Economic Geology
Vol. 74, 1979, pp. 1035–1059

Cu-Zn-Pb Ores in the Aijala-Orijarvi Area, Southwest Finland

ULLA LATVALAHTI

Abstract

The Aijala Cu-Zn ore deposit, the Metsämonttu Zn-Pb ore deposit, and the Orijärvi Zn-Cu ore deposit are located in the leptite zone of southwest Finland. The sulfide ores of central Sweden belong to the same metallogenic province. The zone can be interpreted as a mid-Precambrian island-arc structure.

The volcanic rocks in the Aijala-Orijärvi area are predominantly volcanoclastic, although units of lava origin are also encountered. In chemical composition they are predominantly calc-alkalic, although basaltic volcanite layers of tholeiitic composition are also met with. The lower section of the volcanite formation is composed of a silicic volcanic group whose composition varies from rhyolite to dacite. The chemical composition of the intermediate-basic and basic volcanite groups in the upper section varies from basaltic to andesitic. They often show primary volcanic structures, such as pillow lavas, volcanoclastic structures, and phenocrysts. The volcanites are overlain by argillaceous and arenitic weathering sediments that exhibit primary sedimentary structures such as graded bedding and slumping.

The rocks in the area were metamorphosed in the lower-pressure amphibolite facies. In the Aijala-Orijärvi zone the rocks were folded in two phases, F_1 and F_2. The general regional folding, F_1, is often isoclinal with a gently plunging fold axis. The younger crossfolding, F_2, is more local and shows subvertical fold axes.

The Cu-Zn deposit of Aijala and the Zn-Pb deposit of Metsämontttu are both sulfide disseminations or breccias in the upper part of the acid volcanite group in a pyroclastic unit with quartz and plagioclase phenocrysts. The Orijärvi Zn-Cu ore deposit consists of sulfide disseminations, breccias, and veins of massive sulfides in a zone of cordierite-sericite and cordierite-anthophyllite rocks. The wall rocks of the ores include chlorite-bearing skarns, dolomitic limestones, quartz rocks, and cordierite-anthophyllite rocks.

The mineralization took place after the decline of intense acid pyroclastic volcanism. All three ore deposits are severely deformed and partly remobilized. They are composed of several minor orebodies which in detail cut and brecciate the wall rock but as a whole are stratabound in relation to the country rock.

Each ore deposit has alteration zones whose rocks exhibit dolomitization, silicification, sericitization, and magnesium-iron metasomatism. Associated with the ore deposits at Metsämonttu and Aijala there are alteration pipes of cordierite-anthophyllite rocks and a "blanket" type of alteration zone. As a rule the alteration around the ores has depleted the rocks in sodium and increased the abundances of magnesium, iron, manganese and titanium. The behavior of silicon, aluminum, calcium, and potassium varies when compared with the presumed primary composition.

Even though the proportion on massive sulfides is low, the Aijala Cu-Zn, Metsämonttu Zn-Pb, and Orijärvi Zn-Cu ores may be allied with massive Precambrian volcanic-exhalative sulfide ores as their proximal ore types.

Introduction

THE Aijala-Orijärvi area is part of a leptite zone that in lithology and structure is comparable with the leptite zone in central Sweden (Eskola, 1963; Gavelin et al., 1976). The area is occupied by Svionian schists that are part of the Svecofennian schist zone of the Svecokarelian orogeny (Simonen, 1971).

The volcanic activity took place about 1,880 to 1,920 m.y. ago and the orogeny about 1,800 to 1,950 m.y. ago (Kouvo and Tilton, 1966; Simonen et al., 1978). In Finland this west-trending zone is roughly 110 km long and extends from the southwest coast of the country to the Lohja district in the northeast. It varies in width from 5 to 20 km.

Typical of the leptite zone is an acidic supracrustal rock rich in quartz and feldspar that, depending on the grain size, is hälleflinta, leptite, or leptitic gneiss. It includes both volcanogenic and sedimentogenic leptites. The volcanogenic leptites predominate in the

Aijala-Orijärvi area and on Kemiö, an island some 50 km to the west. Associated with them are basic or intermediate volcanic members, or both. The leptites that are weathering sediments in origin occur in the environment of Lohja, about 30 km east of Aijala-Orijärvi and in the area between Kemiö and Aijala-Orijärvi.

Synkinematic diapiric intrusions occur at the margins of the schist zones. The leptite zone is bordered in the west by what Simonen in his classification of plutonites (1960a) calls a trondhjemitic rock, in the Aijala-Orijärvi area by granodioritic, and in the east by charnockitic plutonic rocks (Hietanen, 1947; Eskola, 1963; Parras, 1941). Associated with them are more basic plutonites, such as quartz diorites, diorites, gabbros, and hornblendites. As a rule the contact of the plutonites with the supracrustal rocks is conformable. In addition to the above synkinematic intrusive rocks, there are postkinematic microcline granites south and north of the leptite zone.

The leptite zone is also a metallogenic zone and includes the sulfide and iron occurrences of southwest Finland and Bergslagen in central Sweden. The largest Swedish ore deposits are the Cu-Zn-Pb deposit at Falun (Geijer, 1916; Koark, 1969) and the Zn-Pb deposits at Kalvbäck (Hübner, 1966), Garpenberg (Du Rietz, 1968), and Saxberg. In Finland the principal ore deposits are the Aijala Cu-Zn deposit, the Metsämonttu and Attu Zn-Pb deposits, and the Orijärvi Zn-Cu deposit. The iron ore deposits in the leptite zone consist of banded iron ores (Nordberg in Sweden and Jussarö in Finland) and skarn iron ores (Dalkarlsberg in Sweden and Malmberg in Finland) (von Knorring, 1955; Frietsch, 1975). There are also small subeconomic apatite- and titanium-bearing iron occurrences in the zone (Wennervirta and Papunen, 1974; Frietsch, 1975).

The Aijala-Orijärvi area was made famous by Eskola in his classical paper on metamorphic facies (1914, 1915) and in a number of works expounding the concept of magnesium metasomatism developed in this area (Eskola, 1920; Tuominen and Mikkola, 1950; Tuominen, 1951). The synorogenic intrusive rocks have been discussed by Tuominen (1961, 1966a and b) and Mikkola (1955); the structure of the area has been studied by Tuominen (1957), the ore deposits by Varma (1954 and 1975), and the lithogeochemistry by Wennervirta and Papunen (1974).

The present study is based on investigations carried out in the area by the Exploration Department of the Outokumpu Company in 1974 to 1978. They included detailed geological mapping, geophysical ground surveys, and revision of known ore deposits. The revision was based on information from the mines and on old drill cores; thus it was possible to elaborate previous concepts of the character of the rocks and the origin of the ores in the Aijala-Orijärvi area and to introduce some new aspects.

In the following, geology of the Aijala-Orijärvi area is revised in light of the results of the studies undertaken; the ore deposits at Aijala, Metsämonttu, and Orijärvi are described, the emphasis being on Aijala and Metsämonttu.

Geology of the Aijala-Orijärvi Area

General

The Aijala-Orijärvi area is located in the middle of the Finnish part of the leptite zone, where the bedrock is well exposed. The synkinematic intrusive southeast of the Aijala mine divides the leptite zone, which trends roughly westward in two parts (Fig. 1). The southern fork extends east via Kuovila. The northern part of the zone, which bends northeast, contains the Aijala and Metsämonttu sulfide deposits. Some 6 km northeast of Aijala the schist zone forks again into two parts and forms a synclinal structure that widens toward the northeast. The northwestern flank of the syncline, and schist zone as well, trends northeast, whereas the part of the schist zone that forms the southeastern flank of the syncline turns east. Associated with the latter is the sulfide ore deposit of Orijärvi.

The synkinematic intrusive is a diapirically uplifted anticline batholith (Eskola, 1914; Hietanen, 1975), which varies from granodiorite to gabbro in composition but also shows hornblenditic portions. In some places, e.g., east of Orijärvi, the intrusive has forced the schists to bend outward from it. The grano- and quartz diorites contain partly assimilated fragments. Small amphibolite fragments predominate, although some 6 km southeast of Aijala there is a schist fragment, 50 to 200 m in size, that consists of layered arkosite and limestone and includes the small occurrence of massive Zn-Cu ore at Nyckeln.

Mapping has shown that the acidic fragmentary pyroclastic rocks grade laterally into volcanic-sedimentary and again into slightly sorted weathering sediments that are predominantly arkosites. In Figure 1 the areas largely occupied by the weathering sediments are included in the sedimentary facies. Likewise areas dominated by volcanogenic rocks are marked on the map as volcanic facies.

In the Aijala-Orijärvi area the volcanogenic rocks are more abundant than in the leptite zone in general, exhibiting large variation in rock types.

Stratigraphy

In his description of the stratigraphy of the Svecofennian schist zone, Simonen (1953, 1960b, 1971) divides it into three parts: the lower, middle, and

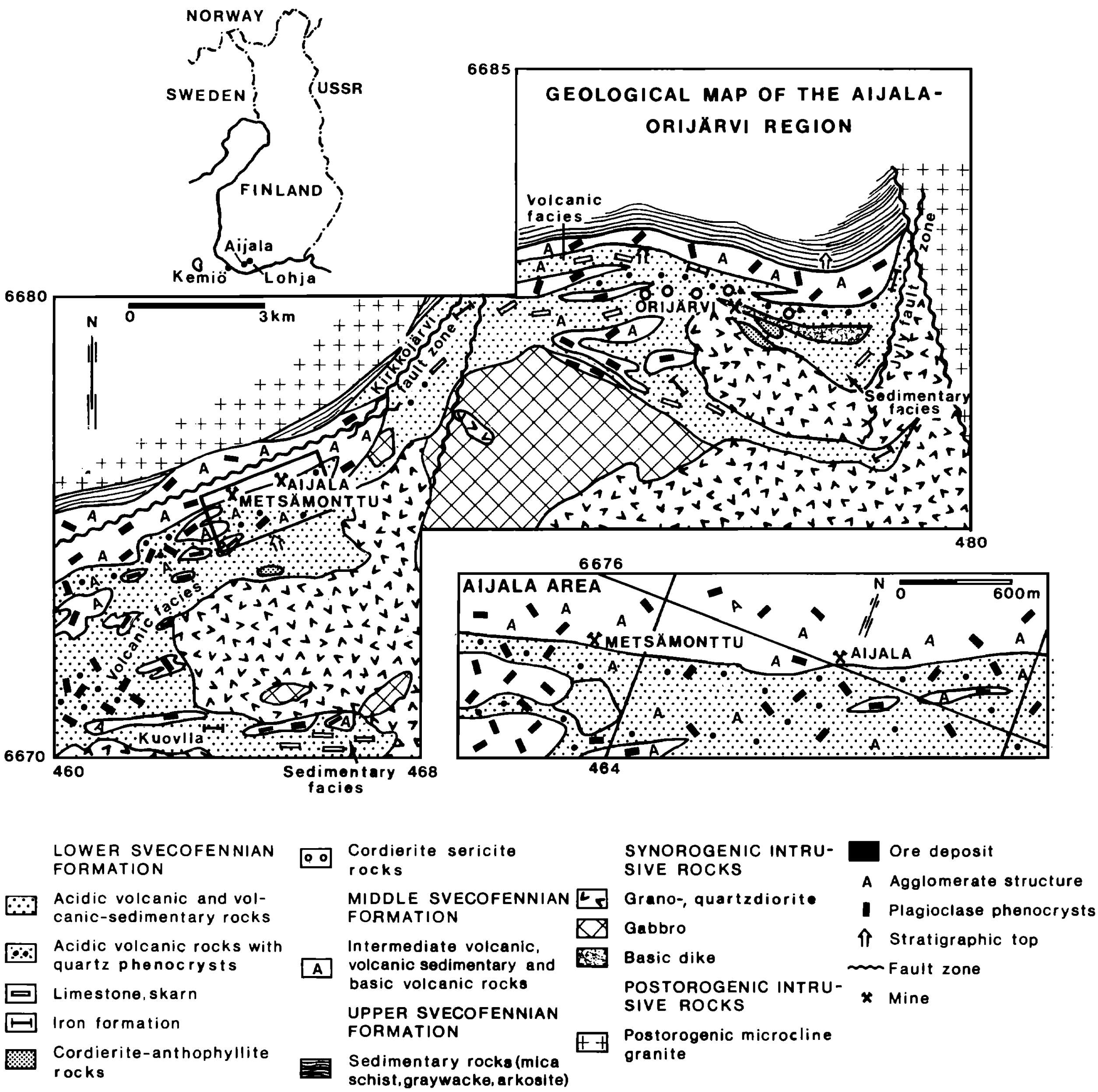

FIG. 1. Generalized geologic map of the Aijala-Orijärvi area with a detailed map of the environment of the Aijala and Metsämonttu ore deposits in the lower right corner.

upper Svecofennian groups. According to him, the lower Svecofennian group contains graywacke schists and quartz-feldspar rocks, or leptites. These are overlain by the middle Svecofennian basic volcanites with sedimentary interlayers. The upper Svecofennian group is composed of argillaceous sediments. The basement of the sequence has not been established. The stratigraphy of the subareas of the leptite zone has been studied in the southwest archipelago by Edelman (1960) and Ehlers (1976), in the Orijärvi area by Mikkola (1961), and in the Lohja area by Härme (1954, 1956).

Table 1 and Figure 2 illustrate the stratigraphy of the Aijala-Orijärvi area based on the classification by Simonen (1960b). The lower Svecofennian group contains the rocks of the leptite formation, including both volcanogenic rocks and rocks derived from weathering products.

In areas predominantly of volcanogenic rocks, such as east of Aijala, or of weathering sediments, such

TABLE 1. Stratigraphy of the Aijala-Orijärvi Area

Upper Svecofennian Group

Argillaceous and arenaceous sediments—mainly phyllites, mica schists, graywackes, graywacke schists, mica gneisses, and arkosites; thickness, highly variable, <3,000 m.

Middle Svecofennian Group

Basic and intermediate volcanogenic—lavas, pyroclastites, and epiclastites; random limestone interlayers; thickness 500 to 1,000 m.

Lower Svecofennian Group

Leptite—hälleflinta—includes: (1) acidic volcanogenic rocks—lavas, pyroclastites, and epiclastites; limestone and iron-formation interlayers; and (2) arenitic sediments; limestone and iron-formation interlayers. Thickness, <3,000 m.

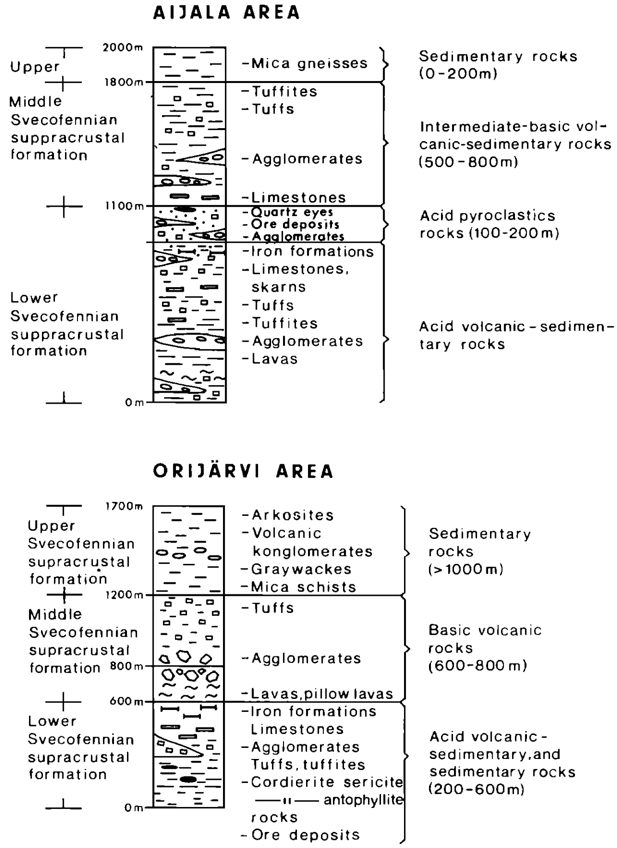

FIG. 2. Stratigraphic sections across the vicinity of the Aijala, Metsämonttu, and Orijärvi deposits.

as in the environment of Kuovila, the rocks do not show clear contacts but grade laterally into one another. The acidic volcanic rocks are mainly pyroclastic or volcanic-sedimentary in origin with occasional lava interlayers. The weathering sediments are poorly sorted arkosites, whose constituents derived from acidic volcanites. The leptites often exhibit narrow limestone and iron-formation intercalations, whose frequency is clearly higher in the sedimentary facies of the leptite zone. The iron-formations are predominantly chert banded or skarn iron interbeds, a few meters in thickness. In the Orijärvi area the volcanites are overlain by a tuff and tuffite unit rich in biotite and containing plagioclase phenocrysts. In the contact there is a narrow limestone bed and a chert-banded iron-formation. There the topmost member in the lower Svecofennian group is a skarn-bearing volcanic conglomerate unit whose pebbles are cherts and fine-grained acidic volcanites with occasional plagioclase phenocrysts.

