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The main metallogenic features
of Finland

By Aarno Kahma



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**THE MAIN METALLOGENIC FEATURES
OF FINLAD**

BY

AARNO KAHMA

WITH TWO TABLES AND ONE APPENDED MAP

Second printing 1979

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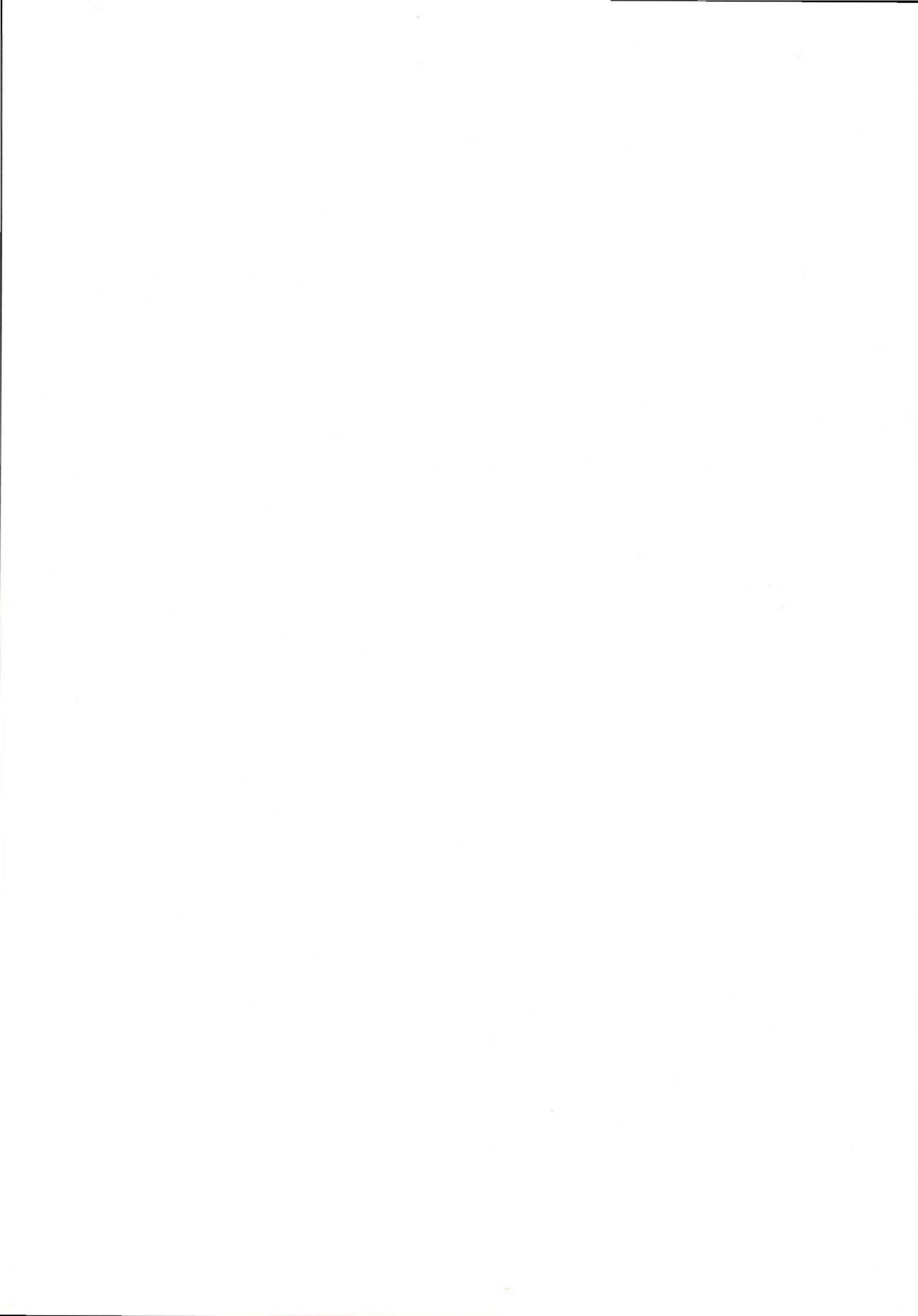
The distribution and genetical characteristics of the sulphidic copper, nickel, zinc and lead ores as well as the chromium, vanadium and iron deposits in the Early and Middle Precambrian bedrock of Finland are outlined in the text. Information on other mineralizations is included in the tables and on the map, scale 1:2 000 000. The map is an adaptation to Finnish conditions of the Metallogenic Map of Europe. A bibliography arranged by mineralizations and a list of other literature relevant to the subject are included.

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INTRODUCTION

The Baltic Shield, which covers a total area of 1 140 000 square kilometers, comprises the Precambrian areas of Finland, Norway and Sweden and the north-westernmost part of the U.S.S.R. Together with the Paleozoic formations of Scandinavia, these areas were classified as belonging to the Fennoscandian region (Ramsay 1898).

The bulk of the geological formations occurring in Finland consists of Precambrian plutonic and metamorphic rocks varying in age from 1 700 to 2 800 million years. These rocks are generally overlain (95—97 %) by thin Quaternary deposits composed of till, sand and clay and averaging only between 6 and 9 m in thickness (Okko in Rankama 1964). There are also tens of thousands of lakes and ponds.

The Precambrian formations of Finland and the most important mineralizations associated with them can be classified as has been done in Table 2 and Map 1. The Precambrian is divided there, according to Rankama and Welin (1972), into Early, Middle and Late Precambrian eras, the ages of which are correspondingly > 2 500 m. y., 2 500—1 400 m. y. and 570—1 400 m. y.

Early Precambrian (Archaean) formations (> 2 500 m. y.) are mostly met with in the eastern parts of Finland, where they merge into corresponding formations on the Soviet side of the national border. The most extensively spread out of the Early Precambrian formations is the pre-Karelian granite-gneiss area; in the still older (ca. 2 800 m. y.) metavolcanics and metasediments, small magnetite deposits have been found.

Of the Middle Precambrian formations, the rocks of the Svecokarelian folded region make up the largest part of the area of Finland. Included among them are crystalline schists of volcano-sedimentary origin as well as ultrabasic, basic, intermediate and acidic intrusions of the same age as or younger than the schists and, further, granitoids. The economically most important ores in the country are associated with these formations.

