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## ON THE SULPHIDE MINERALIZATION IN THE VIHANTI ZINC DEPOSIT, FINLAND

BY AIMO K. MIKKOLA

WITH 8 FIGURES AND 2 TABLES IN TEXT AND 8 PLATES

HELSINKI 1963

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#### ABSTRACT

The paper gives a description of the Vihanti zinc deposit. The ore is located in a horizon of folded sedimentary schists forming a small patch in a generally granitic country rock.

The controlling factors of the localization of the deposit are discussed. Particular attention is given to the sulphide mineralization. Pyrite and pyrrhotite tend to form separate bodies, which, however, are controlled by the same factors as the zinc-, copper- and lead-bearing bodies. The sulphides show mutual patterns resulting from deformation, which has caused a remobilization of some of the ore minerals.

The origin of the Vihanti ore is discussed from the epigenetic and syngenetic points of view.



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#### INTRODUCTION

The Vihanti zinc ore deposit is situated in northern Finland, about 70 kilometers south of the city of Oulu and 40 km from the coast of the Gulf of Bothnia. The geographical location is about  $64^{\circ}25'$ N and  $25^{\circ}08'$ E (Fig. 1).



Fig. 1. The location of the Vihanti Mine.

The terrain is typical of the Central Bothnian flatland. The area is mostly covered by bogs. Here and there low eskers rise above the main level. There are a few lakes, and the rivers are small and shallow. Owing to the flat topography bedrock outcrops are very scarce. This has greatly hampered both exploration work and geological mapping. The geological knowledge of the immediate vicinity of the ore deposit is based on diamond drillings and mine workings.

The discovery of the ore deposit dates back to 1946, when a diamond drill first penetrated an iron sulphide mineralization. Before that the area had been extensively explored geologically and geophysically. Diamond drilling operations were continued until 1953 and started again in 1954 both underground and on the surface. The mining development work was inaugurated in 1951 by the sinking of the Lampinsaari shaft. The mill started production late in 1954 on a small scale, reaching the planned capacity the next year. The present production is about 430 000 tons annually.

A few short papers (Isokangas 1954; Mikkola in Laatio *et al.* 1957; International Geological Congress 1960, Guide to Excursions Nos. A 36 and C 31) have been published concerning the Vihanti ore deposit, and Hyyppä (1948) produced a rather extensive paper about the boulder tracing during the early stages of the prospecting.

The purpose of this paper is to give a more detailed description of the mineralization in the Vihanti deposit. The author participated in the prospecting of the deposit from 1948 to 1950 as the local geologist and in the development of the mine from 1954 to 1958 as the chief geologist of the Vihanti mine. The mineralization studies were later continued by him in the Department of Mining and Metallurgy of the Institute of Technology, Finland.

#### REGIONAL GEOLOGY

According to the General Geological Map of Finland, Sheet C 4 (Wilkman 1931), the bedrock in the Vihanti area consists almost solely of granitic rocks, with the exception of some small basic intrusions. Interest in the ore deposits of the area prompted a recent remapping. The maps, published on the scale 1: 100 000 (Salli 1958, Nykänen 1959), show greater variation in the bedrock. The maps are, however, of a general nature owing to the lack of the outcrops.

The rocks in the district are divided into two main groups, namely, metamorphic supracrustal rocks and intrusive rocks. Considered on a regional scale, the intrusive rocks are overwhelming in abundance. The supracrustal metamorphics form only pathes (c.  $10 \times 5$  km) in the granitic rocks. By origin they are either volcanics or sediments. The last-mentioned rocks, which are the most important from the standpoint of the ore deposits, consist of clastic greywackes and quartzites grading into mica schists and graphite-bearing black schist. The mica schist in many cases contains garnet, cordierite, andalusite or staurolite as porphyroblasts. In places there are dolomite beds overlying the schists. A regional skarnification of dolomite is common in the contacts with schists. In some cases younger granites have caused a strong granitization, which justifies referring to the rock rather as mica gneiss or migmatite.

The volcanics have metamorphosed in the amphibolite facies. Their primary structures are rarely preserved. In places, however, the agglomerates, pillow, and flow structures show the origin of the amphibolites. According to Nykänen (1959) the sedimentary schists seem to lie under the volcanics, although in places they are interbedded.

The intrusive rocks in the surroundings of the ore deposit can be divided into two groups, too. The older of these is a differentiation series consisting of gabbro, diorite, and granodiorite. The gabbro forms rather small masses in the granodiorite. It shows some variation in the mineral composition and texture. The pyroxene and hornblende gabbros grade into each other and an ophitic texture can be seen on the margins of an equigranular massive.