The basic and intermediate volcanites of the middle Svecofennian group are predominantly pyroclastites and lavas, with some narrow limestone intercalations in the basal part. The lowest member consists of lava layers with plagioclase phenocrysts in the Orijärvi area. The upper part of this bed has pillow lava layers and several layers of agglomerate and tuff. The ejecta are angular and often large, andesitic or dacitic volcanites in composition. The horizon of the basic volcanites shows lateral variation. Eastward the abundance of pyroclastics, i.e., agglomerate layers, decreases and they are replaced by tuffites with diopside skarn interlayers, which presumably means that the eruption channel was located in the western margin of the Orijärvi area. The width of the layers fluctuates between 2 and 10 cm.

Between the lower and middle Svecofennian volcanic stages, the Aijala and Orijärvi areas probably underwent a long and peaceful evolution stage, during which tuffites and chemical sediments, such as layers of limestone and iron-formation, were formed in the basin. When volcanic activity started again more basic material, mainly basaltic and andesitic in composition, was erupted.

The upper Svecofennian group in the Aijala and Orijärvi areas includes argillaceous and arenitic rocks, in origin from weathering sediments. In the Aijala area they are layered mica gneisses with occasional narrow interlayers of iron-formation, which are predominantly of silicate facies although oxide facies interlayers are also encountered. In the Orijärvi area the lower part of the weathering sediment unit contains a fine-grained layered mica schist with cordierite porphyroblasts, which is overlain by a narrow bed of a graywacke schist that shows primary sedimentary structures, such as graded-bedding, current bedding, and slumping. This horizon is succeeded by a phyllite with iron sulfides and a narrow volcanic conglomerate bed. The pebbles in the conglomerate are usually of fine-grained acidic volcanites that markedly resemble the acidic volcanite interbed in the lower Svecofennian group. The topmost layers of the sequence are arkosite rich in quartz and feldspar, and mica schist, both of which grade into one another.

No counterpart has been found in the Aijala-Orijärvi area for the mica schist formation that is the lowest member in the Finnish southwest archipelago (Edelman, 1960).

Gavelin et al. (1976) have published a paper on the stratigraphy of the leptite zone in the Stockholm archipelago based on the classification by Simonen (1960b). According to them the lower Svecofennian group consists of metamorphic graywackes and subgraywackes. The middle Svecofennian group is composed of the leptite-hälleflinta formation. The upper Svecofennian group includes dacitic tuffites and paragneisses. The Stockholm archipelago and the Aijala-Orijärvi area differ in stratigraphy. In the Stockholm archipelago the leptite-hälleflinta formation, which correlates with the acid volcanites, belongs to the middle Svecofennian group and the dacitic tuffites to the upper Svecofennian group.

In central Sweden the acidic quartz-feldspar rocks of the leptite zone are divided into three groups according to their chemical composition. Lowest in stratigraphy is natron leptite, in which sodium predominates over potassium. This is overlain by kali leptite, in which potassium predominates over sodium. Between them in composition is the group known as alkali-intermediate leptite, which occurs as interlayers in the natron and kali leptites (Gorbatsev, 1969). As shown by their chemical and mineralogical compositions the pyroclastic volcanites are sodium predominant in the Aijala-Orijärvi area. The potassium abundance increases simultaneously with the decrease in volcanic constituents in the rocks. Hence, the rocks of the sedimentary facies are mainly potassic leptites. In some places, however, e.g., at Aijala, the upper part of the acidic pyroclastic volcanic interbed with quartz and plagioclase phenocrysts contains narrow potassium-bearing tuffite interlayers.

Tectonics

Two folding phases can be discerned in the leptite zone of southwest Finland (Tuominen, 1957; Ehlers, 1976). The older folding phase, F_1, produced in the Aijala-Orijärvi area isoclinal folding with axes plunging gently toward the east. The second and younger folding phase, F_2, resulted in isoclinal folding with subvertical axes plunging at high angles toward the southwest. The axial plane schistosity is subvertical in both cases. Owing to the differences in competence the skarn, limestone, and iron-formation interlayers often show small-scale folding.

In contrast the acidic volcanites seldom exhibit folds or any other tectonic structures. The lineation of folding phase F_2 is practically always visible whereas that of phase F_1 only seldom. Compared with the environment at Orijärvi, Aijala is a "high strain" region, as suggested by the distinctly more deformed ejecta in the agglomerate layers. Likewise the axial plane foliation is more intensely developed at Aijala than at Orijärvi.

Numerous young, postmetamorphic fault zones are encountered in the Aijala-Orijärvi area; the most prominent are the Jyly fault zone east of Orijärvi and the Kirkkojärvi-Kiskojoki fault zone (Fig. 1). Smaller faults are also met with, e.g., in the orebodies. The Metsämonttu ore deposit is cut at the +135 level by a fault gently dipping southward, Figure 10 is a reconstruction of the contacts between the rock types before the faulting. The displacement of the upper part of the orebody is some 270 m north. The orebody is also cut by another and similar fault at the +540 level, which displaced the upper part of the orebody about 80 m northward. The Aijala orebody comes to an abrupt end at the +220 level in a fault and shear zone that dips steeply north (Fig. 12). The Orijärvi deposit is also cut by several faults and shear zones, of which the most prominent are the north-trending faults east and west of the ore deposit.

Metamorphism

Regional metamorphism preceded the emplacement of the microcline granite. Folding phase F_1, which partly preceded and partly overlapped the regional metamorphism, reached its climax before the folding phase F_2. The rocks of the Aijala-Orijärvi area were metamorphosed to low-pressure amphibolite facies. Farther east, in the Lohja area, the metamorphism reached granulite facies (Parras, 1958). The diagnostic mineral assemblage in the Aijala-Orijärvi area is muscovite-quartz-plagioclase (An_{20}).

The PT conditions of the regional metamorphism were close to those of the reaction

$$KAl_3SiO_3O_{10}(OH)_2 + SiO_2 \rightarrow KAlSi_3O_8 + Al_2SiO_5 + H_2O.$$

muscovite + quartz → potassium feldspar + sillimanite

At Orijärvi the cordierite-sericite mica gneiss contains andalusite together with sillimanite. Thus, the temperature of metamorphism exceeded 580°C and the pressure was lower than 5 kb (Vernon, 1976). Since we are dealing with a low-pressure subfacies, the total pressure was presumably about 3 kb. Experiments show that muscovite is decomposed at 650° ± 30°C (Winkler, 1974); thus regional metamorphism took place at a pressure of roughly 3 kb and a temperature of 650° ± 30°C. Eskola (1915) maintains that the Orijärvi granodiorite body caused contact metamorphism whose PT conditions were approximately the same as or slightly lower than those of the succeeding regional metamorphism.

Geology of the Environment of the Ore Deposits

Acidic volcanic rocks

The ore deposits of the Aijala area occur in acidic pyroclastic rocks in a volcanic environment close to the contact of an intermediate-basic volcanite. A pyroclastic rock with quartz and plagioclase phenocrysts and tuff and agglomerate interlayers predominates. Southeast of Aijala a few quartz-porphyry lava units are met with. Some layers show autoclastic structure due to the brecciation of a viscose acid "flow" lava. The breccia matrix and the fragments are of the same quartz and plagioclase phenocryst-bearing material. As a rule the layers are from 2 to 10 m in thickness. In the upper portion of the unit the contacts of the individual layers are rich in skarn minerals. The ejecta in the agglomerate layers are predominantly fine-grained acidic volcanites, although mica-rich tuffite ejecta from 5 to 20 cm in diameter have also been encountered. Some of them contain quartz phenocrysts. Small mica schist fragments, which are easily corroded on the weathered surface to form cavities, are fairly common in some tuff layers; their average diameter is about 5 cm. The size and abundance of the quartz and plagioclase phenocrysts vary from one tuff layer to the next. Some layers contain only quartz phenocrysts. The size of the phenocrysts fluctuates between 0.1 and 2 cm.

The acidic volcanic unit of the Orijärvi area occurs north of and resting on the zone composed of cordierite-sericite and cordierite-anthophyllite rocks. Owing to the decline in sericite abundance the contact of the cordierite-sericite mica gneiss with the acidic volcanite is gradual. No primary volcanic structures except layering have been noted in it. The layers vary from 0.2 to 10 m in width, having contacts rich in skarn minerals. The lower part of the unit is often brecciated by skarn- and carbonate-bearing veins (width < 1 cm), also containing disseminated pyrite. Also encountered in the Orijärvi area is a hypabyssal acidic vein with quartz phenocrysts, which occurs conformably in the zone of the above rocks and varies in width between 50 and 100 m. Similar quartz-porphyry veins are also encountered elsewhere in the Aijala-Orijärvi area.

The main minerals in the tuff layers with quartz and plagioclase phenocrysts are quartz, plagioclase (An_{20-30}), and biotite with variable amounts of microcline. The narrow equigranular tuffite interlayers in the upper part of the unit contain notably more microcline than plagioclase. The quartz phenocrysts are often rounded ellipsoids enveloped by micas: biotite, phlogopite, and sericite. Many of the phenocrysts are partly recrystallized grain aggregates. Nevertheless, some layers free from micas exhibit beautiful subeuhedral quartz phenocrysts that are occasionally surrounded by a seam of microcline grains. The plagioclase phenocrysts are aggregates of several grains in which some of the grains are partly or completely recrystallized. The recrystallization has started from the margins of the phenocrysts, and the cores often contain relicts of primary phenocrysts. Owing to recrystallization, the plagioclases have changed in composition from oligoclase to labradorite. The microscopic fragments, mainly lapilli, are predominantly composed of quartz, plagioclase (An_{20}), and random biotite.

Intermediate-basic and basic volcanites

The intermediate-basic volcanite group that occurs higher in the sequence than the Aijala and Metsämonttu ore deposits is mainly composed of pyroclastic and tuffitic rocks. The agglomerate, lapilli, and tuff layers contain banded mica-rich tuffite interlayers 0.1 to 1 m wide. In general the thickness of the individual layers varies from 1 to 5 m. Between the agglomerate and tuff layers in the lower section of the volcanite group there are narrow diopside skarn interlayers that suggest the volcanism was at least partly submarine. Only a few fragmentary lava beds with plagioclase phenocrysts have been encountered as interlayers in the pyroclastic rocks.

The ejecta in the agglomerate layers are rounded and usually more acidic in composition than the matrix. Acidic, fine-grained volcanites, andesitic-dacitic plagioclase porphyries, and equigranular volcanites of similar composition predominate. In the layers the ejecta vary in size from lapilli (diameter about 1.5 cm) to bombs (diameter about 15 cm); the largest ejecta are some 25 cm in diameter. The tuff layers are homogeneous with frequent plagioclase phenocrysts. The layers are between 0.1 and 10 m in thickness.

The interbeds of basic volcanites in the Orijärvi area are located farther from the ore horizon than in the Aijala area. Their volcanic primary structures are well preserved. The basic lava beds are predominantly plagioclase porphyrites and show pillow lava, amygdaloidal, and porphyric structures. The agglomerate layers contain abundant angular ejecta, the largest of which measure 25 cm in diameter. In composition they are generally dacitic or rhyodacitic and more acidic than the matrix. The tuff layers are equigranular and homogeneous and, like the agglomerate, often form piles of beds. They occasionally contain small lapilli (diameter, 2 cm). East of the Orijärvi area the tuff layers show diopside skarn

TABLE 2. Chemical Composition and CIPW Norms of the Acidic Rocks in the Aijala-Orijärvi Area

	1	3	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	77.59	71.24	71.51	72.80	77.52	65.97	70.16	69.52	72.06	71.50	71.36	73.91	74.50	78.30	73.82
TiO_2	0.10	0.13	0.15	0.23	0.11	0.19	0.21	0.64	0.34	0.34	0.34	0.22	0.18	0.12	0.38
Al_2O_3	11.75	12.88	15.20	14.25	12.31	13.53	12.90	13.58	12.51	13.79	13.31	13.90	13.13	12.5	14.61
Fe_2O_3	0.15[1]	0.20[1]	0.23[1]	0.35[1]	0.17[1]	0.29[1]	0.32[1]	0.51[1]	0.72	0.76	0.99	0.14	1.60	0.17	0.60
FeO	1.12	2.94	1.82	2.32	2.22	1.32	3.55	3.75	3.93	2.07	3.36	1.01	1.36	2.59	0.00
MnO	0.02	0.03	0.03	0.04	0.02	0.05	0.01	0.19	0.19	0.06	0.10	0.00	0.02	0.08	0.00
MgO	0.28	3.32	0.91	1.50	0.21	3.07	3.52	1.22	4.14	1.47	0.87	0.28	0.30	0.07	0.36
CaO	1.86	4.94	3.03	2.90	2.52	3.66	5.88	4.53	1.70	3.54	2.85	1.00	1.42	1.25	2.23
Na_2O	3.96	0.74	3.02	2.77	3.91	1.92	0.61	3.55	1.59	4.48	3.58	2.42	4.08	3.5	4.74
K_2O	1.65	2.10	3.20	1.83	0.71	1.53	2.17	1.47	2.20	1.11	2.26	6.53	3.21	1.25	2.09
H_2O^+	0.07	0.08	0.08	0.05	0.07	1.73	0.70	{0.71	{1.03	0.39	0.45	0.33	{0.39	nd	nd
H_2O^-	0.09	0.74	0.52	0.06	0.59	0.10	0.06			0.17	0.25	0.19		nd	nd
P_2O_5	0.05	0.07	0.06	1.04	0.07	0.04	0.11	0.20	0.00	0.10	0.21	nd	0.01	nd	0.05
CO_2	0.58	0.22	0.25	0.00	0.02	0.05	0.24	nd	nd	nd	nd	nd	nd	nd	nd
Total	99.27	99.63	100.01	100.45	100.14	93.46	100.44	99.87	100.41	99.78	99.93	99.93	100.2	99.81	98.37
Cu	15	68	15	55	16	28	nd	nd	nd	nd	nd	nd	nd	50	nd
Zn	43	110	65	73	84	692	nd	nd	nd	nd	nd	nd	nd	0	nd
Ni	35	28	28	28	48	40	nd	nd	nd	nd	nd	nd	nd	nd	nd
Co	38	68	43	38	16	24	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb	5	13	23	275	56	440	nd	nd	nd	nd	nd	nd	nd	0	nd
S	0.05	0.15	0.05	0.06	0.33	3.65	nd	nd	nd	nd	nd	nd	0.06	nd	nd
Q	43.8	41.8	32.9	44.9	42.5	39.0	38.8	30.9	42.3	31.2	32.7	32.3	34.7	48.5	33.4
C	0.19	0.58	1.4	0.70	4.9	2.3			4.6			1.0	0.39	3.1	0.62
Or	9.9	12.6	19.1	4.2	10.8	9.9	12.9	8.8	13.1	6.6	13.5	38.9	19.0	7.3	12.5
Ab	34.0	6.4	25.8	33.2	23.5	17.7	5.2	30.3	13.0	38.2	30.6	20.7	34.6	29.7	40.6
An	9.0	24.4	14.8	12.1	7.6	19.5	26.2	16.9	8.5	14.4	13.7	5.0	7.0	6.2	10.9
Di							2.0	3.7		2.7	0.49				
Hy	2.5	13.5	5.3	4.3	7.4	10.5	13.8	7.0	16.8	5.1	7.0	1.4	1.7	4.7	0.91
Ol															
Fem	0.22	0.29	0.33	0.25	0.51	0.45	0.46	0.74	1.1	1.1	1.4	0.23	2.32	0.24	
Ilm	0.19	0.25	0.28	0.21	0.44	0.39	0.40	1.2	0.7	0.65	0.65	0.41	0.34	0.22	
Ap	0.12	0.16	0.14	0.16	2.5	0.10	0.26	0.48		0.24	0.48		0.02		0.12

Wet chemical analyses.
[1] Fe_2O_3 computed as 1.5 × TiO_2 (Irvine and Baragar, 1971).
Oxides and S in wt%, trace elements in ppm, nd = not determined.
CIPW norms according to Bingler et al. (1976).
1, Acidic tuff with quartz and plagioclase phenocrysts and lapilli, Aijala.
2, Acidic tuff with quartz phenocrysts, Aijala.
3, Acidic tuff with quartz and plagioclase phenocrysts, Metsämonttu.
4, Acidic tuff with quartz and plagioclase phenocrysts, Metsämonttu.
5, Equigranular acidic tuff, Metsämonttu.
6, Acidic tuff with quartz phenocrysts, Metsämonttu.
7, Arkosite (lower Svecofennian group), Orijärvi.
8, Arkosite (upper Svecofennian group), Orijärvi, Vetjo (Eskola, 1914).
9, Subvolcanic sill with quartz phenocrysts, Iillampi, 1.7 km west of Orijärvi (Eskola, 1914).
10, Quartz porphyry, a contact variant of the Orijärvi granodiorite, Orijärvi (Eskola, 1914).
11, Granodiorite, Orijärvi (Eskola, 1914).
12, Microcline granite, Kisko, Sillanpää (Eskola, 1914).
13, Quartz porphyric leptite, central Sweden, Falun (Geijer, 1915).
14, Rhyolitic tuff with quartz eyes, Canada, Kidd Creek (Hopwood, 1976).
15, "White rhyolite" lava domes, Japan, Kosaka (Tatsumi and Clark, 1972).

interlayers. The Orijärvi ore deposit is cut by a basic subvolcanic dike.