At the beginning of the century, the schist zones running from central Sweden to the southern parts of Finland in an approximately WSW-ENE direction were classified as Svecofennian, and the schists running from Lake Ladoga in a NNW

direction as Karelian formations. Now they are viewed (T. Mikkola 1953, Metzger 1959, Simonen 1960 a and b, 1962, 1964, 1971, Eskola 1961, 1963) as belonging to the same Svecokarelicid geotectonic cycle, the evolutionary sediments of which are met with in the eastern and northern parts of the country close to the ancient pre-Svecokarelicid basal complex, and the geosynclinal sediments, on the other hand, in the southwest. The old terms »Svecofennian» and »Karelian» are used nowadays mainly in a geographical sense. There is reason to emphasize the fact that the significance of radiometric age determinations¹⁾ to the development of present concepts has been of a fundamental nature.

The anorogenic rapakivi massifs that occur in the southeastern and southwestern parts of Finland and contain small veins of tin and lead are among the youngest (1 500—1 700 m. y.) of the Middle-Precambrian formations.

The areas of Jotnian sandstone and siltstone at least a kilometer thick occurring in western Finland date back to the oldest part (1 300—1 400 m. y.) of the Late Precambrian. These rocks are met with in the grabens of Pori and Muhos bounded by faults running approximately SE-NW. The arkose sandstones of southwestern Finland, moreover, are penetrated by hypabyssal diabase dykes (1 300 m. y.), which probably represent intrusion channels of plateau basalts.

The formations of the Paleozoic folded region only just barely touch Finnish territory along the Norwegian border. An economically more interesting Paleozoic formation is the carbonatite plug of Sokli (4 Paarma 1970) in Archaean surroundings in eastern Lapland; associated with it are mineralizations of P, Nb, Fe, REE, Th and U. Unfolded Paleozoic and Jotnian formations are known to exist also at the bottom of the Gulf of Bothnia (Veltheim 1962, 1969; Winterhalter 1972).

The most important structural features of the bedrock are well-preserved schist chains and areas of volcanic and sedimentary origin belonging to both Archaean and Svecokarelicid folded regions as well as faults and fractures. A large number of investigators during the present century have dealt with the faults as well as associated block structures and displacements (Tanner 1911, Sederholm 1913, 1930, Hausen 1940, Brenner 1941, Edelman 1949, 73 Tuominen 1957, Marmo 1959, Härmä 1961, 1963, 1966, Kujansuu 1964, Teisseyre *et al.* 1969, Mikkola 1971, Talvitie 1971, Gaál & Rauhamäki 1970). What fractures and faults originated and moved during the Svecokarelian orogeny of the platform stage that followed it or even during the Quaternary period is a matter of conjecture.

In the view of Paarma and Marmo (1961), Mikkola and Niini (1968), Mikkola (1971) and Gaál (37 Gaál 1972) the movements associated with the fault zone running in a northwesterly direction from Lake Ladoga controlled the genesis of the sulphide ores met with in the vicinity of this zone. The present author also emphasizes the importance of other suitable circumstances in the formation of the sulphide ore belt discussed more closely on p. 13—14.

¹⁾ The majority of the radiometric age determinations presented in this publication were carried out by Dr. O. Kouvo and his associates at the laboratory of the Geological Survey of Finland, in the Annual Reports of which the figures were published between 1964 and 1972.

THE MAIN MINERALIZED AREAS

The most important mineralizations in Finland are listed in Tables 1 and 2. Table 1 shows the annual production of the mines, the tons of ore cumulatively calculated up to the year 1970, and the known reserves. In the table, the information on the sulphide ores has been drawn in the main from Isokangas' (1971) article.

The location of the mineralizations is shown on the appended Map 1. Each mineralization is designated by a reference number, which is used also in the text, in the bibliographic references (in italics) and in the tables.

Although magnetite deposits of small and medium size (Huhus, 44) have been found in Early Precambrian formations (ca. 2 800 m. y.) in eastern Finland and molybdenite, now mined out, was discovered at Mätäsvaara (42 Kranck 1945), virtually all the ores worth mining are contained in the Middle Precambrian Sveco-karelic formations (1 800—2 300 m. y.).

Economically of great importance are the sulphidic copper and zinc ores occurring in crystalline schists, which are likely to contain noteworthy amounts of sulphur, iron, cobalt, nickel, lead, gold and silver, as well as the nickel-copper ores

TABLE 1
Output and reserves of the main ore deposits in Finland

No.	Name	Time of operations	Main products	Annual output	Mined up to	Ore reserves	Known amounts of ore
					1.1.1970	1.1.1970	
					in millions of tons		
11	Rautuvaara (Kolari)	(1975)	Fe	(0.8)	18	18	
14	Kärväsaara } (Misi)	1959—	Fe	0.61	3.3	3.5	6.8
15	Raajärvi }						
19	Kemi (Elijärvi)	1967—	Cr	0.35	0.25	large	large
20	Mustavaara	(1975)	V, (Fe)	(1.6)			
27	Lahnaslampi	1969—	talc	0.2	0.2	8.0	8.0
28	Otanmäki	1952—	V, Fe, Ti	1.2	13.4	20	34
29	Lampinsaari (Vihanti)	1954—	Zn, Cu, Pb, S	0.71	6.8	15	22
31	Hitura	1970—	Ni, Cu	0.17		large	large
32	Pyhäsalmi	1962—	Cu, Zn, S	0.79	5.1	25.8	31
37	Kotalahti	1959—	Ni, Cu	0.48	4.3	8.5	13
38	Luikonlahti	1968—	Cu, Co, Ni, Fe, S	0.52	0.75	large	large
39	Paakkila	1919—1969	asbestos	0.04	6.0		
40	Outokumpu	1913—	Cu, Co, S	0.49	19.7	7.7	27
41	Vuonos	1971—	Cu, Ni			28	28
42	Mätäsvaara	1940—1947	Mo		1.2		1.2
47	Hammasmahti	1972—	Cu, Zn, S	0.4			5
49	Karsikumpu (Hällinmäki)	1966—	Cu	0.6	2.7		3.3
55	Korsnäs	1961—	Pb, REE	0.1	0.6	0.3	0.9
56	Haveri	1942—1960	Au, Cu		1.5		1.5
58	Ylöjärvi	1943—1958	Cu, W		4.0		4.0
73	Orijärvi	1760—1954	Cu, Zn, Pb		1.2		1.2
74	Aijala	1949—1958	Cu, Zn, S		0.8		0.8
»	Metsämonttu	1952—	Pb, Zn	0.08	1.0	0.4	1.4
75	Kimito (Kemiö)	1966—	feldspar	0.13			
77	Jussarö (Jussaari)	1961—1967	Fe, Mn	(0.2)	1.7	23—60	25—60