Microcline granite occurs as the best outcrops in the area. This rock

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is younger than the gabbro-granodiorite series, which it cuts as veins or brecciates along the contacts. Granitization caused by microcline granite is rather common in the granodiorite. In such cases this rock contains microcline as phenocrysts, the amount of which diminishes away from the contact. The granite itself is usually coarse-grained, containing microcline as phenocrysts. The color is red with some grey exceptions.

Some basic dikes are considered to be the youngest rocks in the area. They are known, however, only in the mine workings, so they will be dealt with later.

The main structure of the bedrock in the area is poorly known owing to the lack of outcrops. Some features like folds and fold axes can be observed in separated schist patches. Moreover, the cleavages can be measured, but these are too few for the compilation of a general picture. Some of the igneous rocks show rather distinct foliation, generally striking NW— SE. This is the main strike of the cleavage, too, though with many local exceptions.

#### THE GEOLOGY OF THE MINE

#### ROCKS

The zinc deposit is situated in a rather small mica schist patch surrounded by granodiorite and microcline granite. The lenticular schist zone has the shape of a boomerang opening to the north. The length of the zone is about 10 km and the width around 2-3 km. The ore deposit is in the eastern branch of the boomerang, close to the turning point. There are only a few outcrops in this schist patch, hence the knowledge of the geology is based on the diamond drillings and mine openings. In spite of this limiting factor it has been possible to establish a stratigraphic sequence between the different rock types.

From north to south, or from the footwall to the hanging wall, the sequence is as follows: 1. mica schist; 2. cordierite gneiss, quartzite, and black schist, all in the same stratigraphic position; 3 dolomite and skarn, with ore in the footwall. Then the same rocks are repeated in the opposite direction (Fig. 2).

Mica schist to the north of the ore zone is usually rather fine-grained biotite schist having in places abundant garnet as porhyroblasts. Other main constituents are quartz and plagioclase. The schist shows some inhomogeneity caused by lenticular skarn lenses and amphibolite bands. These are parallel to the schistosity and represent calcareous beds in the primary sediment. On the southern side the mica schist contains some cordierite, staurolite, and andalusite as porphyroblasts. They are very markedly altered to pinite and sericite, respectively. The structure on this side is more gneissic than on the northern side, owing to the nearness of the microcline granite.

The horizon above the mica schist consists mainly of quartzite. Up to the dip this rock grades into a rather coarse-grained cordierite gneiss. This is situated partly in between the mica schist and the quartzite, partly replacing the last-mentioned. Cordierite gneiss has a rather high Mg-content depending on minerals like cordierite, phlogopite partly altered to chlorite, and talc. As a curiosity the rock contains occasionally corundum as finegrained aggregates.



Fig. 2. Geology of the 200-m and 250-m levels. Map compiled by the Geological Staff of the Vihanti Mine.

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The rock locally called quartzite is inhomogeneous. It consists of light grey quartzite, pebble quartzite, greywacke, and dark-colored mica quartzite. There is some grading in the grain size of the quartzite. Light-colored coarse-grained quartzite is in the footwall of the horizon and fine-grained quartzite close to the hanging wall. The pebble quartzite can be either light or dark of color. The lastmentioned contains some biotite and iron sulphides. The pebbles, which have a distinct bluish color, consist mostly of quartz or quartzite. Only occasionally is some plagioclase present. The pebbles are mostly rounded and slightly elongated, parallel to the cleavage. The size of the pebbles generally varies from 1 to 3 mm. The mineral compositions of two different quartzites and pebble quartzites are shown in Table I as obtained by the counting method. Stratigraphically the pebble quartzite is most commonly situated at the top of the horizon, but it can be met with even in the ore (skarn horizon) as narrow bands.

Table	Ι.	Mineral	composition	of	quartzites	obtained	by	point	counting	method.
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	1.	2.	3.	4.
Quartz	74.0	85.2	61.7	73.0
Feldspar	3.9	3.6	5.4	7.3
Mica	3.3	6.0	23.0	4.0
Sulphides	15.0	4.3	5.2	5.3
ourmaline	3.0			
ccessories	0.8	0.9	0.6	1.0
Pebbles	—	_	4.1	9.4
	100.0	100.0	100.0	100.0

1. Quartzite band in the ore, hanging wall, J. stope.

2. Fine-grained quartzite in the footwall, 200 m level.

3. Bleached pebble quartzite in the footwall contact, P-5 raise.

4. Pebble quartzite in the footwall of the ore, 200 m level.

Down to the dip the quartite grades into a black schist. This rock is very fine-grained and dark-colored. The color is caused by graphite and biotite flakes and a fine dissemination of iron sulphides. The other constituents are quartz and some plagioclase. Primary calcareous bands are altered to tremolite-bearing schist. It is not uncommon for the quartzitic black schist to grade into a porphyroblastic black tremolite schist.