The volcanic layers differ conspicuously from each other in mineralogy. The main minerals in the pyroclastic rocks are hornblende and cummingtonite, often as intergrowths. Other main minerals are plagioclase, biotite, and quartz. Plagioclase occurs as euhedral phenocrysts and as a constituent in the matrix. The phenocrysts are often zonal and vary from andesine to labradorite in composition. The predominant minerals in the tuffitic layers are biotite, plagioclase (An_{20-30}), and quartz, some layers also contain garnet and cordierite porphyroblasts. The major minerals in the diopside skarn layers are diopside, plagioclase (An_{40-50}), tremolite, and quartz.

Chemical composition of the volcanites

Volcanites have been classified on the basis of their chemical composition and the parameters derived from it by many investigators, e.g., Nockolds (1954), Irvine and Baragar (1971), Middlemost (1972), and Le Maitre (1976). In the present study the

TABLE 3. Chemical Compositions and CIPW Norms of the Intermediate and Basic Rocks in the Aijala-Orijärvi Area

	1	2	3	4	5	6	7	8	9	10
SiO_2	50.91	49.72	52.43	47.72	49.22	49.92	50.99	50.56	49.15	48.90
TiO_2	0.54	0.55	0.39	0.65	0.41	0.67	0.65	0.96	1.52	0.97
Al_2O_3	19.02	19.30	18.58	18.47	18.41	13.09	15.18	16.38	17.73	17.58
Fe_2O_3	0.81[1]	0.83[1]	0.59[1]	0.98[1]	0.62	1.01[1]	1.87	1.78	2.76	1.46
FeO	10.94	10.09	7.88	10.54	11.16	10.72	8.09	6.67	7.20	10.74
MnO	0.21	0.19	0.14	0.15	0.02	0.23	0.18	0.16	0.14	0.16
MgO	5.88	4.49	3.64	5.70	4.66	9.99	10.00	7.70	6.91	7.79
CaO	7.57	12.28	10.65	11.05	11.88	9.98	8.60	10.06	9.91	10.82
Na_2O	2.69	1.85	2.92	2.55	2.49	1.48	2.67	2.25	2.88	2.32
K_2O	0.27	0.35	1.16	0.83	0.42	0.45	0.38	0.90	0.72	0.27
H_2O^+	0.22	0.06	0.08	0.07	0.78	0.11	0.95	2.06	nd	nd
H_2O^-	1.74	0.87	1.07	1.22	0.08	2.03	0.10	0.23	nd	nd
P_2O_5	0.14	0.13	0.10	0.11	0.16	0.12	nd	0.12	0.26	0.09
CO_2	0.08	0.00	0.00	nd	0.24	0.00	nd	nd	nd	nd
Total	101.02	100.71	99.63	100.04	100.55	99.80	99.66	99.82	101.76	101.10
Cu	115	88	64	136	nd	116	nd	nd	nd	nd
Zn	100	112	96	104	nd	108	nd	nd	nd	nd
Ni	20	68	12	68	nd	144	nd	nd	nd	nd
Co	60	64	56	68	nd	72	nd	nd	nd	nd
Pb	0	52	24	44	nd	56	nd	nd	nd	nd
S	0.24	0.20	0.05	1.85	nd	0.36	nd	0.10	nd	nd
Q	1.03	0.72	0.75					0.74		
C	0.88									
Or	1.6	2.1	7.0	5.0	2.5	2.7	2.3	5.6	4.2	1.5
Ab	23.0	15.7	25.7	21.7	21.2	12.8	22.9	19.5	23.9	19.4
An	37.0	43.4	34.7	37.0	38.0	28.4	28.7	32.7	32.8	36.4
Di		14.1	15.4	14.8	17.0	17.5	11.8	14.4	11.4	13.3
Hy	33.9	21.4	15.3		9.5	35.1	25.1	22.6	8.0	12.9
Ol				18.4	9.7	0.26	5.2		13.0	12.3
Fem	1.2	1.2	0.87	1.4	0.90	1.5	2.7	2.6	3.3	1.8
Ilm	1.0	1.0	0.75	1.3	0.78	1.3	1.3	1.9	2.84	1.8
Ap	0.34	0.31	0.24	0.26	0.38	0.29		0.29	0.61	0.21

Wet chemical analyses
[1] Fe_2O_3 computed as 1.5 × TiO_2 (Irvine and Baragar, 1971).
Oxides and S in wt%, trace elements in ppm, nd = not determined.
CIPW norms according to Bingler et al. (1976).
1, Tuff with plagioclase phenocrysts, Metsämonttu.
2, Tuff with plagioclase phenocrysts, Metsämonttu.
3, Tuff, Metsämonttu.
4, Tuff with plagioclase and uralite phenocrysts, Metsämonttu.
5, Lava with plagioclase phenocrysts, 4.2 km west of Orijärvi.
6, Dike with uralite phenocrysts, about 500 m west of Metsämonttu.
7, Basic sill, Orijärvi (Eskola, 1914).
8, Hornblende gabbro, Kisko, Hauksuo (Eskola, 1914).
9, An average basalt with high alumina, North America, Cascades, and Oregon Plateau (Waters, 1962).
10, High alumina basalt, Japan, Sukokumo-Yama (Kuno, 1967).

classification is based mainly on that by Irvine and Baragar (1971). Tables 2 and 3 list some chemical compositions of volcanites from the Aijala-Orijärvi area. The CIPW norms were calculated by means of a computer program by Bingler et al. (1976). The analytical data of the diagrams were obtained by X-ray diffraction. The total iron was computed to FeO subtracting the sulfide iron.

The volcanites of the Aijala-Orijärvi area are of subalkaline composition (Fig. 3). The line that separates the alkaline and subalkaline fields from each other was drawn after Irvine and Baragar (1971), and the rocks were subdivided into acidic, intermediate-basic, and basic volcanites.

The differentiation series of the volcanites can be determined by means of an AFM diagram. The boundary between the calc-alkalic and tholeiitic series, however, varies as shown by the classifications of Kuno (1953) and Irvine and Baragar (1971). The AFM diagram of the volcanites of the Aijala-Orijärvi area (Fig. 4) shows that the majority of the chemical compositions of the rocks fall within the field of the calc-alkalic series. The compositions of the intermediate-basic and basic volcanites show a large scatter and some of the rocks seem to belong to the tholeiitic series.

The composition of the differention series, however, shows a trend perpendicular to the FeO-MgO

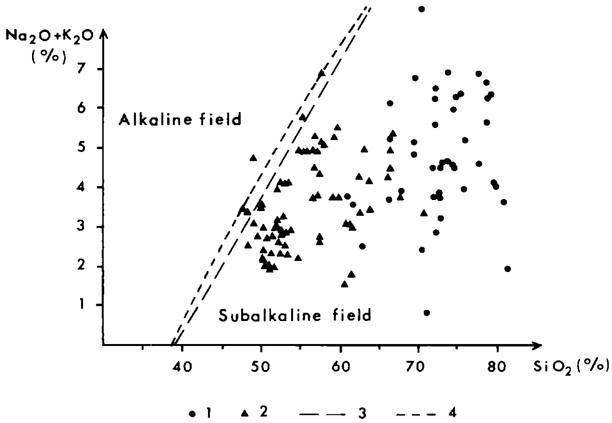

FIG. 3. SiO_2 vs. $Na_2O + K_2O$ in volcanic rocks: 1, acidic volcanic rocks; 2, intermediate and basic volcanic rocks. Boundaries: 3, MacDonald and Katsura (1964) and 4, Irvine and Baragar (1971).

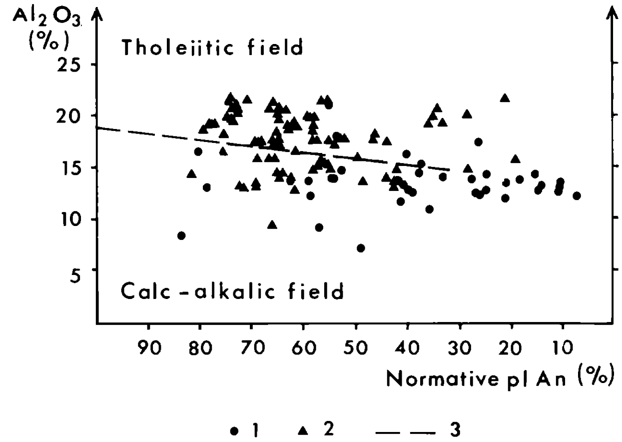

FIG. 5. Al_2O_3 vs. anorthite content in normative plagioclase of volcanic rocks: 1, acidic volcanic rocks; 2, intermediate and basic volcanic rocks. Boundary: 3, Irvine and Baragar (1971).

side of the AFM diagram, a feature that has been used to distinguish tholeiitic from calc-alkalic volcanites (Miyashiro, 1974). Irvine and Baragar (1971) prefer the diagram in which the composition of the normative plagioclase is plotted as a function of Al_2O_3 (Fig. 5). In both diagrams the location and scatter of the composition points of the rocks is partly due to the narrow biotite-rich tuffite interlayers in the intermediate-basic volcanites in the Aijala area. Apart from calc-alkalic volcanites, there are also tholeiitic volcanites, basalts in composition, in the Aijala-Orijärvi area.

The Ab-An-Or diagram (Fig. 6) mainly reflects the chemical composition of the feldspars in the rocks and the classification based on that. The figure shows that, consistent with the chemical composition of dacite given by Nockolds (1954), the acidic volcanites are sodium-bearing dacites. The acidic volcanites with plagioclase of high normative anorthite content occur in the contacts of the layers of tuff with quartz and plagioclase phenocrysts. The equigranular microcline-bearing tuff in Aijala and the acidic volcanite in Orijärvi are richest in potassium. The intermediate-basic and basic volcanites fall in the andesite and basalt field with a rather high potassium content. The Al_2O_3 content varies, some of the basalts showing abundances exceeding 16 percent (Table 3).

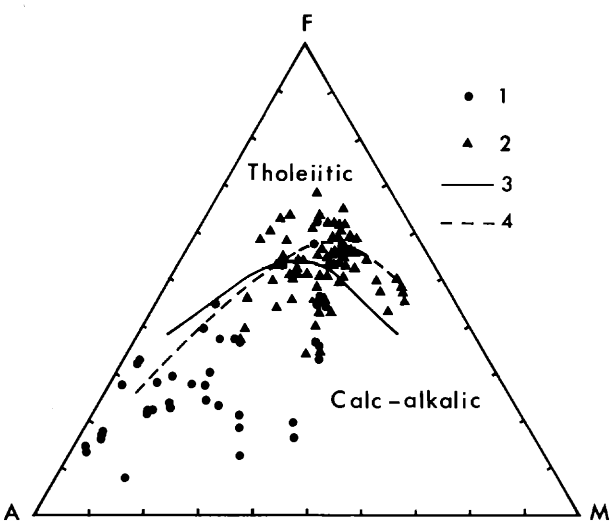

FIG. 4. Chemical compositions of volcanic rocks in an AFM diagram: 1, acidic volcanic rocks, 2, intermediate and basic volcanic rocks. Boundaries: 3, Irvine and Baragar (1971); 4, Kuno (1953).

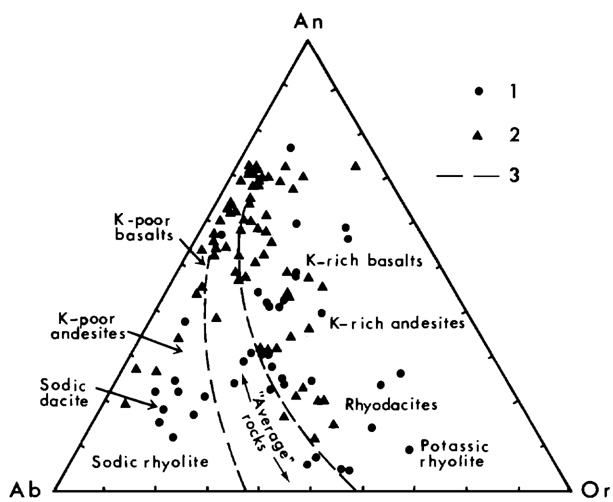

FIG. 6. Chemical compositions of volcanic rocks in a normative Ab-An-Or diagram: 1, acidic volcanic rocks; 2, intermediate and basic volcanic rocks; 3, average composition fields of rock types and boundaries according to Irvine and Baragar (1971).

TABLE 4. The Hoist and Grade of the Ores in Aijala, Metsämonttu, and Orijärvi Mines

	Aijala (1949–1958)		Metsämonttu (1952–1974)		Orijärvi (1932–1954)	
	Ore hoist (metric tons)	Grade	Ore hoist (metric tons)	Grade	Ore hoist (metric tons)	Grade
Cu %	840,000	1.58	491,500	0.27	552,700	0.74
Zn %			126,500	3.51	552,700	3.01
Pb %			860,200	0.79	552,700	0.87
S %	791,600	14.23	408,500	13.29		
Au g/metric ton			783,200	1.40		
Ag g/metric ton			783,200	25.02		

Grades are averages weighed by the annual hoists.

Aijala Cu-Zn, Metsämonttu Zn-Pb, and Orijärvi Zu-Cu Ore Deposits

General

The Aijala, Metsämonttu, and Orijärvi sulfide ore deposits are mined out. Mining started at the Orijärvi deposit in 1757 but considerably later at Aijala and Metsämonttu. The deposits were mined in the 1950s and 1970s. The total ore hoist from the mines and the metal contents are listed in Table 4. As the table indicates, the Aijala deposit was mined mainly for copper; Metsämonttu for zinc, lead, and silver; and Orijärvi for zinc and copper.

Figure 7 shows the Zn-Pb-Cu diagrams of the ore deposits. In the Aijala ore the metal contents fall close to the Cu-Zn side; in the Metsämonttu ore the contents plot closer to the Zn-Pb side; in the Orijärvi ore there are portions that in composition resemble both the Aijala and Metsämonttu ores.

The Aijala and Metsämonttu ore deposits, which are about 1.5 km apart, are located in a stratigraphic horizon that exhibits signs of mineralization for a distance of about 3 km (Fig. 1). The Orijärvi ore deposit is also located in a zone that shows signs of mineralization for a distance of several kilometers; it, however, is the only deposit that has been exploited in this zone.

The orebodies were small and their metal contents varied greatly. The sulfides occurred as disseminations or breccia matrix and less seldom as massive veins. The orebodies often showed sharp contacts with the wall rock. The high-grade sulfide accumulations are marked on the map as ores; the deposits do not contain massive sulfides in amounts worth mentioning.

The stratigraphic position of the ore deposits

On a large scale all three ore deposits are stratabound; in detail, however, they show cutting and breccia structures in relation to the wall rock. The most distinctly stratabound are the Aijala and Metsämonttu deposits, which occur in the contact between the acidic volcanite and the intermediate-basic pyroclastic volcanites (Metsämonttu) or close to it (Aijala).

The Orijärvi ore deposit is located in a zone of acidic cordierite-sericite and cordierite-anthophyllite rocks. Eskola's (1914) opinion was that the rocks are pelitic sediments in origin which underwent magnesium metasomatism brought about by synkinematic granodiorite. In the stratigraphic classification by Simonen (1960b, 1971), the Aijala, Metsämonttu, and Orijärvi deposits belong to the lower Svecofennian group (Fig. 2).