contained in basic or ultrabasic rocks. Over 90 per cent of the mined sulphide ores and known reserves (reckoned in tons) belong to deposits that are situated in a belt from about 40 km to 150 km broad and at least 400 km long running from Lake Ladoga diagonally in a SE-NW line across Finland on the northeastern side of the deep negative gravimetric anomaly (ca. 20 mgal) shown on Map 1. In the following, it will be referred to as the Main Sulphide Ore Belt. It includes, according to the terminology proposed by Chatalov (in Bogdanov *et al.* 1967), the Outokumpu Ore District and the ore zones of Vihanti and Kotalahti.

On the southwestern side of the Main Sulphide Ore Belt, there occur rather small sulphidic, copper, zinc, lead and nickel ores, like the deposits at Karsikumpu (49), Ylöjärvi (58), Haveri (56), Orijärvi (73), Aijala-Metsämonttu (74), Korsnäs (55), Petolahti (54), Sääksjärvi (57) and Stormi (64); small beryllium-, niobium- and lithium-bearing pegmatite deposits, like the ones at Haapaluoma (51), Kaatila (50), Eräjärvi (59), Tammela (69, 70) and Kimito (75). Further, on the north shore of the Gulf of Finland, there are the magnetite occurrences of medium or small size met with at Jussarö (77) and Nyhamn (79).

On the northern side of the Main Sulphide Ore Belt, moreover, there are the important titanium-vanadium magnetite deposits of Otanmäki (28) and Mustavaara (20) as well as the large chromite deposit of Kemi (19), at the far end of the Gulf of Bothnia. Known in northern Finland, in addition, are a number of magnetite deposits of small or medium size — in the area of Misi (14, 15) and Kolari (9—11) — and there is the extensive Kittilä district, north of the Arctic Circle, where interesting copper (7—8) and iron-manganese mineralizations (5) are under investigation. In eastern Lapland, close to the Soviet border, there is the Hercynian carbonatite plug of Sokli (4). It was discovered a few years ago (4 Paarma 1970) and the possibilities of the economic exploitation of which are currently being investigated. In the granulite area in the northern part of Lapland, furthermore, quite a few small placer gold deposits are known (1 Stigzelius 1954).

Main Sulphide Ore Belt

The sulphide ores of the Main Sulphide Ore Belt are divided on the map, chiefly on the basis of their location, associations of elements and rocks and the isotopic composition of the lead, into the Outokumpu Ore District (38, 40, 41), Vihanti Ore Zone (29, 32, 35) (29 Rouhunkoski 1968) and Kotalahti Nickel-Copper Ore Zone (37 Gaál 1972).

Ni, Cu ores in the Kotalahti Ore Zone

The most significant part of the nickel-copper deposits known at present is located in the Ni, Cu ore zone of Kotalahti, which extends across a distance of over 400 km. Contained in the zone are, for example, the deposits of Hitura (31), Makola

(30), Kotalahti (37), Laukunkangas (61), and Parikkala (62). The deposits at Kotalahti, Hitura and Makola have been the target of mining operations.

The host rock of these, mostly pipe-like deposits is generally serpentinite, pyroxenite or norite. In addition to the main ore minerals, pyrrhotite, pentlandite and chalcopyrite, they are apt to contain magnetite, pyrite, sphalerite, cubanite, gersdorffite, millerite and bornite as well as, in the form of alteration products, in many instances also mackinawite, violarite and melnikovite (37 Haapala 1969, 37 Papunen 1970).

The U, Th-Pb determination made from the zircon of a differentiate (diorite) in the host rock of the Kotalahti ore has given an age of 1925 m. y. (37 Kouvo in Geological Survey of Finland, Ann. Rep. 1972 — abbreviated GSF in this text).

These nickel-copper deposits are classified as belonging to early magmatic ores. In the nickel-copper ore zone of Kotalahti, the mineralization has been controlled, according to Gaál (37 Gaál 1972), by the following four factors:

- (1) Occurrence in basic to ultrabasic plutonic rocks;
- (2) Connection with transcurrent faults;
- (3) Connection with domes and brachyantiforms;
- (4) Interaction between the basic magma and the country rocks.

Of the interactions in the country rocks caused by the hot basic magma, the most important is sulphurization. Häkli (1971) reports that at least a portion of the sulphur contained in the basic nickel-bearing magma derived from sulphide-bearing mica gneisses. The hot basic magma also naturally brought about facies changes in surrounding country rocks. The charnockites belonging to the granulite facies surrounding the intrusives originated, according to Gaál and Rauhamäki (1971), in this manner.

Cu, Co, Zn, Ni and S ores in the Outokumpu Ore District

Known to exist in the Outokumpu Ore District, which is located in eastern Finland, are half a dozen sulphidic copper deposits, which contain cobalt, zinc and nickel in noteworthy amounts as well as a little chromium. They occur in an area measuring about 60 km × 100 km in association with metamorphic Svecokarelic quartzites, mica and black schists, carbonate and skarn rocks and serpentinites. Of these deposits, Outokumpu, which was discovered in 1910, is economically the most important and it is also the one that has been described in detail.

The Outokumpu copper ore (40) is located in a brecciated Svecokarelic quartzite horizon running SW-NE for a length of about 4 km, on the hanging wall of which occurs an ophiolitic serpentinite lens and on the foot wall alternating layers of black and mica schist. The quartzite horizon is a quartzose rock that may have been originally a siliceous sinter (40 Huhma & Huhma 1970). The serpentinite lenses are surrounded in many places by dolomite, at the contacts of which against quartzite

chromium-bearing skarn minerals are to be found. The center of the ore deposit lies in an axial depression, and its lateral dip varies between 30° and 80° SE.

