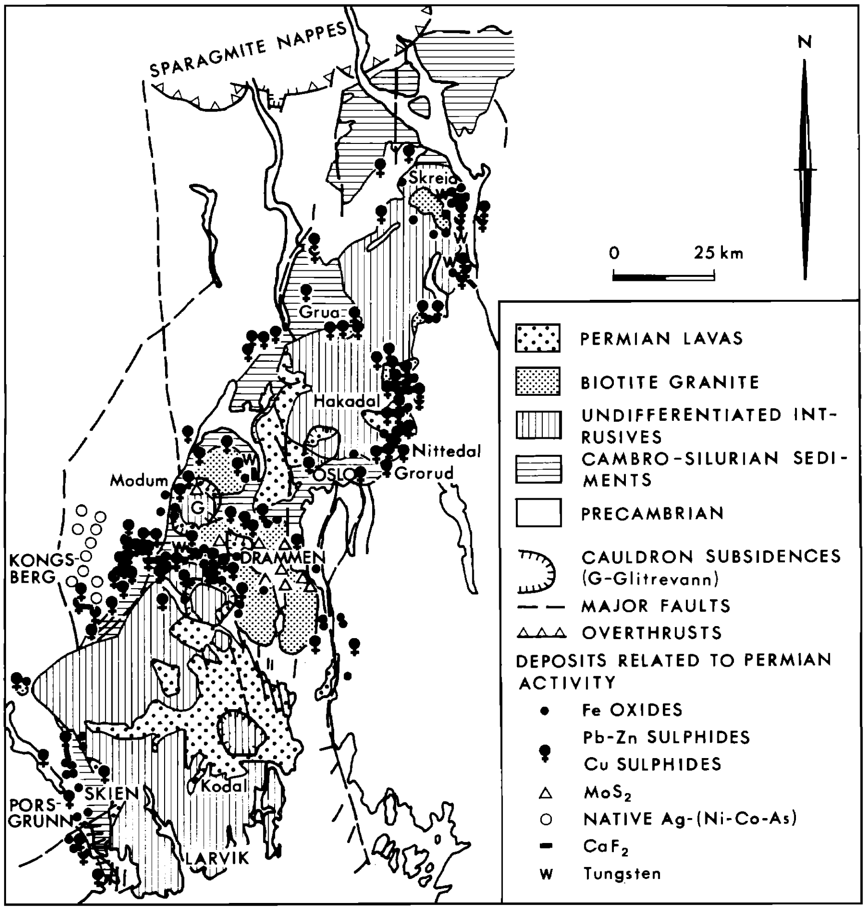

FIG. 9. The mineral deposits of the Oslo igneous province (modified after Vokes and Gale, 1976).

at the present time to produce a nepheline-feldspar concentrate which goes to the glass and ceramic industries (see Geis, 1979).

Mineral Deposits in the Sedimentary Platform Cover of the Baltic Shield

To the east and southeast of the Caledonian front in both Sweden and Norway occur scattered remnants of the lower Paleozoic and later sedimentary rocks which were deposited on the late Precambrian peneplane of the Baltic Shield. Lower Paleozoic (Cambro-Silurian) remnants in central and southern Sweden are mainly unaffected by later tectonic movements, but in the Oslo region of Norway they have been deposited in open folds with northeast-trending axes as a result of the Caledonian movements.

Cambro-Silurian and Mesozoic (Triassic to Cretaceous) rocks are also present in the southernmost part of Sweden (Scania), but economic interest is directed mainly toward the Cambro-Silurian outliers in south-central Sweden and, to a much lesser extent, in the Oslo region of Norway.

The main object of interest are the so-called alum shales of Middle and Upper Cambrian age. In south-central Sweden these shales occur horizontally, tectonically undisturbed, and up to some tens of meters in thickness. They contain interesting uranium deposits, mainly in the *Peltura scarabaeoides* zone in the Upper Cambrian, a horizon which covers large areas. The economically most important deposit, Ranstad, is situated in Billingen, Västergötland, and covers more than 500 km^2. The uranium-bearing layer is 2.5 to 4.0 m thick. The grade is 0.025 to 0.32 percent uranium and the technically recoverable quantity of uranium is at least 300,000 metric tons. Ranstad is one of the largest low-grade uranium deposits in the world. Since the beginning of the decade, the aim of the mining has been total recovery of all the potentially economic constituents. The shales contain locally (especially in Närke) high amounts of organic material and some hydrocarbons; in addition there are relatively high contents of vanadium, molybdenum, magnesium, sulfur, nickel, and chromium, which can all be recovered together with such elements as aluminum and potassium. At present (1978) an extraction of about 1 million metric tons of shale per year is planned.

In Scania, in southern Sweden, there are chamosite-goethite-siderite ores in 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.

Mineral Deposits Connected with Paleozoic Rifting

The Oslo paleorift

In the southwest foreland area of the Caledonian orogenic belt, in the Oslo paleorift zone (Dons and Larsen, 1978) of southwestern Scandinavia, metallic and nonmetallic mineral deposits, apparently genetically connected with tectonic and magmatic activity related to rifting which culminated in Permian times, occur in considerable numbers and variety. With some few important exceptions, these deposits have not proved to be of great economic importance, actual or potential. They are, however, of great scientific importance and interest in that they are the results of the youngest of the metallogenetic epochs recorded in the region.

The main features of the geology of the Oslo paleorift, including the metallogeny, have recently been discussed in a publication of the Geological Survey of Norway (Dons and Larsen, 1978) to which interested readers are referred.