The lowest member in the volcanic formation, the equigranular volcanite bed, is exposed south of Metsämonttu, about 300 m south of the ore deposit (Fig. 1). It shows a dome-like rounded structure, some 400 × 400 m in size, which is almost completely surrounded by a tuff with quartz and plagioclase phenocrysts and which rests stratigraphically on equigranular tuff. Interlayers of equigranular, potassium-bearing (microcline-bearing) tuffite occur in the upper part of the unit of volcanite with quartz and plagioclase phenocrysts, close to the contact with the intermediate-basic volcanite group. In the top portion of the unit the contacts between the layers are often rich in skarn minerals. The sulfide horizon proper is located in the upper part of the acidic pyroclastite with skarn and carbonate rock interlayers. In the lateral extension of the sulfide horizon there is first a pyrite-rich horizon (the sulfide facies of iron-formation) that is succeeded by the horizons of the banded iron-formation (the oxide facies of iron-formation).

The intermediate-basic volcanite unit resting on the acidic volcanite formation is a product of volcanic activity. It contains agglomerate and tuff interlayers, which were formed during a stage of active volcanism, and tuffite interlayers which refer to subdued volcanism. As a rule the tuffite interlayers are most abundant at the base of the unit, where narrow diopside skarn and mica(biotite)-rich interlayers, from 1 to 10 cm in thickness, alternate.

In the Orijärvi area there are two mineralized horizons in the zone of andalusite-, cordierite-, seri-

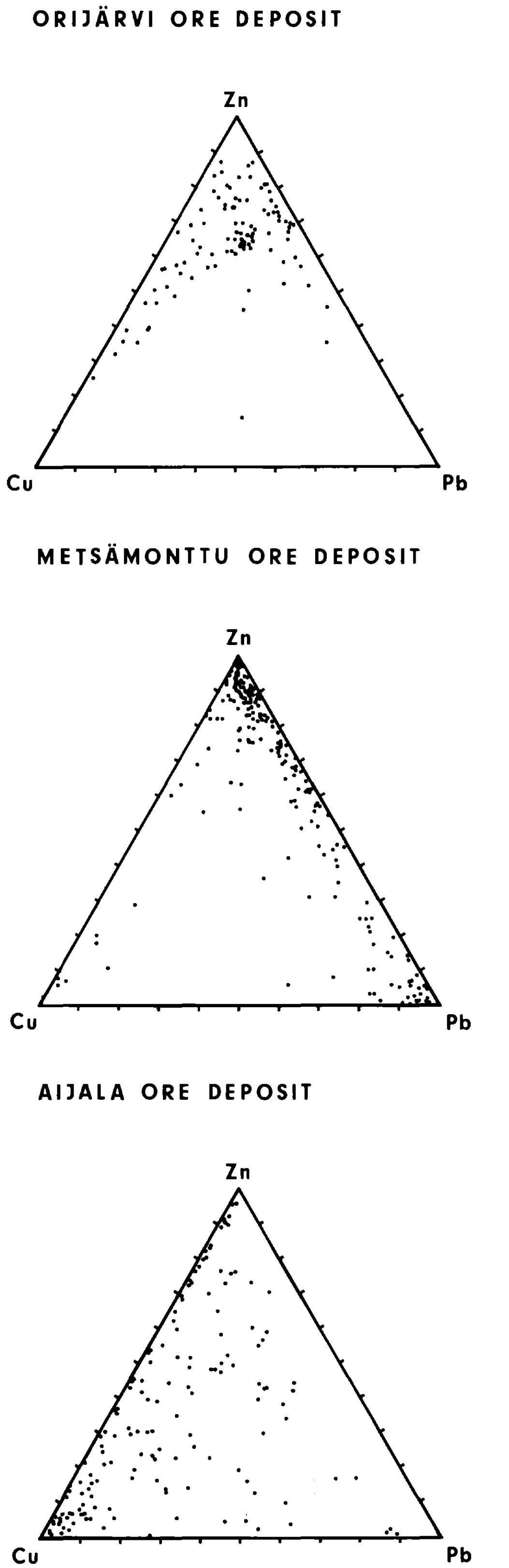

FIG. 7. Compositions of the Aijala, Metsämonttu, and Orijärvi ores in a Cu-Zn-Pb triangular diagram.

cite-, and anthophyllite-bearing rocks; the ore deposit is located in the lower part of this zone. The second mineralized horizon is the upper part of the zone and includes a small Zn-Pb-Au-Ag showing (Iillampi) about 1.7 km northwest of the Orijärvi ore deposit. Its wall rocks contain andalusite-bearing cordierite sericite mica gneisses that often have gahnite as an accessory. Higher in the sequence above the Orijärvi deposit there are andalusite-sericite mica gneisses with a narrow magnetite-bearing skarn interlayer (Fig. 8).

Cordierite- and anthophyllite-bearing lenses occur in the zone in several horizons, although only some of them are related to the mineralized horizons. In composition and texture the rocks vary greatly in and among the lenses, ranging from cordierite-anthophyllite gneisses to cordierite-anthophyllite mica gneisses and rocks. Some of these rocks, however, show primary layering as relict structure. The cordierite-anthophyllite rock below the Orijärvi deposit is homogeneous and coarse-grained. A hypabyssal contact variant with quartz phenocrysts of synorogenic granodiorite is encountered about 200 m southwest of the Orijärvi deposit.

Mode of occurrence of the ores

The ore deposits consist of several separate orebodies, small in size and narrow and elongated in shape. Their major axis lies parallel to the b-lineation of folding phase F_2. The orebodies occur either side by side or en enchelon, depending on their relation to the fold structures (Figs. 9 and 11). The shapes of the Aijala, Metsämonttu, and Orijärvi orebodies have been affected by folding phase F_2, whose direction parallels the major axes of the orebodies. In Aijala and Metsämonttu the axis is subvertical, about 80° to 85° southwest, but at Orijärvi it is somewhat less steep, 45° to 50° northeast. The Orijärvi ore deposit is cut by a subvolcanic dike of basaltic composition, which further enhances its incoherent character.

Postfolding fault and shear zones brecciate and cut the orebodies. Often associated with them are dense joint networks filled with narrow zeolite veins or slickensides coated with chlorite. The largest displacements are due to faults that cut the Metsämonttu deposit and whose surface is coated with unmetamorphosed clay.

The Aijala copper ore deposit contains several separate orebodies (Figs. 9 and 10). As shown by Figure 9 there is a fold structure at the eastern end of the formation in which the orebodies conform with the axial plane foliation of a fold (F_2). In the Metsämonttu deposit the dolomitic limestones and chlorite-bearing tremolite-diopside skarns are more

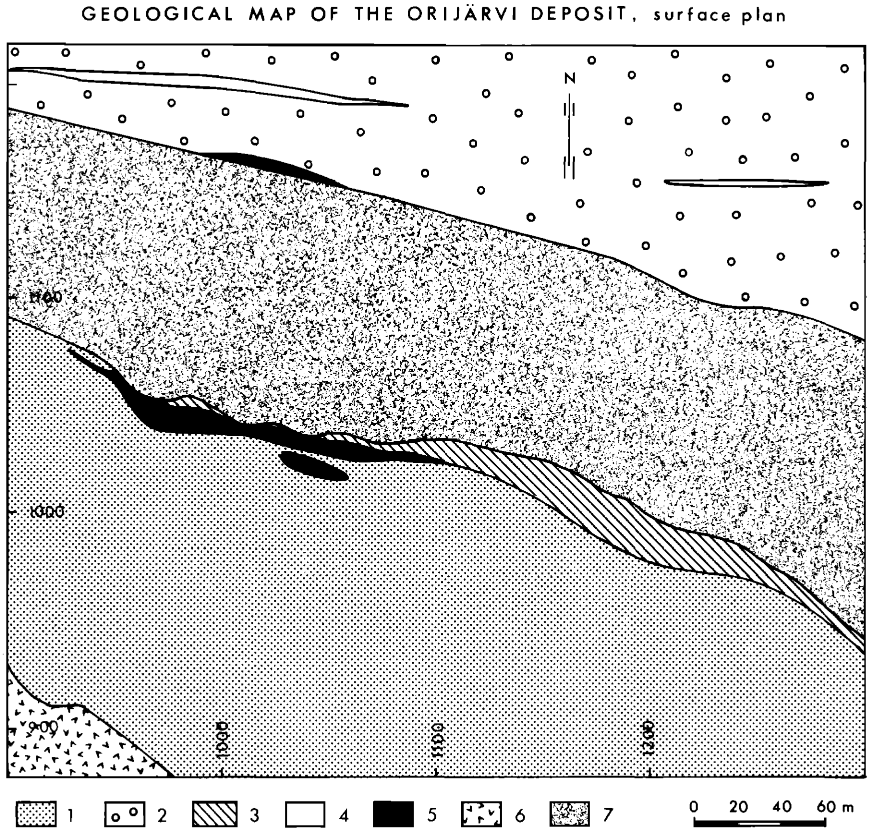

FIG. 8. Surface plan of the geology of the Orijärvi ore deposit: 1, cordierite-anthophyllite rock; 2, acidic cordierite-bearing sericite mica gnesis; 3, quartz rock; 4, magnetite-bearing skarn; 5, ore; 6, hypabyssal contact variant of granodiorite; and 7, basic, subvolcanic dike.

abundant close to the surface than deeper down (Figs. 11 and 12). The cordierite-anthophyllite rocks and cordierite mica gneisses increase in abundance from the upper part of the ore deposit downward so that at the +510 level they predominate distinctly over the dolomitic limestones and skarns. At the same time the size of the orebodies, notably their width but also their zinc and lead contents, decreases. The ores of the Aijala, Metsämonttu, and Orijärvi are at their thickest, up to 20 m, in the dolomitic limestones and skarns; in general, however, they are less than 10 m thick. Their length along the strike varies from 100 to 150 m.

The Orijärvi deposit resembles that of Metsämonttu; the wall rocks, distribution of metals, and their mode of occurrence are all much alike. The economic orebodies are located in chlorite-bearing tremolite-diopside skarns, although quartz rocks and cordierite-anthophyllite rocks also occur as wall rocks. At Orijärvi the orebodies are smaller and more broken than at Metsämonttu.

The lead in the Aijala and Orijärvi ores is 1,750 to 1,800 m.y. old (Kouvo and Kulp, 1961; Simonen et al., 1978). The sulfur isotope composition of the Aijala galena is $\delta^{34}S = -2.7$ per mil and that of the Orijärvi galena $\delta^{34}S = +0.0$ per mil (Ault and Kulp, 1960). To date no statistical studies have been done on the sulfur isotopes.

Ore types

Structural ore types: The ores of Aijala, Metsämonttu, and Orijärvi can be classified as breccia ores, massive vein ores, and disseminations.

The breccia ores are economically the most important ore types. In detail they clearly brecciate, cut, and replace the wall rocks but as a whole they conform with bedding. The contacts of the ores with the wall rocks are sharp in both structure and metal contents. As a rule the breccia ores occur in chlorite-bearing tremolite-diopside skarns, dolomitic limestones, and occasionally also in quartz rocks. They are submassive and contain only a few small wall-rock fragments. Microscopic examinations show that the sulfides replace amphiboles and pyroxenes along the cleavages and brecciate the carbonate, quartz phlogopite aggregates. The breccia ores in skarns and dolomitic limestones are distinctly richer in lead and silver than are the other ore types. The breccia ores in quartz rocks and cordierite mica gneisses are iron sulfide-predominant, with some sphalerite and sporadic chalcopyrite.

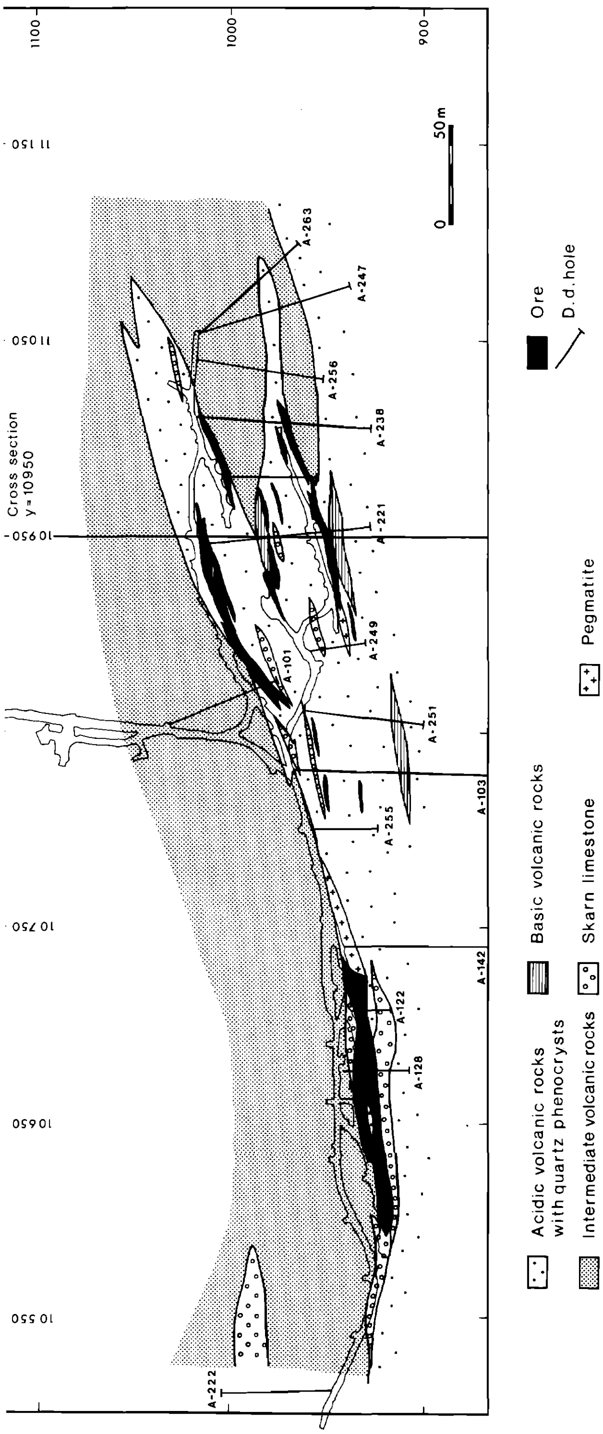

FIG. 9. Geologic plan of the Aijala ore deposit (+115 level).

Veins of massive sulfides from a few centimeters to several meters in width are common in all three ore deposits and are composed mainly of pyrrhotite and pyrite. The veins cut the wall rocks with sharp contacts and occasionally contain wall-rock fragments. The chlorite-bearing shears are filled with veins of remobilized iron sulfides or contain coarse-grained iron sulfide disseminations.

Disseminated sulfides occur in places in association with the breccia ores, replacing amphibole and pyroxene grains. A persistent dissemination of iron sulfides is met with in the cordierite-anthophyllite rocks and sericite or muscovite gneisses; the former contain pyrrhotite and pyrite but the latter only pyrite.

Compositional ore types: In chemical composition the ores of Aijala, Metsämonttu, and Orijärvi can be divided into several types.

The Aijala deposit consists of copper and pyrite orebodies. The copper orebodies occur predominantly from the surface down to the +220 level and contain sphalerite, galena, arsenopyrite, and iron sulfides in variable grades. As a rule the margins of the

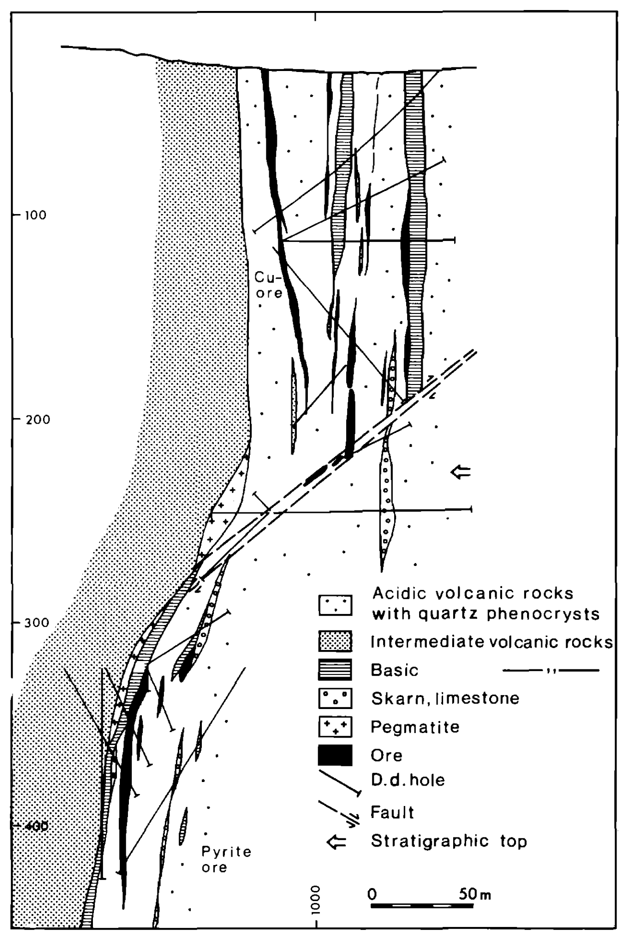

FIG. 10. Section across the Aijala ore deposit (section Y = 10,950).