The discovery of the Outokumpu ore in 1910 proved of fundamental importance to the development of modern mining operations in Finland. Up to the end of 1970, the mine had yielded some 20 million tons of ore. The ore contains an average of 3.8 % copper, 28 % iron, 25 % sulphur, 1 % zinc, 0.12 % nickel, 0.24 % cobalt and 0.8 ppm gold, 9 ppm silver, 25—50 ppm selenium and 0.002—0.154 % tin as well as 0.01 % Cr₂O₃. The Ni:Co ratio varies in different parts of the ore, but it averages 1:2.

The principal minerals are chalcopyrite, pyrrhotite, pyrite and sphalerite. In addition, the minerals contents include cubanite, mackinawite, cobalt-pentlandite, magnetite, stannite, eskolaite and karelianite (40 Kouvo & Vuorelainen 1958, 40 Kouvo *et al.* 1963, 40 Long *et al.* 1963, 40 Thayer *et al.* 1964).

A large number of sulphur-isotope determinations (Kouvo 1958, 40 Mäkelä 1973) have been made from the ore. The total variation of the $\delta^{34}\text{S}$ values of 258 sulphide samples is 25 ‰ (+5.8 . . . —19.2 ‰). On the basis of the sulphur isotope proportions, Mäkelä has interpreted the stratification in the predominantly pyritiferous type of ore to represent the primary sedimentary structures. According to him, the sulphur-isotope compositions of the remobilizes produced by the metamorphism are on the average 2.6 ‰ lighter than the primary sulphide material.

The lead model age of the galena contained in the Outokumpu ore has been measured to be approximately 2 300 million years (Kouvo 1958, Kouvo *et al.* 1961), whereas the age of the uraninite is 1 900 m.y. (Kouvo & Tilton 1966). The higher lead model age in comparison with the U, Th-Pb age suggests that the lead contained in the ore had separated 2 300 m.y. ago from the uranium-thorium-lead surroundings, which caused the isotope composition of the lead to undergo continual change; but in the revolutionary phase of the Svecokarelicid geological cycle, it had become remobilized, in which case the age of the uraninite present in the ore, 1 900 m.y., would represent this stage (see, however, Kanasewich 1968).

Greatly deviating ideas have been advanced concerning the genesis of the Outokumpu ore — and specifically the origin of the ore solutions. In the earliest hypotheses, the ore was assumed to have been borne by the granite or the serpentinite on the hanging wall of the ore or by the intermediary subinclusion (40 Trüstedt 1921, 40 Mäkinen 1921, 40 Eskola 1933, 40 Väyrynen 1939, 40 Vähätalo 1953, 40 Diesler 1953). More recently, the ore has been viewed as originally syngenetic, and the remobilization of the sulphide material is regarded as having taken place in connection with the metamorphism (40 Borchert 1954, 40 Saksela 1957, Mikkola 1971, 40 Mikkola & Väisänen 1972, 40 Mäkelä 1973).

As for other ore deposits of the Outokumpu type, mention should be made of the copper-nickel ore at Vuonos, on the extension of the ore field, at a distance of about 6 km to the northeast (40 Huhma & Huhma 1970). It is also situated in an axial depression. Noteworthy, too, is the copper ore of Luikonlahti (38).

Zn, Cu, Pb and S ores in the Vihanti Ore Zone

The Vihanti Ore Zone (29 Rouhunkoski 1968) is located in western Finland on the northeastern side of a negative gravimetric anomaly running SE-NW and a fault zone associated with it. There, in an area about 40 km broad and at least 200 km long, some ten sulphide deposits containing varying amounts of zinc, copper, lead and barium as well as a little gold and silver are known to exist in highly metamorphosed Svecokarelicidic crystalline schists.

The crystalline schists include dolomites, mica schists, mica gneisses and acidic or basic volcanic rocks, which changed generally in connection with the mineralizations into skarn and cordierite-anthophyllite rocks.

The lead model ages determined from the galena contained in the sulphide deposits of the zone vary between 2 025 m. y. and 2 100 m. y. (Kouvo & Kulp 1961, 29 Rouhunkoski 1968). The zinc ore of Lampinsaari, which was discovered in 1947, is the best described of the deposits in the zone.

The Lampinsaari (Vihanti) zinc ore (29) is located in a highly metamorphic, Svecokarelicidic schist complex running ENE-WSW and composed of dolomite, skarn, quartzites and cordierite rocks. The most important of the zinc ore bodies lies at the northern margin of the monocline in drag-folded parts of the contact between the quartzite and the dolomite, where they replace the calcareous rocks. Among the surrounding rocks, noteworthy are the magnesium-rich gneisses, which contain an abundance of cordierite and which, like certain of the altered skarns, too, are assumed (29 Rouhunkoski 1968) to have formed metasomatically. The pyrite ores, on the other hand, are located at the southern edge of the schist complex, being in most instances contained in quartzite, which has been observed to be brecciated in many places.

The zinc ore contains an average of 10—11 % zinc, 0.53—0.85 % copper, 0.46—0.54 % lead, 2.3—2.5 % barium oxide, 0.4 ppm gold and 26—30 ppm silver.

The principal minerals met with are sphalerite, chalcopyrite, galena, pyrite and pyrrhotite, and the accessories are cubanite, valleriite, arsenopyrite, stannite, molybdenite, native gold and silver.

The lead model age obtained for the galena of the Lapinsaari ore is 2 050 m.y. and that for the lead separated from the feldspar contained in the granite penetrating the ore 1 830 m.y.

The origin of the ore solutions has been variously viewed as syngenetic (29 Mikkola 1963), magmatic (29 Rouhunkoski 1968) and metamorphic (40 Mikkola & Väisänen 1972, Mikkola 1971). The lead model ages (2 025—2 100 m.y.) of the galenas determined from the deposits of the Vihanti Ore Zone (30 determinations) and the lead model age (1 830 m.y.) of the granite penetrating the Vihanti ore may be explained, as in the case of Outokumpu, as follows: The lead material of the Vihanti Ore Zone appears to have become separated at a relatively early stage, 2 025—2 100 m.y. ago, into the volcanites or sediments and then as late as the revo-

lutionary stage of the Svecokarelicid cycle possibly remobilized and traveled to the present locations in the ore deposits — without the isotope composition of their lead having notably changed.