The paleorift is represented at the present-day land surface chiefly by extensive outcrops of intrusive and extrusive igneous rocks, mainly of Permian age, and by lesser outcrops of Permian sedimentary rocks. These have an irregular fringe or border of lower Paleozoic sedimentary rocks, preserved from erosion by the down-faulting associated with the rift system. These lower Paleozoic rocks lie unconformably on the peneplaned surface of the Precambrian rocks of the Sveconorwegian part of the Baltic Shield (Fig. 9).

In addition to events recorded in the Oslo region per se (see Dons and Larsen, 1978, p. 9–10) the late Paleozoic events in the southwest Scandinavian region are also represented by a number of important tectonic lineaments in the Precambrian rocks surrounding the region. The more important of these lineaments—fault, breccia, and mylonite zones—along which the late Paleozoic movements took place represent tectonic lines which were probably originally active as early as late Precambrian. Of particular interest from a metallogenetic point of view are the southerly expressions of the Oslo rifting which are present along the Norwegian Skagerrak coast and in southernmost Sweden (Scania).

The mineral deposits connected with the rifting events can be said to comprise two main groupings: those within the magmatic rocks of the Oslo province proper, or closely connected to them (roughly within the contact-metamorphic aureoles); and those occurring within the surrounding lower Paleozoic sedimentary rocks and the Precambrian rocks of the Sveconorwegian province of the Baltic Shield. The deposits comprise oxidic ores of Fe, Mn, Ti, and W; sulfidic ores of Zn, Pb, Cu, Mo, and Bi; and ores of native silver/Co-Ni arsenides, as well as fluorite, barite, apatite, and, locally, beryl and helvine occurrences.

Several different types of deposit can be distinguished, each showing a distinct spatial and genetic relationship to the supposed parent igneous rocks. These types have been summarized by Ihlen and Vokes (*in* Dons and Larsen, 1978) as follows.

Magmatic segregation deposits: These are not at all frequent in the Oslo province, though one representative of this class is among the economically most significant deposits yet found in the region. This is the P-Ti-Fe-bearing jacupirangite body at Kodal in Vestfold, just north of Larvik (Nielsen, 1967; Bergstøl, 1972). The deposit is situated in the northern part of a large larvikite massif in the southern area of the Oslo region, and has the form of a large dike, 20 to 35 m wide and about 2 km long in an east-west direction, dipping steeply to the south. It has been estimated that 50 million metric tons of ore are potentially available by open-cast mining. Exploitation has so far been hindered by metallurgical difficulties.

Vein deposits within the Oslo province proper: Vein deposits carrying mainly sulfides of Mo, Cu, Pb, and Zn occur scattered in most rock types encountered within the Oslo region. Among the intramagmatic deposits of this type, the most noteworthy are the molybdenite-bearing quartz veins and related types in the biotite granite massif of the Drammen district.

Possible porphyry-type molybdenum mineralizations: Possible porphyry-type molybdenum deposition has recently been recognized at several places within the Oslo province. An account of the occurrences in the Glitrevann cauldron north of Drammen (Fig. 9) is given by Geyti and Schønwandt (1979). These discoveries may prove to be the most important ore geological developments in the Oslo province in recent decades, but the investigations are still in their infancy.

Contact-metasomatic deposits: These are the classical ore deposits of the Oslo region, though they are now definitely of much more historical than actual or potential economic importance. They are situated along the exocontact at the immediate junction between granites and adjacent sedimentary rocks, or a short distance away, rarely exceeding a few hundred meters. In the latter case, the ore and accompanying alteration is almost always spatially related to igneous dikes emanating from the main magmatic bodies.

The metals represented in the Oslo contact deposits are, classically, Zn, Pb, Cu, and Fe, with lesser Bi, Ni, and Co, but in recent years numerous tungsten mineralizations (as $CaWO_4$) have been discovered within the thermal aureoles. So far these have not shown any economic potential.

Vein-type deposits in the Precambrian basement and overlying lower Paleozoic sediments: These deposits, of varying mineralogy, occur within a 20- to 25-km-wide zone around the plutonic intrusives of the Oslo region, as well as in connection with the already-mentioned rift structures along the Skagerrak coast of Norway and in southern Sweden (Scania). Deposits of this type were worked for native Ag over a period of 300 years in the Kongsberg area to the west of the Oslo province but are now apparently exhausted. Potentially economic deposits of fluorite in the Kongsberg and Porsgrunn areas, as well as at Brantevik and Onslunda in southernmost Sweden (formerly mined), are also included in this category.

The Sokli Carbonatite Complex

The complex, in northern Finland, was discovered by Rautaruukki Oy in 1967 by airborne geophysical survey. It is the most western representative of the Kola alkalic rock province. The environment of the Sokli carbonatite is Archean gneiss, but the age of carbonatite ranges from 334 to 378 m.y. (Vartiainen and Woolley, 1974). According to Vartiainen and Paarma (1979), the location of the carbonatite complex was controlled by the Kandalaksha deep fracture zone, which can be traced by Landsat imagery as a lineament over 150 km long. The complex consists of a magmatitic core, metacarbonatite and metaphoscorite zones, and a transition zone that passes into the large fenite aureole surrounding it. The carbonatite body covers an area of about 20 km^2, and its upper part is weathered to a depth of 10 to 100 m. Phosphorus ores as apatite-francolite regolith and hydromica-apatite residue occur in the weathered part, and pyrochlore and magnetite-apatite ores in the deeper parts. The pyrochlore mineralization is characterized by enrichment of U and Ta and local Th-pyrochlore. Magnetite-apatite ores also occur in the deeper parts. The complex is still under investigation.

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