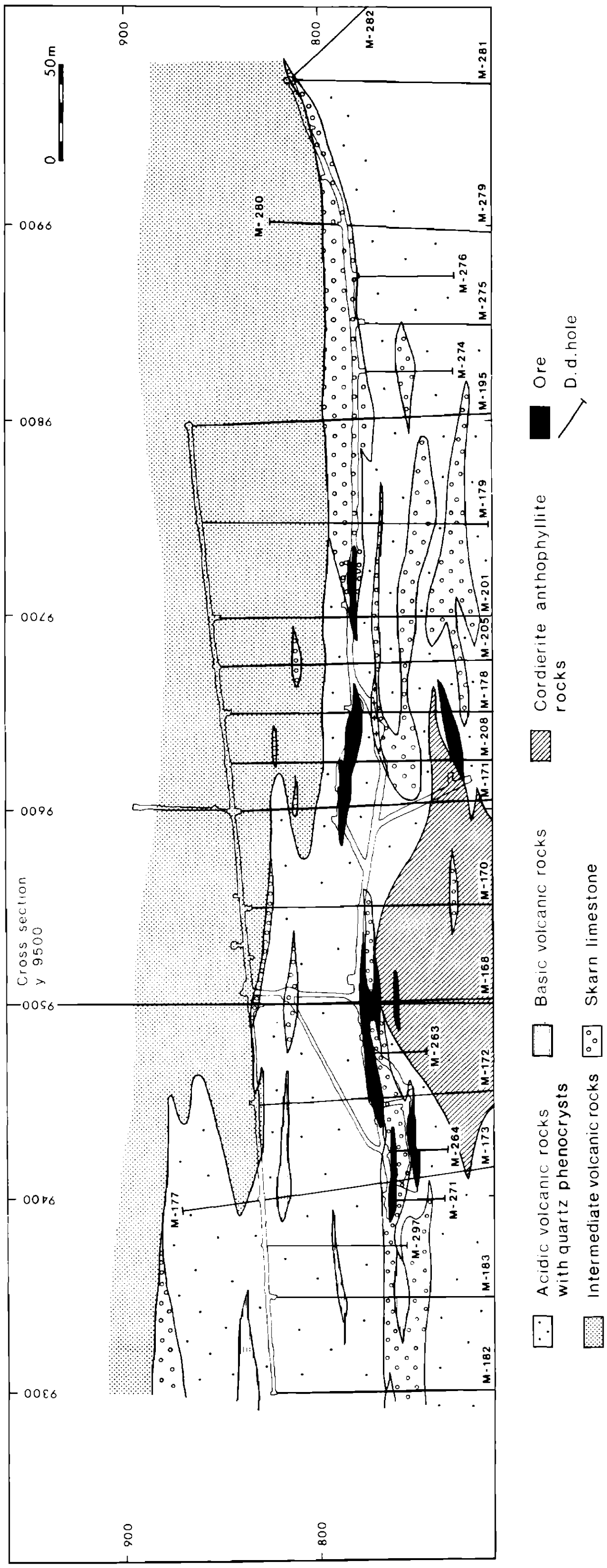

FIG. 11. Geologic plan of the Metsämonttu ore deposit (+320 level).

orebodies are richer in iron sulfides in relation to chalcopyrite than are the cores. The pyrite ores, with pyrite as the major ore mineral, occur in the downward continuation of the copper orebodies. Some trace elements in the ores show the following abundances expressed in geometric means: Ni, 48 ppm; Co, 74 ppm; and Hg, 10.44 ppm ($n = 37$).

On the basis of their chemical composition the orebodies in the Metsämonttu deposit can be classified as zinc-lead, zinc-iron, and copper orebodies. The zinc-lead orebodies occur mainly in chlorite-bearing diopside skarns and dolomitic limestones. The zinc-iron orebodies are located in muscovite and cordierite gneisses. The copper orebody in cordierite gneiss in the eastern part of the deposit has a slightly mineralized continuation that extends to the Aijala deposit. The geometric means of some trace element abundances are: Ni, 27 ppm; Co, 19 ppm; and Hg, 20.15 ppm ($n = 19$).

The ores at Aijala and Metsämonttu are exceptionally rich in mercury, which correlates distinctly with zinc; highest recorded mercury content was 142 ppm. Some samples were assayed for Sb, which correlates with lead; the highest abundance encountered was 575 ppm Sb.

The Orijärvi ore deposit has the same ore types as the Metsämonttu deposit. At Orijärvi, however, they do not form such discrete systems as at Metsämonttu but occur in narrow, broken, and discontinuous orebodies. In both places the ores show variations in the (Zn, Pb)/Cu ratio among the orebodies: the ores in the dolomitic limestones or skarns have a higher (Zn, Pb)/Cu ratio than those in cordierite-anthophyllite rocks. At Orijärvi the occurrence of copper in the cordierite-anthophyllite rocks is more common than it is at Metsämonttu.

Ore mineralogy

The Aijala, Metsämonttu and Orijärvi deposits are simple in ore mineralogy. Pyrrhotite, pyrite, chalcopyrite, sphalerite, and galena are the major ore minerals and only their mutual abundances vary from deposit to deposit and orebody to orebody. The deposits show, however, a marked difference in the accessory minerals.

The ore minerals fill cracks in or replace silicates. They also occur as veins of massive sulfides, blebs, and disseminations. Fault and shear zones of different ages have affected the ore, remobilizing and recrystallizing it partly. The sheared ores have been susceptible to supergene alterations, which are best manifested at Aijala in the alteration of pyrrhotite into pyrite and marcasite; the unsheared ores are practically unaltered.

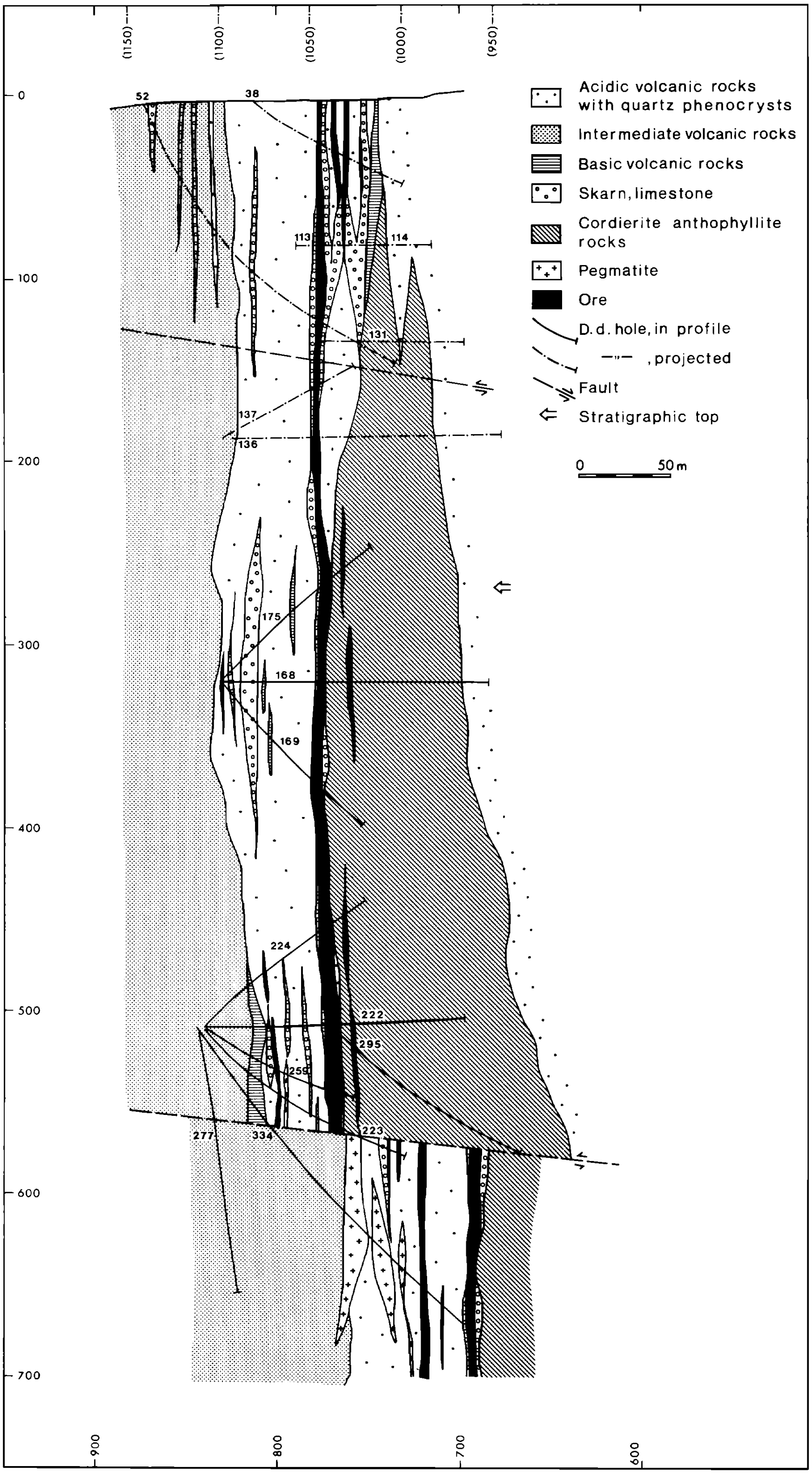

Fig. 12. Section across the Metsämonttu ore deposit (Y = 9,500).

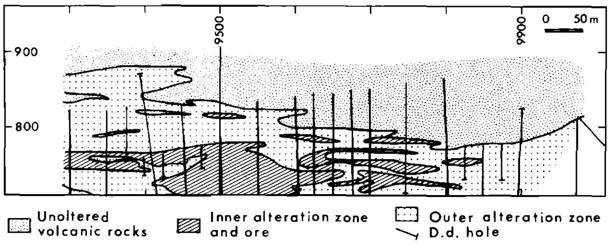

FIG. 13. Plan of the Metsämonttu ore deposit showing the alteration zones associated with the ore (+320 level).

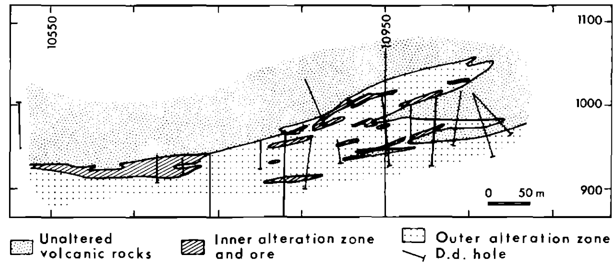

FIG. 15. Plan of the Aijala ore deposit showing the alteration zones associated with the ore (+115 level).

The mineral assemblage of the Aijala ore contains pyrite, pyrrhotite, and chalcopyrite as major ore minerals. Sphalerite, galena, and arsenopyrite also occur. Cubanite, magnetite, fahlore, native silver, and various sulfosalts in association with galena are the accessories. Pyrrhotite often exhibits deformation lamellae and pyrite cataclastic fracturing.

Three ore mineral assemblages occur in the Metsämonttu deposit, both separately and together with other assemblages:

1. The predominant ore minerals in the zinc-lead ores are sphalerite, galena, pyrrhotite, and pyrite. Chalcopyrite, boulangerite, tetrahedrite, arsenopyrite, molybdenite, magnetite, and geochronite are the accessories, to mention but a few. Various sulfosalts and native metals, such as arsenic, antimony, bismuth, silver, and gold, are often encountered in association with galena. Sphalerite frequently contains exsolution bodies of chalcopyrite and pyrrhotite. Boul-

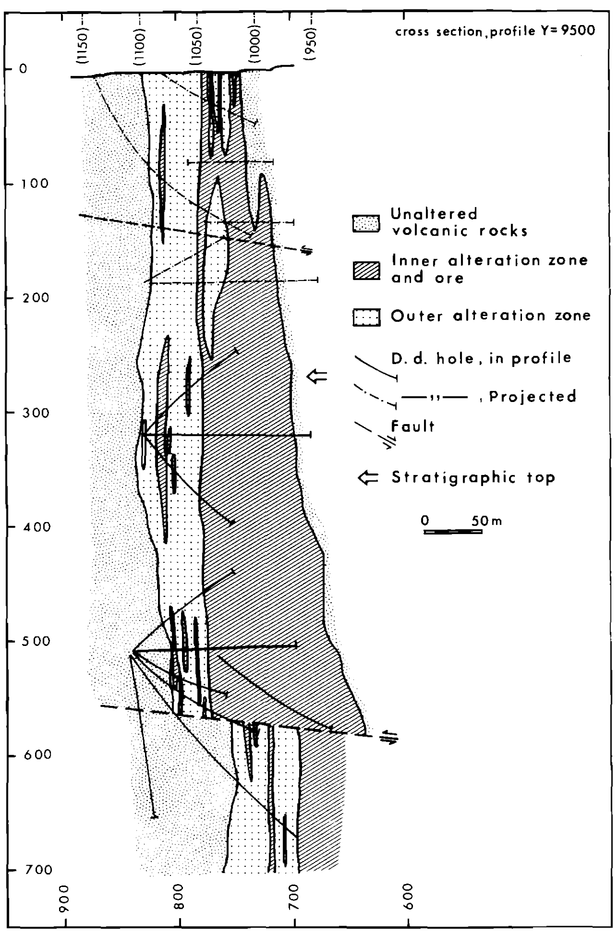

FIG. 14. Section across the Metsämonttu ore deposit showing the alteration zones (Y = 9,500).

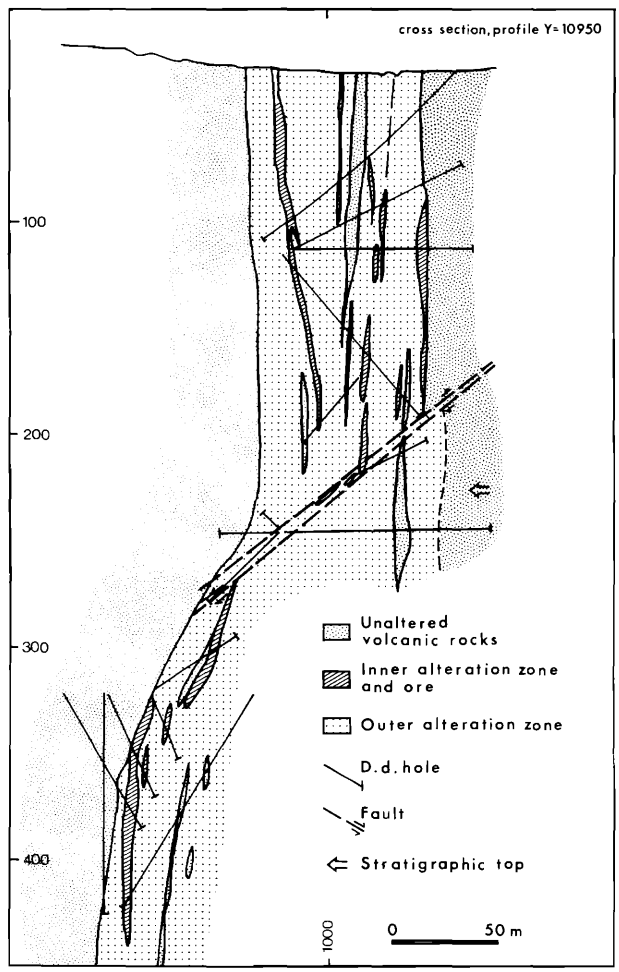

FIG. 16. Section across the Aijala ore deposit showing the alteration zones (Y = 10,950).

angerite occurs mainly as inclusions in galena. Chalcopyrite exhibits cubanite lamellae and tetrahedrite inclusions.

2. The predominant ore minerals in the zinc-iron ores are pyrrhotite, pyrite, and sphalerite. Chalcopyrite, galena, magnetite, ilmenite, and marcasite are the accessories. Marcasite is a supergene alteration product of pyrrhotite. Sphalerite often shows exsolved pyrrhotite.