Another possible explanation is this: The lead model ages (2 025—2 100 m. y.) might represent a mixture of the remobilized pre-Svecokarelicid lead (2 800 m. y.) and the lead met with in the Svecofennidic formations of southwestern Finland (1 800—1 900 m.y.).

The first view impresses me as more acceptable, for it is hard to imagine 19 determinations from a zone over 200 km long giving the same reading within the margins of error of the method as the product of a random mixture. The age determinations made from the albite diabase sills occurring in the schists of northern and eastern Finland (Sakko 1971) also strongly support the first of the explanations.

Some 100 km to the southeast from the Lampinsaari zinc ore, there occurs the large Pyhäsalmi sulphide ore deposit (32), which contains an average of 0.85 % copper, 2.8 % zinc, 37 % sulphur, 33 % sulphidic iron and 4.9 % BaO. The principal minerals are pyrite, sphalerite and chalcopyrite as well as, along the margins of the deposit, pyrrhotite (32 Helovuori 1964). The massive sulphide ore is situated in a gently folded monocline of a schist complex composed of Svecokarelicid acidic and basic metavolcanics and cordierite-anthophyllite and sericite rocks. The lead model age determined from the ore is 2 055 m.y. (Kouvo & Kulp 1961).

About 60 kilometers southeast of the Pyhäsalmi mine, there occurs the Säviä (35) copper ore, which is situated in a partly brecciated schist complex composed of garnet, cordierite and anthophyllite-sillimanite gneisses and amphibolites. In addition to the chief mineral constituent, chalcopyrite, there are to be found in places sphalerite and pyrrhotite. The lead model age is 2 025 m. y. (Kouvo in GSF 1965, 1966).

Other copper ores

Deviating from the sulphide ore types described in the foregoing, there is the Hammaslahti (47) (Pyhäselkä) copper ore located in the southeastern part of the Main Sulphide Ore Belt. It lies at the western margin of a syncline composed of Karelicid phyllites, arkoses and black schists within a shear zone in impure arkose. According to Hyväinen's report (47 GSF 1970) there are to be met with in addition to the chief minerals, chalcopyrite and pyrrhotite, small amounts of sphalerite and galena as well as microscopic quantities of scheelite, mackinawite, cubanite, fahlerz and arsenopyrite. In contrast to the Outokumpu ore type, the Hammaslahti ore contains only little cobalt and nickel.

**The sulphide ores of southern Finland and the
Main Sulphide Ore Belt compared**

Known to exist on the southwestern side of the Main Sulphide Ore Belt, in addition to a few small nickel-copper deposits (54, 57 and 67) contained in Svecokarelidic crystalline schists, are the following sulphide deposits: Karsikumpu (49), Haveri (56), Ylöjärvi (58), Orijärvi (73), Aijala and Metsämonttu (74) and Korsnäs (55), of which the first deposits have been classified as pneumatolytic and the other ones as hydrothermal deposits (49 Hyväinen 1969, 56 Stigzelius 1944, 58 Himmi 1954, 58 Clark 1965, 73 Eskola 1914 and 1950, 73 Tuominen & T. Mikkola 1950). When these Svecofennian sulphide deposits are compared with the sulphide deposits of the Vihanti and Outokumpu areas belonging to the Main Sulphide Ore Belt, the following should be taken into account:

1. There occur regenerated, strata-bound features in the polymetallic sulphide ores belonging to the Outokumpu and Vihanti types (40 Borchert 1954, 40 Saksela 1957, Mikkola 1971, 40 Mikkola & Väisänen 1972, 40 Mäkelä 1973), whereas the main part of the Svecofennian sulphide deposits in southern Finland (e.g., Ylöjärvi, Korsnäs and Karsikumpu) are to be regarded mainly as belonging to the class of primary, epigenetic deposits.
2. The mean of the lead model ages of the sulphides of the Vihanti Ore Zone is 2 050 m.y. and that of the Outokumpu Ore District about 2 300 m.y., whereas the lead model ages of the sulphide deposits and prospects on the southwestern side of the Main Sulphide Ore Belt vary between 1 800 and 1 920 m.y. Kouvo (1958), Vaajoki & Kouvo (1959), Kouvo & Kulp (1961) have called attention to the systematic difference in lead model age prevailing between the Svecofennian and Karelian areas. Their view is that the Svecofennian geosynclinal rocks may have undergone only one major orogenic event and that 1 800 m. y. According to Kanasewich (1968), the Svecofennian lead model ages represent a comparatively rare example of an one-stage event. Vinogradov *et al.* (1959) have also divided the leads of the ores of the Baltic Shield into Svecofennian and Karelian types.
3. From 50 to 55 % of the Svecokarelidic formations situated on the northeast side of the negative gravimetric anomaly and its extensions in Finnish territory consist of crystalline schists, the volcanic or sedimentary origin of which can be recognized; in the Svecokarelidic formations on the southwest side of the gravimetric anomaly, such schists account for only 10—20 % of the total, whereas 20—30 % consists of migmatites, which probably derive from schists, and about 60 % of acidic, intermediate and basic intrusives (see, Simonen 1962). The Svecokarelidic formations on the northeastern side of the fault zone associated with the gravimetric anomaly contain, in addition to the amphibolite facies, notable quantities also of rocks of the epidote-amphibolite and greenschist facies, whereas the corresponding formations on the southwestern side of the anomaly belong almost exclusively to the amphibolite facies. These circumstances appear to show that the mean metamorphic tem-

perature of the Svecofennian schists on the southwestern side of the fault zone associated with the gravimetric anomaly had been higher than on the northeastern side, probably owing to the many intrusives on the southwestern side and, perhaps, the deeper niveau of the earth's crust.

4. The ores of the Main Sulphide Ore Belt are located in an area from 50 to 150 km broad and at least 400 km long between the negative gravimetric anomaly and the pre-Svecokarelicidic basement complex (2 800 m. y.). Notwithstanding the fact that the areas on the southwestern side of this Main Sulphide Ore Belt have on the average more outcrops and are therefore geologically better mapped, only a few small or medium-sized sulphide ores are known from this area, whereas the large deposits of the Main Sulphide Ore Belt contain at present more than 90 % of the known sulphide ore resources. This appears to indicate that the conditions for the formation of the sulphide ores, as far as the supply and transport of the ore material and the temperature of the surroundings are concerned, had been extraordinarily favourable.