3. The copper ores contain chalcopyrite, pyrrhotite, and pyrite as major minerals and galena, sphalerite, cubanite, and native gold as accessories.

The major ore minerals of the ore types at Orijärvi are the same as those at Metsämonttu. Chalcopyrite, however, is more often included in the major minerals. In addition to it the ores contain sphalerite, galena, pyrrhotite, and pyrite. The predominant accessories are ilmenite, magnetite, fahlore, gudmundite, molybdenite, uraninite, cubanite, and native gold. Sulfosalts and silver minerals as well as various native metals are rather rare.

Altered Rocks

General

The dolomitic limestones, chlorite-bearing tremolite-diopside skarns, quartz rocks, cordierite-biotite gneisses, cordierite-anthophyllite rocks, and often also cordierite-bearing sericite and muscovite schists and gneisses that are associated with the Aijala, Metsämonttu, and Orijärvi ores are considered as rocks of altered chemical composition; the degree of alteration in the rocks varies greatly, however.

The rock types in the alteration zones at Orijärvi and Metsämonttu (Figs. 13 and 14) are similar; at Metsämonttu, though, the pattern is simpler. In both deposits cordierite-anthophyllite rocks occur below the ore as funnel-shaped alteration pipes related to the mineralization and are generally located close to the volcanic discharge channel. Above, partly below, and on the continuation of both deposits there is a "blanket" type of alteration zone consisting of cordierite-bearing sericite and muscovite schists and gneisses. Folding, deformation, and the remobilization of ores have to a certain extent affected mutual locations of the ores and the alteration zone.

The alteration zone of the Aijala ores is of the blanket type and no alteration pipe has been encountered around the ores (Figs. 15 and 16). The alteration zone is composed of cordierite-bearing sericite and muscovite schists and gneisses, chlorite-bearing tremolite-diopside skarns, and dolomitic limestones.

On the basis of the areal distribution and chemical composition of the rock types the alteration zones associated with the ores can be divided into an inner alteration zone, composed of the alteration pipe and the wall rocks of the ore lenses, and an outer zone, made up of blanket-type altered acidic rocks.

In the following the alteration zones of the Aijala and Metsämonttu ores are discussed, but the characteristics are applicable also to the Orijärvi ore deposit.

Outer alteration zone

The outer alteration zones of the Aijala, Metsämonttu, and Orijärvi deposits have undergone sericitization. The internal heterogeneity of the zones partly reflects the primary heterogeneity of the tuffs with quartz and plagioclase phenocrysts and partly the variation in the degree of alteration. The zones exhibit all the intermediate types from slightly altered cordierite- and sericite-bearing acidic rocks with quartz eyes to completely altered sericite and muscovite schists and gneisses. Some of the quartz eyes are relicts of quartz phenocrysts. The contact of the outer alteration zone with the underlying acidic tuff is gradual.

The Aijala and Metsämonttu deposits have a common outer alteration zone, which is about 3 km long and extends from west of the Metsämonttu deposit to east of the Aijala deposit. It is widest, 50 to 100 m, at Aijala but narrows down to 0.5 to 2 m in width in the extensions of the ore deposit.

The predominant minerals in the rocks of the alteration zone are quartz, plagioclase (An_{20-50}), muscovite, sericite, biotite, phlogopite, and cordierite. The quartz eyes are recrystallized quartz aggregates enveloped by mica. Plagioclase is partly or completely sericitized and the cordierite porphyroblasts pinitized. Pyrite, which often occurs as disseminations, is the most common opaque.

Inner alteration zone

The rocks in the inner alteration zone have undergone varying degrees of magnesium-iron metasomatism and silicification. The impure limestones have turned into dolomitic limestones and chlorite-bearing tremolite-diopside skarns. The acidic tuffs with quartz and plagioclase phenocrysts have altered into cordierite-biotite gneisses, and cordierite-anthophyllite rocks. The former contain sporadic quartz eyes. The plagioclase phenocrysts are partly or completely altered. The quartz rocks are the result of the silicification of an acidic rock.

Quartz rocks and chlorite-bearing tremolite-diopside skarns are only encountered as wall rocks of the ores. The cordierite-anthophyllite rocks and cordierite-biotite gneisses constitute alteration pipes below the Metsämonttu and Orijärvi ore deposits; in the Metsämonttu deposit the pipe is about 100 to 200 m long and 50 to 100 m wide, extending down

TABLE 5. Chemical Compositions of Rocks in the Alteration Zones associated with the Ores in the Aijala-Orijärvi Area

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	82.15	87.4	23.41	58.72	56.29	43.71	65.85	60.6	43.55	57.65	74.34	76.47	64.9	51.60
TiO_2	0.10	0.1	0.10	0.10	0.62	0.50	0.27	0.2	0.56	0.00	0.14	0.16	0.2	0.58
Al_2O_3	11.10	5.6	3.71	11.51	17.98	18.84	13.07	19.7	20.50	16.84	14.19	10.28	18.4	26.9
Fe_2O_3	0.15[1]	0.15[1]	0.15[1]	0.15[1]	0.93[1]	0.75[1]	0.41[1]	0.5	0.84	0.85	0.21[1]	0.24[1]	1.2	0.87[1]
FeO	0.41	3.3	7.13	1.59	9.23	18.65	5.65	8.6	10.98	10.33	1.52	3.30	4.5	3.51
MnO	0.01	0.0	0.31	0.03	0.11	0.12	0.03	0.2	0.01	0.00	0.02	0.02	0.0	0.01
MgO	0.28	3.1	11.39	9.94	7.68	9.40	2.59	8.6	15.01	5.30	2.14	1.93	4.8	7.24
CaO	1.71	0.1	30.76	11.17	1.65	0.63	4.13	0.2	0.36	1.28	1.58	1.65	2.3	2.50
Na_2O	2.38	0.1	0.15	0.43	0.37	0.36	2.05	0.1	0.44	2.34	2.22	1.69	0.3	1.57
K_2O	1.59	0.0	0.09	1.34	0.86	1.59	2.11	0.4	4.70	2.36	2.38	1.80	2.2	4.07
H_2O^+	0.07	{0.3	0.08	0.11	0.17	0.22	0.09	{0.9	2.12	1.60	0.09	0.06	{1.2	0.89
H_2O^-	0.15		1.82	1.71	2.32	2.64	1.53		0.12	1.08	1.00	0.72		0.12
P_2O_5	0.03	nd	0.05	0.06	0.13	0.18	0.10	nd	0.17		0.03	0.06	nd	0.18
CO_2	0.25	nd	21.07	1.45		0.17	0.20	nd	0.16	nd	nd	nd	nd	0.03
Total	100.38	100.0	100.22	98.31	99.34	97.76	98.08	100.0	99.52	99.63	99.86	98.38	100.0	100.07
Cu	85	nd	68	2,530	40	155	380	nd	nd	nd	4	30	nd	nd
Zn	20	nd	115	123	148	105	500	nd	nd	nd	48	120	nd	nd
Ni	33	nd	45	35	48	5	25	nd	nd	nd	20	35	nd	nd
Co	23	nd	45	58	44	75	35	nd	nd	nd	12	0	nd	nd
Pb	490	nd	113	17,150	60	0	65	nd	nd	nd	28	85	nd	nd
S	0.05	nd	2.05	0.83	0.72	3.52	2.70	nd	nd	nd	0.07	2.45	nd	nd
Q	58.0	79.5		18.6	26.2	5.9	30.2	38.6		16.5	45.3	52.2	40.0	8.9
C	2.4	5.3			13.1	16.7	0.15	18.9	14.9	8.4	5.2	2.8	11.5	16.1
Or	9.4			8.3	11.4	9.9	13.0	2.4	28.6	14.4	14.3	10.9	13.2	24.5
Ab	20.2	0.85		3.8	3.2	3.2	18.9	0.85	3.8	20.4	19.0	14.6	2.6	13.5
An	8.3	0.50	11.9	26.8	7.6	2.1	20.6	1.0	0.70	6.5	7.7	8.0	11.5	11.4
Di				24.4										
Hy	1.2	13.7		17.4	35.6	59.6	16.7	37.2	27.3	32.5	7.9	10.7	19.1	24.0
Ol			39.1						22.0					
Fem	0.22		0.28	0.23	1.4	1.14	0.62	0.73	1.3	1.3	0.31	0.35	1.8	
Ilm	0.19	0.19	0.25	0.20	1.2	1.0	0.53	0.38	1.1		0.27	0.31	0.38	1.1
Ap	0.07		0.15	0.15	0.32	0.45	0.25		0.41		0.07	0.15		0.43

Wet chemical analyses.
[1] Fe_2O_3 calculated as 1.5 × TiO_2 (Irvine and Baragar, 1971).
Oxides and S in wt%, trace elements in ppm, nd = not determined.
CIPW norms according to Bingler et al. (1976).
1, Quartz rock, Metsämonttu.
2, Quartz rock, Orijärvi mine (Eskola, 1920).
3, Dolomitic limestone, Metsämonttu.
4, Skarn, Metsämonttu.
5, Cordierite mica gneiss, Metsämonttu.
6, Cordierite-anthophyllite rock, Metsämonttu.
7, Cordierite mica gneiss, Metsämonttu.
8, Cordierite-anthophyllite rock, Orijärvi mine (Eskola, 1920).
9, Cordierite-anthophyllite rock, Orijärvi.
10, Cordierite-anthophyllite rock, Orijärvi, Tarklahti (Eskola, 1914).
11, Cordierite-sericite mica gneiss, Metsämonttu.
12, Cordierite-sericite mica gneiss, Aijala.
13, Cordierite gneiss, Orijärvi mine (Eskola, 1915).
14, Cordierite-sericite mica gneiss, Iillampi, 1.7 km west of Orijärvi.

to a depth of at least 600 m. In the Orijärvi ore deposit the alteration pipe has not been intersected by drilling but according to available data it is over 400 m long and 200 m wide and reaches a depth of at least 250 m. In both deposits the cordierite-anthophyllite rock grades into cordierite-biotite gneiss. In Metsämonttu the contact with the underlying phenocrystic tuff is sharp.

The main minerals in the dolomitic limestone in the inner alteration zone are carbonate, diopside, tremolite, chlorite, olivine, and chondrite. The olivine grains are often serpentinized. The main minerals in the tremolite-diopside skarns are diopside, tremolite, chlorite, biotite, phlogopite, quartz and plagioclase (An_{40-60}) with occasional opaques and carbonate. In the quartz rocks the predominant mineral is quartz, in addition to which they contain variable amounts of muscovite, opaques, and chlorite. The cordierite mica gneisses are composed of quartz, biotite, phlogopite, cordierite, and plagioclase (An_{25-35}) with occasional microcline and muscovite. Cordierite often shows pinitization and plagioclase sericitization.

In the cordierite-anthophyllite rocks, cordierite, anthophyllite, phlogopite, biotite, chlorite, quartz, and plagioclase (An_{20-30}) are the main minerals, with magnetite as a common accessory. There are variants that are free from plagioclase and contain quartz as the sole light mineral.

Chemical Composition of the Altered Rocks

The altered rocks and the lithologic groups in the alteration zones show changes in chemical composition compared with the presumed primary rocks. If the comparison is based on the chemical composition of the unaltered rocks, such as impure limestones or acidic tuffs (Tables 5 and 6), the gains and losses of the elements can be estimated.

Diagrams corresponding to those of the volcanites were constructed for the altered rocks; these include SiO_2 vs. $Na_2O + K_2O$ (Fig. 17), AFM (Fig. 18), normative anorthite in plagioclase vs. Al_2O_3 (Fig. 19), and the Ab-An-Or diagram (Fig. 20). In all these figures a distinction is made between the rocks of the inner and outer alteration zones.

The primary rocks differ in composition and hence the diagrams of the altered rocks also show large scatter; nevertheless, the following generalizations can be made.

1. The rocks in the inner alteration zone are frequently poorer in SiO_2 and alkalies and richer in MgO and FeO than the rocks in the outer alteration zone. There are, however, no differences in the compositions of the normative feldspars.

2. Comparison of the diagrams of the volcanites and altered rocks shows that the sum of alkalies in the rocks of the inner zone is on an average lower than that in the volcanites (Fig. 17). As a rule the altered rocks are also richer in MgO in relation to FeO and alkalies (Fig. 18). Moreover the volcanites are poorer in K_2O and CaO in relation to Na_2O than the altered rocks (Fig. 20).

3. If it is presumed that the primary compositions of the altered rocks were those of the tuffs with quartz and plagioclase phenocrysts and impure limestones; a rough estimate can be made of the changes in the element abundances. Table 6 shows the chemical compositions of the unaltered rocks and the geometric means and standard deviations of the chemical compositions of the altered rocks. If the rocks were altered at constant volume, then the abundances of all the main elements must have changed.

4. In the outer alteration zone sericite and muscovite schists and gneisses are depleted in SiO_2, Na_2O, and CaO, whereas the abundances of MgO, Al_2O_3, FeO, and K_2O have increased. The TiO_2, MnO, and P_2O_5 contents are slightly higher than they are in the tuff with quartz and plagioclase phenocrysts.

5. If the quartz rocks in the inner alteration zone were primarily similar to the acidic tuff in composition, then the SiO_2 content increased in the alteration process, the TiO_2 has remained the same, and the contents of all the other main elements have decreased, notably those of Al_2O_3, Na_2O, and CaO. The cordierite-biotite gneisses and cordierite-anthophyllite rocks of the alteration pipes show the most distinct gain in MgO, FeO, Al_2O_3, and TiO_2 compared with the acidic tuffs. They also exhibit slightly higher MnO and P_2O_5 contents than the acidic tuffs,

TABLE 6. Chemical Compositions of Unaltered and Altered Rocks

	Unaltered rocks		Alteration zones: Outer		Alteration zones: Inner							
	Tuff with quartz and plagioclase phenocrysts n = 1 d = 2.68	Limestone n = 1 d = 2.71	Sericite-cordierite rocks n = 28 d = 2.70		Quartz rock n = 1 d = 2.67	Skarns and skarn-bearing rocks n = 15 d = 3.10		Cordierite mica gneisses n = 13 d = 2.71		Cordierite-anthophyllite rocks n = 11 d = 2.82		
			$\bar{x}_G$	SD		$\bar{x}_G$	SD	$\bar{x}_G$	SD	$\bar{x}_G$	SD	
SiO_2	77.59	8.47	71.66	4.40	82.22	37.86	19.97	62.51	4.46	56.19	4.32	
TiO_2	0.10	0.02	0.21	0.04	0.10	0.28	0.32	0.41	0.36	0.57	0.14	
Al_2O_3	11.75	1.16	13.38	4.35	11.11	14.61	2.60	18.51	3.84	17.86	2.45	
FeO^x	1.12	0.72	2.10	1.82	0.41	3.95	3.29	4.61	3.51	10.91	3.19	
MnO	0.02	0.13	0.09	0.05	0.01	0.98	0.05	0.15	0.21	0.15	0.09	
MgO	0.28	1.65	2.83	1.12	0.28	8.30	4.26	4.97	2.53	9.86	2.39	
CaO	1.86	51.47	1.57	1.73	1.17	10.82	6.75	2.02	2.76	1.26	2.04	
Na_2O	3.96	0.07	1.31	0.78	2.38	1.09	0.73	0.97	1.03	0.40	0.19	
K_2O	1.65	0.32	2.02	1.26	0.59	0.92	0.58	1.76	0.91	1.55	0.69	
P_2O_5	0.05	1.78	0.07	0.11	0.03	0.35	1.67	0.14	0.09	0.13	0.03	
Total	98.38	65.79	95.24		98.30	79.16		96.05		98.88		

XRF analyses.
$\bar{x}_G$ = geometric mean, SD = standard deviation, FeO^x = total iron as FeO, d = density.

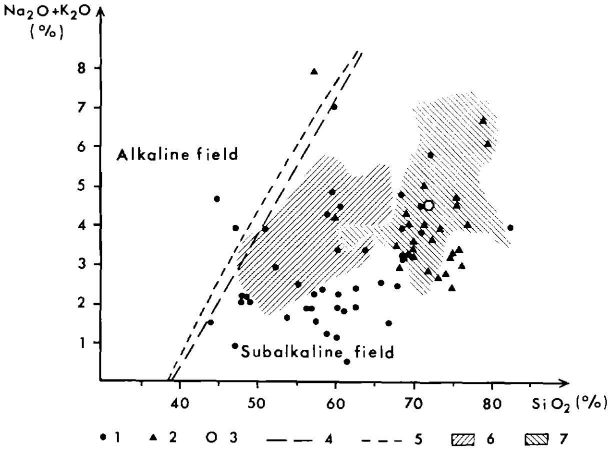

FIG. 17. SiO₂ vs. Na₂O + K₂O in altered rocks: 1, rocks in inner alteration zone; 2, rocks in outer alteration zone; 3, the parent rock. Boundaries: 4, MacDonald and Katsura (1964); 5, Irvine and Baragar (1971); 6, composition fields of basic and intermediate volcanites; 7, acidic volcanites in the Aijala-Orijärvi area.