It is on the basis of the following model that an attempt will be made to explain the foregoing facts and points of view. The sulphide material and the lead contained in it occurring in the deposits of the Vihanti Ore Zone and possibly the Outokumpu Ore District separated at a relatively early stage, 2 050 m.y. and ca. 2 300 m.y. ago, respectively, into mainly volcanic and/or sedimentary formations that had risen up close to the pre-Svecokarelicidic continental shelf. These formations may correspond to island arcs after the plate-tectonical model (see, Dewey & Bird 1970). Apparently owing to the geotectonic position and, possibly, hotter environment of the Svecofennian sulphide deposits, the separation of their lead from the uranium-thorium surroundings seems to have been retarded (see Neuvonen 1961). Their crystallization presumably took place fairly simultaneously with the intrusions surrounding the metavolcanics and metasediments, during the revolutionary phase of the Svecokarelicidic geotectonic cycle 1 800—1 920 m.y. ago. Then, also the previously crystallized sulphides of the ores of the Vihanti and Outokumpu types could, owing to strong tectonic movements and the thermal influence of intrusions in the proximity, have remobilized in part and possibly also undergone concentration without any appreciable change taking place in the isotope composition of their lead.

The possibility should not be overlooked, either, that some fault associated with the present negative anomaly (as, e.g., Kinturinjärvi) might represent in the area of the Vihanti Ore Zone a fault directed underneath the original island arc and continental shelf. On the other hand, the somewhat contradictory observations made recently of the mylonites at the southeast end of the negative gravimetric anomaly call for a cautious approach. Many detailed geological and geophysical field and laboratory investigations, new radiometric determinations and also new working hypotheses and models would undoubtedly be needed before the reasons can be explained in detail why the bulk of the sulphide ore resources known at present in Finland are located in the Main Sulphide Ore Belt.

The chromite ore of Kemi

The chromite ore of Kemi (Elijärvi) (19) is situated in a sill or dyke-shaped intrusive scores of kilometers long and composed of basic and ultrabasic rocks. The intrusive rests between Archaean gneissose granite and Svecokarelicid schists. This formation, which at its thickest measures ca. 2 km and has a NE strike and dips ca. 70° NW, consists of anorthosite, norite, gabbro, hornblendite, pyroxenite and serpentinite beds. The last-mentioned rocks are found in association with the chromite ores in the close proximity of the footwall contact of the sill.

The chromium mineralization runs parallel to the general strike as a layered, slightly disseminated ore type and — particularly in the Elijärvi deposit — as a brecciated ore, in which fragments composed of layered ore types are brecciated by the massive chromite ore. The main mineral constituent is chromite, which is alumoberezowskite (Vaajakoski & Heikkinen in 19 Kahma *et. al.* 1962), and its Cr:Fe = 1.55 (19 Kujanpää 1971). The only economically noteworthy ore mineral is the chromite, which occurs as idiomorphic grains averaging 0.2 mm in size. The other oxides include magnetite, ilmenite, hematite and rutile. In addition, small amounts of pyrite, chalcopyrite and millerite are present. The gangue consists mainly of talc, carbonate and serpentine.

The ore is classified among early magmatic deposits (19 Härmä 1949, Veltheim in 19 Kahma *et. al.* 1962, 19 Kujanpää 1971). The layered type or ore has become differentiated in the basal portions of the originally nearly horizontal sill. It might be assumed to have brecciated in the movements that forced the sill out of its horizontal position into an inclined one (65—70°), whereupon the spaces between the autoliths of the layered ore type had been filled by a later differentiate richer in chromite.

Iron ores

Nuutilainen and Paakkola (1973) divide the iron deposits of Finland into five genetic classes:

- I Magmatic segregation deposits
- II Contact-metasomatic deposits
- III Bedded deposits
- IV Residual deposits
- V Bog and lake deposits

The ores of greatest economic significance, Otanmäki (28), Mustavaara (20), Misi (14—15) and Kolari (11), are situated in northern Finland and belong to classes I and II. Deposits mainly classifiable as belonging to Class III occur in different parts of the country, but only the deposit at Jussarö (77), on the coast of the Gulf of Finland, has been the target of mining operations in recent decades.

V, Ti magnetite ores

The V, Ti magnetite deposit of Otanmäki is located on the southwestern side of Lake Oulunjärvi. The deposit consists of several hundred steeply dipping ore bodies, which occur in the form of lenses or veins. Together with closely associated brecciated anorthosites, these ore bodies enclose in the shape of an arch the amphibolite contained within them. On the south side of this arch, hornblende gabbro is further met with; and in the proximity of its contact with the amphibolite, there occurs a group of ore bodies running parallel to the arch formed by the main ore deposits. The ore bodies and their host rock exhibit banding, and in the richer, compact ore bodies intrusive features can also be observed.

The most important minerals contained in the ore are vanadium-bearing magnetite and ilmenite. In places, the magnetite has undergone martitization, and it contains ilmenite exsolutions as well as ulvite, hercynite and pleonast. The ilmenite has hematite exsolutions. In addition, the ore contains from one to two per cent of sulphides: pyrite, pyrrhotite, sphalerite, chalcopyrite and pentlandite.

The annual production of the mine amounts to 1.2 million tons of ore, which contains an average of 38—40 % of magnetite, 27—31 % ilmenite and 1—2 % pyrite. The most valuable product of the mine is vanadium, which accounts for an average of 0.62 % of the magnetite concentrate.

The magnetite deposit of Otanmäki is classified as belonging to liquid magmatic ores, the genesis of which has been linked to the conspicuously differentiated basic rocks occurring in the surroundings (28 Pääkkönen 1956, 28 Paarma 1954, 28 Vaasjoki 1947, Nuutilainen and Paakkola 1973).

Magnetite deposits in northern Finland

The magnetite deposits of the Misi area (14—15) are situated as stocks or stratiform lenses mainly in serpentinites, gabbros and skarn rocks. In association with these rocks, there also occur albitites, albite gabbros, and gabbros, which are in many instances markedly scapolitized, as well as crystalline schists composed of dolomites, arkoses and mica schists.

The ore contains mostly magnetite, which has partly turned into martite, as well as small amounts of pyrite. The most important deposits in the area occur at Raajärvi (15), Leveäselkä and Kärväsvaara (14). Some 450 000 tons of ore are mined each year at Raajärvi. It yields about 300 000 tons of magnetite concentrate with an iron content of 65 %.