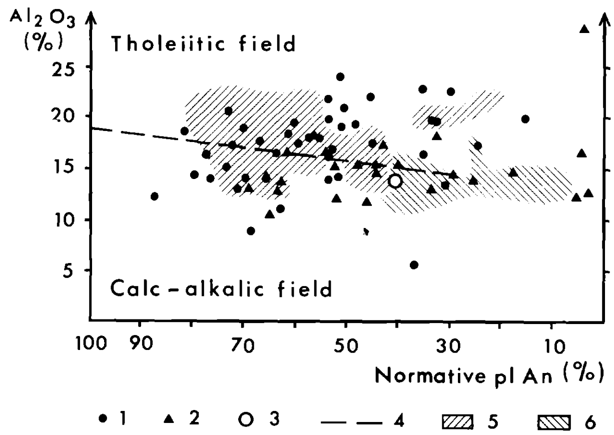

FIG. 19. Al_2O_3 vs. anorthite content in normative plagioclase for the altered rocks: 1, rocks in inner alteration zone; 2, rocks in outer alteration zone; 3, the parent rock. Boundary: 4, Irvine and Baragar (1971); 5, composition field of basic and intermediate volcanites; 6, acidic volcanites in the Aijala-Orijärvi area.

provided that the volume has remained constant. The abundances of SiO_2 and Na_2O, however, have decreased.

6. The skarns that primarily were carbonate-bearing tuffs with quartz and plagioclase phenocrysts (in the contacts between the layers) were depleted in SiO_2, Na_2O, and K_2O and enriched in MgO, FeO, and Al_2O_3. The abundances of MnO and TiO_2 probably also increased while the abundance of CaO remained the same.

7. In chemical composition the dolomitic limestones and some of the skarns in the inner alteration zone were originally impure limestones. In the dolomitic limestones the MgO and FeO contents increased while the CaO content decreased. The skarns were depleted in CaO and P_2O_5 whereas the other main elements increased in abundance.

8. Figure 21 illustrates the change in main element abundances across the Metsämonttu ore deposit at the +510 level. The differences between the compositions of the unaltered intermediate-basic tuff above the ore on the left and the outer and inner alteration zones to the right of it are distinct as are the internal elemental variations within the zones.

9. In the inner alteration zone, or alteration pipe, the average abundances of FeO, MgO, TiO_2, and S are higher than in the outer alteration zone or in the intermediate-basic volcanites. Figure 21 also shows that the MgO and S abundances decline almost linearly stratigraphically downward from the ore (to

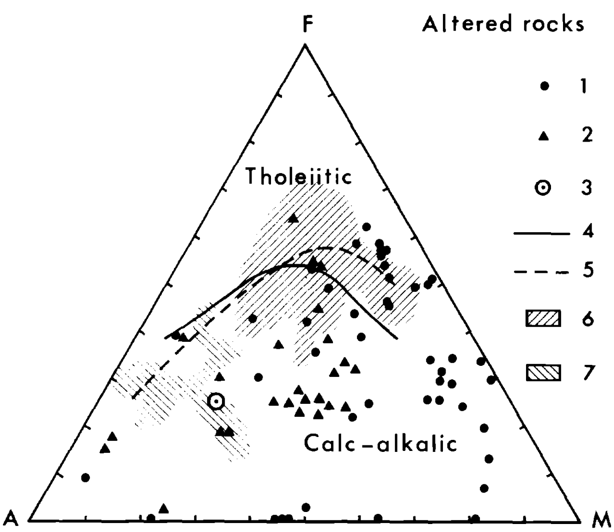

FIG. 18. Chemical compositions of altered rocks in an AFM diagram: 1, rocks in inner alteration zone; 2, rocks in outer alteration zone; 3, the parent rock. Boundaries: 4, Irvine and Baragar (1971); 5, Kuno (1954); 6, compositions of basic and intermediate volcanites; 7, acidic volcanites in the Aijala-Orijärvi area.

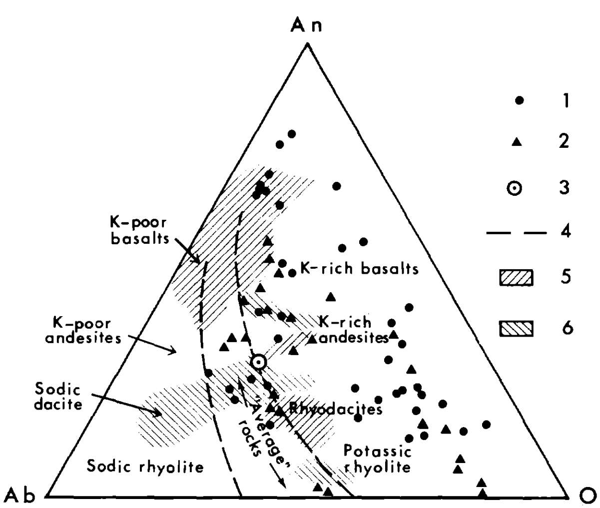

FIG. 20. Chemical compositions of altered rocks in a normative Ab-An-Or triangular diagram: 1, rocks in inner alteration zone; 2, rocks in outer alteration zone; 3, the parent rock; 4, average compositions and boundaries of rocks according to Irvine and Baragar (1971); 5, composition fields of basic and intermediate volcanites; 6, acidic volcanites in the Aijala-Orijärvi area.

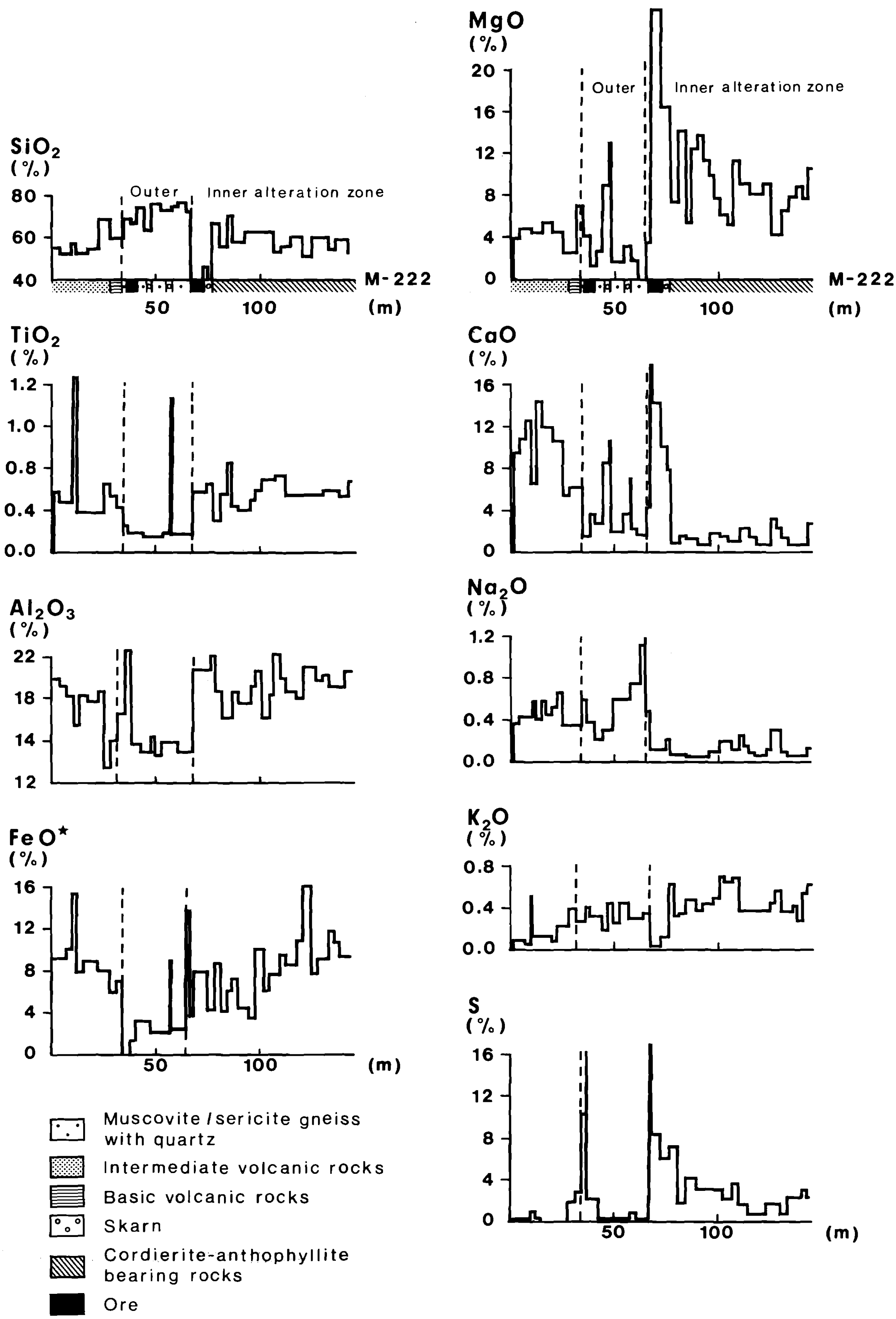

FIG. 21. Contents of major elements across the Metsämonttu ore deposit. The top of the deposit is on the left.

the right in Fig. 21), whereas the FeO abundances increase outward from the ore. The MgO/FeO ratio is highest adjacent to the ore and decreases gradually away from it.

Discussion

Both the Precambrian volcanic-exhalative massive sulfide ores and the younger Kuroko type of Zn-Pb-ores are associated with hydrothermal alteration zones (Tatsumi et al., 1972; Sangster, 1974).

The Kuroko-type ores occur on the flanks of domes composed of acidic, rhyolitic-dacitic pyroclastic volcanites. Lower-most there is a copper-bearing pyrite ore that is succeeded by a barite-bearing Zn-Cu-Ag polymetallic sulfide ore. The alteration related to the ores constitutes four zones: outer-most is the montmorillonite and zeolite zone; this is succeeded by the sericite-chlorite-pyrite zone, the sericite-chlorite-quartz zone and, closest to the ore, the silicified zone (Matsukuma and Horikoshi, 1970), which contains some sericite and chlorite. According to Iijima (1974), in the Hokuroku area all the alteration zones associated with Kuroko ores are characterized by magnesium metasomatism. Potassium metasomatism has affected the sericite and chlorite zones. In contrast, the montmorillonite zone is depleted in potassium. The sericite-chlorite zone has lost potassium and all the zones are depleted in sodium.

The alteration took place owing to the influence of sea water on unconsolidated sediments. In the ore deposits the alteration zones occur in both the footwall and hanging wall of the ore, i.e., the deposits show an alteration pipe and blanket-type alteration zones.

Precambrian massive sulfide ores occur in pyroclastic volcanites that vary from dacite to rhyolite in composition on the flanks of the volcanic domes. The acidic pyroclastic rocks show layers with quartz phenocrysts or agglomerates containing the sulfide fragments known as "mill rock" (Stanton, 1960; Sangster, 1974; Hopwood, 1976; Vernon and Flood, 1977). They are subdivided into distal and proximal types whose characteristics have been described by Plimer (1978).

Sangster (1974) maintains that acidic intrusions are more frequent than basic or ultrabasic intrusions in the environment of massive sulfide ores. The acidic intrusions represent that part of the magma of acidic volcanism which later invaded the supracrustal rocks. The ores exhibit zonality similar to that of the Kuroko ores; the hanging wall of the ore is predominantly zinc-lead and the footwall predominantly copper-pyrite. The ores have lost their primary structures as a result of postdepositional metamorphism and several deformation stages.

The wall rocks of the ores are altered, showing an alteration pipe in the footwall. Sericitization, silicification, carbonatization, and chloritization are the principal types of alteration. The latter is related to magnesium metasomatism. With the increase in the degree of metamorphism the chloritized zone has often altered into cordierite-anthophyllite rocks (Sangster, 1974).

The behavior of the elements in the alteration zone of the massive Precambrian sulfide ores is not as regular as in the Kuroko ores but varies from one deposit to the other. Generally the alteration zones show a gain in magnesium, iron, and manganese and a loss in sodium, calcium, and silicon. Depending on the deposit, aluminium, potassium, and titanium are considered as elements whose contents have remained almost unchanged (Simmons et al., 1973; Franklin et al., 1975; Nichol et al., 1977).

Alteration zones associated with Precambrian sulfide ores have been described from Canada by Descarreaux (1973), Spitz and Darling (1975), Franklin et al. (1975), Roberts and Rearden (1978), and MacGeehan (1978). Nilsson (1968), who has described the alteration zone of the Boliden copper ore in Sweden, subdivides the zone into three subzones: nearest to the ore is the innermost alteration zone with andalusite- and quartz-rich sericite-quartz schists. It is depleted in iron and magnesium but enriched in aluminum, potassium, titanium, silicon, and water. The middle alteration zone is composed of pale sericite-quartz schist, and it, too, has lost iron and magnesium. The outermost zone is composed of chlorite-bearing sericite-quartz schist and is enriched in magnesium, iron, sulfur, and water in relation to the other elements. Nilsson (1968) also points out that all three alteration zones are depleted in sodium and calcium in relation to the other elements.

The alteration zone associated with the Kalvbäcken Zn-Pb ore of the Falun type has undergone magnesium metasomatism and silicification. The zone includes quartz rocks, Ca-Mg skarns, and Mg skarns (Hübner, 1966).

The Vihanti ore deposit in Finland has an alteration zone of cordierite gneiss, skarns, and dolomite with a gain in magnesium (Rouhunkoski, 1968).

With reference to the data in the literature on Precambrian massive sulfide ores and Kuroko ores, the Aijala, Metsämonttu, and Orijärvi deposits exhibit features that are typical of both ore types.

At Aijala and Metsämonttu the environment of the ore deposits is composed of acidic and intermediate-basic pyroclastic rocks. The ores occur in acidic volcanites close to the contacts between the rock types. The volcanites belong predominantly to the calc-alkalic suite.

The Orijärvi ore deposit occurs in a zone of cordierite-sericite and cordierite-anthophyllite rocks that grade into an unaltered acidic volcanite through a cordierite-sericite schist.

Although ores are of breccia rather than massive type, all three deposits are roughly stratabound; in detail, however, they cut the wall rocks. The metals are distributed in the orebodies at Orijärvi, Aijala, and Metsämonttu in such a manner that the stratigraphic upper parts are richer than the lower parts in zinc and lead in relation to copper. The wall rocks of the ores include dolomitic limestones, chlorite-bearing tremolite-diopside skarns, quartz rocks, cordierite-bearing sericite and muscovite gneisses and schists, cordierite-biotite gneisses, and cordierite-anthophyllite rocks.

A blanket type of alteration zone and an alteration pipe are associated with the Metsämonttu and Orijärvi ore deposit. Only the blanket type of alteration has been encountered at Aijala.

Sericitization has taken place in the outer zone, due to which the abundances of SiO_2, Na_2O, and CaO have decreased and those of MgO, Al_2O_3, FeO, and K_2O have increased, provided that the alterations took place in constant volume and that the primary composition of the rocks was that of tuffs with quartz and plagioclase phenocrysts. The inner alteration zone is characterized by magnesium-iron metasomatism and silicification. The magnesium-iron metasomatism enhanced the abundances of MgO, FeO, Al_2O_3, and TiO_2 but reduced those of SiO_2 and Na_2O. The silicification depleted the zone in all elements except SiO_2.

Summary and Conclusions

The volcanism in the Aijala-Orijärvi area was predominantly calc-alkalic, although tholeiitic layers are also encountered. The volcanites of the intermediate-basic and basic volcanite group are largely volcanoclastic rocks that formed under submarine conditions. The basaltic pillow lavas, the layering and laminar structure in the tuffites and the limestones, and the banded iron-formations encountered in the area all suggest eruptions in fairly shallow water.