The Misi ores are believed (15 Nuutilainen 1968) to have crystallized under hydrothermal conditions from hydromagma, differentiates of which the albite gabbros, albitites, serpentinites and magnetite ores are viewed as being.

The Kolari iron-ore district (9—11) is located in northern Finland close to the Swedish border. It consists of a number of small or medium-sized iron deposits

of which the one at Rautuvaara (11) has been more thoroughly investigated and is economically the most important.

The magnetite ore of Rautuvaara is situated in Svecokarelicid metamorphic and skarned carbonate- and sapropel-bearing metasediments and metavolcanics, which are penetrated by acidic intrusives. The nearly vertically dipping, ruler-shaped ore body contains some 18 million tons of ore with an average iron content of 37 per cent. Further, the ore contains from 2 to 5 per cent of sulphides, mainly pyrrhotite. Magnetite is the principal mineral component, and the gangue includes diopside, amphibole, plagioclase and olivine.

Rautuvaara is included (11 Shaikh 1964, Nuutilainen and Paakkola 1973) among metasomatic iron ores, but the existence of a hematite deposit, at Taporova (10), is also known in the Kolari district. It has been interpreted to be a syngenetic deposit.

Magnetite deposits in southern Finland

On the southern Finnish coast, there occur quite a number of small and medium-sized magnetite deposits, among which mention should be made of the ones at Jussarö, Kalkskär and Nyhamn.

Discovered in 1814, the iron-ore field of Jussarö (77), which lies mostly under water, occurs in banded and folded Svecokarelicid crystalline schists surrounded by acidic intrusives. The schists consist of metavolcanics and metasediments. The chief ore mineral constituent is magnetite. The ore has been a target of mining operations in the periods 1834—1861 and 1961—1967. The ore contains an average of 21—27 % Fe, 1.7—1.8 % Mn (in garnet), 40—45 % SiO₂, 0.02—0.04 % P and 0.01 % S.

The origin of the ore has been viewed as both magmatic (77 Saksela 1938, 1970) and syngenetic (77 Mikkola 1966).

CONCLUDING REMARKS

With the exception of the economically unimportant placer gold of Lapland (1—3) and the manganiferous lake ores, the ore deposits of Finland are situated in Early Precambrian (ca. 2 800 m.y.) and Middle Precambrian (1 500—2 300 m.y.) formations.

The sulphide ores of importance from the standpoint of the national economy can be divided into copper-nickel deposits associated with basic and ultrabasic rocks (ca. 1 900 m.y.) and the sulphide ores found in well-preserved Svecokarelicid crystalline schists (1 800—2 300 m.y.), which contain varying amounts of copper, zinc, cobalt, nickel and lead.

Over 90 per cent of the sulphide ore so far mined in Finland and existing in the known reserves belongs to deposits situated in the Main Sulphide Ore Belt. This belt extends diagonally across the country over a breadth of between 40 and 150 km in a northwesterly line from Lake Ladoga to the coast of the Gulf of Bothnia. The Main Sulphide Ore Belt includes, for example, the Outokumpu Ore District and the Kotalahti Nickel-Copper Ore Zone and The Vihanti Zinc Ore Zone. On the western side of the Gulf of Bothnia, though not on any direct extension of the afore-mentioned ore belt, a corresponding polymetallic sulphide ore area, (Skelleftefältet) occurs in Sweden.

On the northern side of the Main Sulphide Ore Belt there occur the important chromite ore of Kemi and the only iron deposits being mined in this country at present (1973), the most notable of which are the vanadium-titanium-bearing magnetite deposits of Otanmäki and Mustavaara. No iron and phosphorus ores comparable in magnitude to those occurring in northern Sweden and the Kola Peninsula in the Soviet Union have been discovered in northern Finland.

In the southern Finnish coastal region, the Svecokarelicid crystalline schists are known to contain small sulphide ores as well as some iron deposits. In economic significance, however, these occurrences do not correspond to the otherwise analogous polymetallic ore district of central Sweden.

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SUMMARY LIST OF DEPOSITS

- | | |
|--|--|
| 1 Lemmenjoki (Au) | 41 Vuonos (Cu, Ni, Co, S) |
| 2 Ivalojoki (Au) | 42 Mätäsvaara (Mo) |
| 3 Tankavaara (Au) | 43 Paukkajanvaara (U) |
| 4 Sokli (P, REE, Nb) | 44 Huhus (Fe) |
| 5 Porkonen-Pahtavaara (Fe, Mn) | 45 Otravaara (pyr) |
| 6 Sirkka (Ni, Cu, Co) | 46 Karhunsaari (pyr) |
| 7 Riikonkoski (Cu) | 47 Hammaslahti (Cu) |
| 8 Pahtavaoma (Cu) | 48 Valkeavaara (Fe) |
| 9 Juvakaisenmaa (Fe) | 49 Karsikumpu (Hällinmäki) (Cu) |
| 10 Taporova (Fe) | 50 Kaatila (Li, Be, Nb) |
| 11 Rautuvaara (Fe) | 51 Haapaluoma (Li, Be) |
| 12 Kesänkitunturi (U) | 52 Seinäjoki (Sb) |
| 13 Jauratsi (Fe) | 53 Vittinki (Fe, Mn) |
| 14 Kärväsvaara (Fe) | 54 Petolahti (Ni, Cu) |
| 15 Raajärvi (Fe) | 55 Korsnäs (Pb, REE) |
| 16 Tervola (Vähäjoki) (Fe) | 56 Haveri (Au, Cu, Co) |
| 17 Tervola II (Cu, Au) | 57 Sääksjärvi (Ni, Cu) |
| 18 Ylitornio (Mo) | 58 Ylöjärvi (Cu, W, Ag, As) |
| 19 Kemi (Elijärvi) (Cr) | 59 Eräjärvi (Li, Cs, Be) |
| 20 Mustavaara I (V, Fe, Ti) | 60 Varparanta (Mo) |
| 21 Mustavaara II (Ni, Cu) | 61 Laukunkangas (Ni, Cu) |
| 22 Puolanka (Cu, pyr, Zn) | 62 Parikkala (Ni, Cu) |
| 23 Arola (Ni) | 63 Telkkälä (Ni, Cu) |
| 24 Nuottijärvi (U, Th) | 64 Stormi (Ni, Cu) |
| 25 Jormua (talc) | 65 Kylmäkoski (Ni, Cu) |
| 26 Tuomivaara (Fe) | 66 Eurajoki (Sn, Be) |
| 27 Lahnaslampi (talc) | 67 Inkeroinen (Pb) |
| 28 Otanmäki (V, Fe, Ti) | 68 Ravijoki (Pb) |
| 29 Lampinsaari (Vihanti) (Zn, Cu, Pb, S) | 69 Hirvikallio (Li) |
| 30 Makola (Ni, Cu) | 70 Luolamäki (Li, Cs) |
| 31 Hitura (Ni, Cu) | 71 Pernaja (Pb) |
| 32 Pyhäsalmi (Cu, Zn, S) | 72 Sillböle (Fc) |
| 33 Kalliokylä (Cu, Zn, S) | 73 Orijärvi (Cu, Zn, Pb) |
| 34 Kaustinen-Alaveteli (Li) | 74 Aijala, Metsämonttu (Zn, Cu, Pb, S) |
| 35 Säviä (Cu, Zn) | 75 Kimito (Kemiö) (Ta, Be, Li) |
| 36 Siilinjärvi (P) | 76 Attu (Pb, Zn) |
| 37 Kotalahti (Ni, Cu) | 77 Jussarö (Jussaari) (Fe) |
| 38 Luikonlahti (Cu, Co, Ni, Fe, S) | 78 Kalkskär (Fe) |
| 39 Paakkila (asb) | 79 Nyhamn (Fe) |
| 40 Outokumpu (Cu, Co, Zn, S) | |



AGE m.y. Not to scale	ERA	TECTONIC POSITION	MAIN TYPES OF ROCK	MAIN TYPES OF MINERALIZATIONS							
				HUST ROCK (COUNTRY ROCK)	CONTENT	OTHER CHARAC- TERISTICS	RADIOMET- RIC AGES	SIZE 0<1<2	GENESIS	NO.	EXAMPLES
2800	EARLY PRECAMBRIAN	ARCHAEOAN FOLDED REGION	Metavolcanics and metasediments Basic, intermediate and acidic intrusions Granite gneiss UNCONFORMITY	Ferruginous schists	Fe	banded	Re/Os 2700 2800	1	+	44	Huhus
				Gneissose granite (granite)	Mo	disseminated		1	+	42	MÄTÄSVÄARA
				Iron formation (spilitic formations)	Fe, Mn	banded	2200 2075 2075	1	+	5	Porkonen-Pahtavaara
				Albitite, mica schist (spilite, albite gabbro)	Cu	disseminated		1	+	7,8	Riiikonkoski; Pahtavuoma
				Skarn (amphibolite, gneiss, granite)	Fe	compact	2200 2075 2075	1	+	11	RAUTUVAARA (Kolari)
				Serpentinite, skarn (albite gabbro, dolomite, quartzite)	Fe	compact		1	+	15	RAAJÄRVI (Misi)
				Iron formation (leptite, gneiss, acidic intrusions)	Fe, Mn	banded	2200 2075 2075	1	+	77	JUSSARÖ (Jussaari)
				Serpentinite, hornblendite, pyroxenite, anorthosite	Cr	layers, breccia		2	+	19	KEMI (Elijärvi)
				Hornblende schist, gabbro, anorthosite	V, Ti, Fe	compact lenses;	>2020	2	+	28,20	OTANMÄKI; MUSTAVAARA
				Arkose (black schist, phyllite)	Cu	disseminated		2	+	47	PYHÄSELKÄ (Hammaslahti)
1900	MIDDLE PRECAMBRIAN	SVEOKARELIDIC FOLDED REGION (Karelian)	Metavolcanics and metasediments Ultrabasic, basic, intermediate and acidic intrusions Granitoids	Quartzite, skarn (black schist, serpentinite)	Cu, Zn, Fe, Co, Ni, Au, S	breccia, disseminated	2300 1900 2300	2	+	40,41	OUTOKUMPUS; VUONOS
				Skarn, (quartzite, black schist, serpentinite)	Cu, Fe, Co	breccia, disseminated		2	- - ?	38	LUIKONLAHTI
				Skarn garnet-cordierite schist, quartzite	Zn, Pb, Cu, Ba, S	disseminated	2050 2055 2025	2	+	29	LAMPINSAARI (Vihanti)
				Metavolcanics, cordierite-anthophyllite-sericite rocks	Cu, Zn, Fe, S	nearly compact;		2	- - ?	32,35	PYHÄSALMI; Säviä
				Serpentinite	Ni, Cu	disseminated	1920 1920	2	+	31,30	HITURA; Makola
				Peridotite, perknite, gabbro, diorite	Ni, Cu	disseminated, compact;		2	+	37,61	KOTALAHTI; Laukunkangas
				Skarn, amphibolite (diorite, quartz diorite)	Cu	disseminated compact	1850 1900 1800 1800	1	+	49	KARSIKUMPU (Hälinmäki)
				Intermediate volcanic rocks; amphibolite	Cu, W, Ag, Au, Cu, Co	breccia		1	+	58,56	YLÖJÄRVI; HAVERI
				Cordierite-anthophyllite rock; skarn, amphibolite	Pb, Cu, Zn; Cu, Zn, Pb	disseminated breccia		1	+	73,74	ORIJÄRVI; AIJALA
				Skarn, pegmatite	Pb, REE	fracture zone		1	+	55	KORSNÄS
1400	PALEO-LATE PRE- CAMBRIAN	PLATFORM	Anorogenic granites	Rapakivi granite	Sn, Be, W (Zn, Pb, Cu)	greisen, veins	1550 1700	0	+	66	Eurajoki
				Rapakivi granite	Pb	veins		0	+	67	Inkeroinen
1300	JOTNIAN	Arkose Claystone Diabase									
350				Regolith, carbonatite	P, Nb, Fe, REE, Th, U	weathered plug	350	2	+	4	Sokli

TABLE 2

Summary of the distribution of ores and mineralizations in Finland.

For explanation of columns RADIOMETRIC AGES and GENESIS, see legend to Map 1.
The NO. column refers to Summary list of deposits.

Main Sulphide Ore Belt

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