Predominantly calc-alkalic volcanites occur at the margins of the present island arcs and continents (Miyashiro, 1974). Geological features similar to those of recent young island-arc formations have been reported from the Precambrian Abitibi greenstone belts in Canada (Goodwin, 1974; Condie, 1976). The leptite zone characterized by acidic calc-alkalic volcanites in central Sweden and southwestern Finland, including the Aijala-Orijärvi area, has been correlated with an island-arc structure (Hietanen, 1975). According to Simonen et al. (1978), the lead isotope compositions of the ore deposits in southwestern Finland show that these deposits are located approximately in an orogenic zone, i.e., their lead derived from the earth's crust. In both Finland and Sweden Zn-Cu-Pb ores of Falun type occur in this volcanite environment and have many geological features in common.

It appears that when volcanic activity quieted down in the Aijala-Orijärvi area, the earth's crust sank and the geosyncline north of Orijärvi filled with sediments. The regional folding F_1 was very likely related to the diapiric uplift of the synorogenic intrusions. The folding stage F_2 occurred before the emplacement of the postorogenic microcline granites, because the synorogenic intrusive rocks exhibit lineation parallel to F_2, which is not detectable in the microcline granites. The regional metamorphism was partly contemporaneous with phase F_1 and continued during and after phase F_2. After the folding the area underwent block movements; the most marked produced the Kirkkojärvi-Kiskojoki and Jyly shear and fault zones, in both of which the eastern block was uplifted in relation to the western one (Tuominen, 1957).

Eskola's (1914, 1950) opinion was that the ores of Aijala, Metsämonttu, and Orijärvi are products of pneumatolytic metasomatism brought about by synkinematic granodiorite (oligoclase granite). The intrusion generated a zone of altered rocks in which iron and magnesium replaced calcium, sodium, and potassium, resulting in the formation of the cordierite-anthophyllite rocks and the ores.

The ores at Aijala, Metsämonttu, and Orijärvi were formed during a period of subdued volcanic activity. It was preceded by intense eruptions of acidic pyroclastites, which gave rise to the tuff bed with quartz and plagioclase phenocrysts. Because of its porosity, sea water and hydrothermal solutions circulated readily in the bed. Since quartz phenocrysts are encountered not only in the tuff with quartz and plagioclase phenocrysts but also in the matrix of the agglomerate layers and in the acid ejecta in the agglomerate, it is possible that some of the quartz phenocrysts were formed after the piling up of rocks. The silicon necessary for their formation could have precipitated from the thermal silica-bearing solutions circulating in the bed.

It was the porosity of the rock that allowed the metal-bearing solutions to circulate and the metals to precipitate. According to Large (1977) and Andrews and Fyfe (1976), the commonest carriers of metals are slightly acidic (pH 4–6) and reducing Na-Ca-Cl solutions from which metals precipitate when conditions change, e.g., when the temperature drops or when the pH, f_{O_2}, or sulfur content changes.

The Aijala and Metsämonttu ore deposits have a common blanket type of alteration zone. Below the Metsämonttu ore and associated with it is an alteration pipe that is generally believed to form in or close to a discharge channel (Sangster, 1974). Obviously the Aijala and Metsämonttu ores are genetically related to each other; thus the Aijala Cu-Zn ore represents the lower part of the ore formation and the Metsämonttu Zn-Pb ore the upper part. The ores occur in a common alteration zone with a slightly mineralized zone between them that extends from Aijala to Metsämonttu.

The Aijala, Metsämonttu, and Orijärvi ore deposits underwent several deformations, of which the most significant were due to folding phases F_1 and F_2, which gave the orebodies their present shape. Younger faults and shear zones cut the orebodies into pieces.

The Aijala, Metsämonttu, and Orijärvi deposits share some features with the Precambrian massive sulfide ores and the Kuroko type of Zn-Pb-Cu ores.

Acknowledgments

I am grateful to the Outokumpu Company for permission to undertake this study and publish the findings. I should also like to thank Professor H. Papunen, Mrs. Maija Huhma, and Mr. P. Hautala for the many fruitful and inspiring discussions about the geology of the Aijala-Orijärvi area. The manuscript was translated into English by Mrs. Gillian Häkli; Dr. T. A. Häkli offered assistance with the editorial work. To all these persons the author would like to record her appreciation.

Outokumpu Oy
P. O. Box 27
SF-02201 Espoo 20, Finland
March 12, 1979

REFERENCES

Andrews, A. J., and Fyfe, W. S., 1976, Metamorphism and massive sulphide generation in oceanic crust: Geoscience Canada, v. 3, p. 84–93.
Ault, W. U., and Kulp, J. L., 1960, Sulfur isotopes and ore deposits: Econ. Geol., v. 55, p. 73–100.
Bingler, E. C., Trexler, D. T., Kemp, W. R., and Bonham, H. F., Jr., 1976, Petcal: A Basic language computer program for petrologic calculations: Nevada Bur. Mines Geology, Rept. 28, p. 1–27.
Condie, K. C., 1976, Plate tectonics and crustal evolution: New York, Pergamon Press, Inc., 288 p.
Descarreaux, J., 1973, A petrochemical study of the Abitibi volcanic belt and its bearing on the occurrences of massive sulphide ores: Canadian Mining Metall. Bull., v. 66, no. 730, p. 61–69.
Du Rietz, T., 1968, Huvuddragen av Garpenbergstraktens bergbyggnad: Sveriges Geol. Undersökning., ser. C., no. 631, 22 p. (in Swedish)
Edelman, N., 1960, The Gullkrona region, SW-Finland: Comm. Géol. Finlande Bull., no. 187, 87 p.
Ehlers, C., 1976, Homogeneous deformation in Precambrian supracrustal rocks of Kumlinge area, southwest Finland: Precambrian Research, v. 3, p. 481–504.
Eskola, P., 1914, On the petrology of the Orijärvi region in south-western Finland: Comm. Géol. Finlande Bull., no. 40, 279 p.
—— 1915, On sambandet mellan kemisk och mineralogisk sammansättning hos Orijärvi-traktens metamorfa bergarter: Comm. Géol. Finlande Bull., no. 44, 145 p. (in Swedish)
—— 1920, Om metsomatiska omvandlingar i silikatbergarter: Norsk Geol. Tidsskr., no. 6, p. 89–107. (in Swedish)
—— 1950, Orijärvi re-interpreted: Comm. Géol. Finlande Bull., no. 150, p. 93–102.
—— 1963, The precambrian of Finland, *in* Rankama, K., ed., The Precambrian, v. 1: New York Interscience Pub., p. 145–264.
Franklin, J. M., Kasarda, J., and Poulsen, K. H., 1975, Petrology and chemistry of alteration zone of the Mattabi massive sulfide deposit: Econ. Geol., v. 70, p. 63–79.
Frietsch, R., 1975, Brief outline of the metallic mineral resources of Sweden: Sveriges Geol. Undersökning, ser. C., no. 718, 64 p.
Gavelin, S., Lundström, I., and Norström, S., 1976, Svecofennian stratigraphy on Utö, Stockholm archipelago: Sveriges Geol. Undersökning, ser. C., no. 719, 44 p.
Geijer, P., 1916, Falutraktens berggrund och malmfyndigheter: Sveriges Geol. Undersökning, ser. C., no. 275, 316 p. (in Swedish)
Goodwin, A. M., 1974, The most ancient continental margins, *in* Burk, C. A., and Drake, C. L., ed., The geology of continental margins: New York, Springer-Verlag, p. 767–780.
Gorbatsev, R., 1969, A study of Svecofennian supracrustal rocks in central Sweden: Lithological association, stratigraphy, and petrology in the northwestern part of the Mälaren-Hjälmaren Basin: Geol. Fören. Stockholm, Förh., v. 91, p. 479–535.
Härme, M., 1954, Structure and stratigraphy of the Mustio area, southern Finland: Comm. Géol. Finlande Bull., no. 166, p. 29–48.
Hietanen, A., 1947, Archean geology of the Turku district in southwestern Finland: Geol. Soc. America Bull., v. 58, p. 1019–1085.
—— 1975, Generation of potassium-poor magmas in the northern Sierra Nevada and Svecofennian of Finland: Jour. Research U. S. Geol. Survey, v. 3, p. 631–645.
Hübner, H., 1966, Die Geologie der Sulfiderzlagerstätte Kalvbäcken: Sveriges Geol. Undersökning, ser. C., no. 615, 85 p.
Hopwood, T. P., 1976, "Quartz-eye"-bearing porphyroidal rocks and volcanogenic massive sulfide deposits: Econ. Geol., v. 71, p. 589–612.
—— 1956, Lounais-Suomen ja Keski-Ruotsin kallioperän vertailua: Geologi, no. 2, p. 11–12 (in Finnish).
Iijima, A., 1974, Alteration zones, Hokuroku district: Soc. Mining Geologists Japan, Spec. Issue 6 (IMA-IAGOD Meetings 1974, Proc., IAGOD vol.), p. 267–289.
Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Jour. Earth Sci., v. 8, p. 523–548.
Koark, H. J., 1969, Zur Altersstellung und Entstehung der Sulfiderze vom Typus Falun: Geol. Rundschau, v. 57, no. 1, p. 123–146.
von Knorring, O., 1955, A mineralogical and geochemical study of the metamorphic iron-ores of S.W. Finland: Ph.D. thesis, Univ. Leeds, 169 p.
Kouvo, O., and Kulp, J. L., 1961, Isotopic composition of Finnish galenas: New York Acad. Sci. Annals, v. 91, p. 476–491.

Kouvo, O., and Tilton, G. R., 1966, Mineral ages from the Finnish Precambrian: Jour. Geology, v. 74, p. 421–442.
Kuno, H., 1953, Formation of calderas and magmatic evolution: Am. Geophys. Union, no. 34, p. 267–280.
Large, R. R., 1977, Chemical evolution and zonation of massive sulfide deposits in volcanic terrains: Econ. Geol., v. 72, p. 549–572.
MacDonald, G. A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Jour. Petrology, v. 5, p. 82–133.
MacGeehan, P. J., 1978, The geochemistry of altered volcanic rocks at Matagami, Quebec: a geothermal model for massive sulfide genesis: Canadian Jour. Earth Sci., v. 15, p. 551–570.
Le Maitre, R. W., 1976, The chemical variability of some common igneous rocks: Jour. Petrology, v. 17, p. 589–637.
Matsukuma, T., and Horikoshi, E., 1970, Kuroko deposits in Japan, a review, *in* Tatsumi, T., ed., Volcanism and ore genesis: Tokyo, Univ. Tokyo Press, p. 153–179.
Middlemost, E. A. K., 1972, A simple classification of volcanic rocks: Bull. Volcanol., no. 24, p. 383–397.
Mikkola, T., 1955, Origin of ultrabasics in the Orijärvi region: Comm. Géol. Finlande Bull., no. 168, p. 39–51.
—— 1961, Sediment groups, particularly flysch, of the Precambrian in Finland: Comm. Géol. Finlande Bull., no. 196, p. 51–65.
Miyashiro, A., 1974, Volcanic rocks series in island arcs and active continental margins: Am. Jour. Sci., v. 274, p. 321–355.
Nichol, I., Bogle, E. W., Lavin, O. P., McConnell, J. W., and Sopuck, V. J., 1977, Lithogeochemistry as an aid in massive sulphide exploration, *in* Prospecting in areas of glaciated terrain, 1977: London, Inst. Mining Metallurgy, p. 63–71.
Nilsson, G. A., 1968, Wall-rock alteration at the Boliden Deposit, Sweden: Econ. Geol., v. 63, p. 472–494.
Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. America Bull., v. 65, p. 1007–1032.
Parras, K., 1941, Das Gebiet der Pyroxen führenden Gesteine im westlichen Uusimaa in Südfinnland: Geol. Rundschau, no. 32, p. 484–507.
—— 1958, On the charnockites in the light of a highly metamorphic rock complex in southwestern Finland: Comm. Géol. Finlande Bull., no. 181, 137 p.
Plimer, I. R., 1978, Proximal and distal stratabound ore deposits: Mineralium Deposita, v. 13, p. 345–353.
Roberts, R. G., and Reardon, E. J., 1978, Alteration and ore-forming processes at Mattagami Lake mine, Quebec: Canadian Jour. Earth Sci., v. 15, p. 1–21.
Rouhunkoski, P., 1968, On the geology and geochemistry of the Vihanti zinc ore deposit Finland: Comm. Géol. Finlande Bull., no. 236, 121 p.
Sangster, D. F., 1974, Precambrian volcanogenic massive sulphide deposits in Canada, a review: Canada Geol. Survey Paper 72-22, 43 p.
Simmons, B. D., and the Geological Staff, Lake Dufault District, Falconbridge Copper Ltd., 1973, Geology of the Millenbach massive sulphide deposit, Noranda, Quebec: Canadian Mining Metall. Bull., v. 66, p. 67–78.
Simonen, A., 1953, Stratigraphy and sedimentation of the Svecofennidic, early Archean supracrustal rocks in southwestern Finland: Comm. Géol. Finlande Bull., v. 160, p. 37–64.
—— 1960a, Plutonic rocks of the Svecofennides in Finland: Comm. Géol. Finlande Bull., no. 189, 101 p.
—— 1960b, Pre-Quaternary rocks in Finland: Comm. Géol. Finlande Bull., no. 11, 49 p.
—— 1971, Das Finnische Grundgebirge: Geol. Rundschau, v. 60, p. 1406–1421.
Simonen, A., Helovuori, O., and Kouvo, O., 1978, Laatokan-Perämeren-vyöhykkeen kallioperän erikoispiirteistä ja iästä, in Laatokan-Perämeren malmivyöhyke; Vuorimiesyhdistys-Bergsmannaföreningen r.y., p. 10–18 (in Finnish).
Spitz, G., and Darling, R., 1975, The petrochemistry of altered volcanic rocks surrounding the Louvem copper deposit, Val d'Or, Quebec: Canadian Jour. Earth Sci., v. 12, p. 1820–1849.
Stanton, R. L., 1960, General features of the conformable "pyritic" orebodies. Part I-Field association: Canadian Inst. Mining Metall Trans. v. 63, p. 22–27.
Tatsumi, T., and Clark, L. A., 1972, Chemical composition of acid volcanic rocks genetically related to formation of the Kuroko deposits: Geol. Soc. Japan Jour., v. 78, no. 4, p. 191–201.
Tatsumi, T., Takagi, Y., and Otagaki, T., 1972, Geology of the Kuroko deposits: Joint Meeting MMIS-AIME 1972, Tokyo, p. 1–13.
Tuominen, H. V., 1951, Metamorphic concentration of magnesium and iron in the Orijärvi region: A reply: Comm. Géol. Finlande Bull., v. 154, p. 234–238.
—— 1957, The structure of Archean area Orijärvi, Finland: Comm. Géol. Finlande Bull., no. 177, 32 p.
—— 1961, The structural position of the Orijärvi granodiorite and the problem of synkinematic granites: Comm. Géol. Finlande Bull., no. 196, p. 500–515.
—— 1966a, Structural control of composition in the Orijärvi granodiorite: Comm. Géol. Finlande Bull., no. 222 p. 311–329.
—— 1966b, On synkinematic Svekofennian plutonism: Comm. Géol. Finlande Bull., no. 222, p. 387–392.
Tuominen, H. V., and Mikkola, T., 1950, Metamorphic Mg-Fe enrichment in the Orijärvi region as related to folding: Comm. Géol. Finlande Bull., no. 150, p. 67–92.
Varma, A., 1954, The copper-zinc-lead ore deposit of Orijärvi. The copper-zinc-lead ore deposit of Aijala and Metsämonttu, *in* Aurola, E., ed., The mines and quarries of Finland: Finland Geol. Survey, Geoteknillisiä julkaisuja, no. 55, p. 18–34.
Warma, A., 1975, Outokumpu Oy: n Aijalan ja Metsämontun kaivosten vaiheita: Vuoriteollisuus-Bergshanteringen, Helsinki, v. 33, no. 2, p. 94–98 (in Finnish).
Waters, A. C., 1962, Basalt magma types and their tectonic association: Pacific Northwest of the United States: Am. Geophys. Union Mon. 6, p. 158–170.
Vernon, R. H., 1976, Metamorphic processes, reactions and microstructure development: London, George Allen and Unwin, Ltd., 247 p.
Vernon, R. H., and Flood, R. H., 1977, "Quartz-eye"-bearing porphyroidal rocks and volcanogenic massive sulfide deposits—a discussion: Econ. Geol., v. 72, p. 698–701.
Winkler, H. G. F., 1974, Petrogenesis of metamorphic rocks: New York, Springer-Verlag, 320 p.
Wennervirta, H., and Papunen, H., 1974, Heavy metals as lithogeochemical indicators for ore deposits in the Iilinjärvi and Aijala fields, SW-Finland: Finland Geol. Survey Bull., no. 269, 22 p.