Stratigraphically all these rocks belong to the same horizon. The contacts are gradational from the quartzite in both directions. The black schist signifies a change in the sedimentary facies, but the cordierite-bearing rock may be a metamorphic derivative (Tuominen and Mikkola 1950).

Dolomite forms the highest horizon in the sedimentary series exposed in the mine workings. This bed is rather inhomogeneous at the bottom. There are narrow quartzite bands and the dolomite is partly altered into skarn. The purest dolomite is fine-grained (1 to 3 mm) and grey or creamy in color. The rock invariably contains some impurities, serpentine being the most common. It occurs either as narrow veinlets or individual »drops,» measuring about 1 mm in diameter. The drops are originally forsterite grains, remnants of which are still left in the serpentine. Besides serpentine, dolomite always contains some pyrite and pyrrhotite as impurities.

From the standpoint of the ore deposit, skarn is the most important rock. It is an alteration product of dolomite in association with rocks rich in silica. Caused by metamorphism, the skarnification is a regional phenomenon, and it occurs throughout the district. In this light and judging by its simple mineral composition, one can conclude that it is a real reaction skarn. The most typical skarn minerals are diopside and tremolite. They occur either together or in masses consisting chiefly of one of these minerals. Quartz, plagioclase, and calcite invariably occur with these minerals in small amounts. Accessories are brown tourmaline, apatite, corundum, and sulphides. Talc and serpentine are alteration products after tremolite and diopside.

The intrusive rocks are exposed only as dikes in the mine workings. The oldest of these are plagioclase-hornblende dikes, which generally have a strike parallel to the cleavage. The contact relations indicate them to be older than the ore deposition. The microcline granite so common in the surroundings occurs in the mine only as dikes which are either porphyritic or equigranular. Pegmatite dikes with huge microcline grains are also met with. The granitic dikes contain some unusual minerals like dumortierite, deep green apatite (wilkeite), spessartite and tourmaline.

Porphyritic plagioclase-hornblende dikes form the youngest group of intrusives in the area. They are located in the cross faults cutting all the afore-mentioned rocks and even the ore. The main constituents are plagioclase, hornblende, and quartz. The first-mentioned also forms phenocrysts up to 4 mm in length. The center of the zonal phenocrysts has the composition  $An_{35-45}$ , while the outer rim has only  $An_{25-30}$ . Where these dikes had been subjected to later movements, hornblende has altered to biotite or chlorite.

#### STRUCTURE

The sediments are so strongly metamorphosed that it is not possible to determine the tops and bottoms of the beds. According to the drag folding and the results obtained from the diamond drilling, the sequence from bottom to top is: mica schist, quartzite, and dolomite. The same sequence is also found in the area of the Raahe map sheet (Nykänen 1959). The main ore bodies are located in the northern limb of a syncline (Fig. 3).



Fig. 3. Cross section at y = 1650. Map compiled by the Geological Staff of the Vihanti Mine.

The southern limb is intersected by diamond-drill holes disclosing some pyrite mineralization in the same structural position but not of commercial value. The axial plane of the main syncline has a southerly dip of about 70—80 degrees at the east end of the ore body, but a more gentle one, about 40 or 50 degrees, at the west end. The fold axis has a westerly plunge of between 10 and 20 degrees. The major fold is overturned to the north. Structurally the limbs differ from each other. The southern limb, so far as is known, runs rather in a straight line, while the northern one has small folds and dragfolds. The cleavage is parallel to the axial plane, its main strike being N 75 E. The bedding and cleavage are parallel except in the crests and troughs of the fold.

Jointing and faulting are common in the Vihanti Mine, but only the latter is to be considered in this connection. There are two systems of faults. The strike faults are most likely of a pre-ore age. In the Ristonaho body a strike fault close to the footwall is mineralized in the same way as the main body except with regard to the grain size, which is only a fraction of that in the ore. This is probably due to the very fine-grained pre-ore gauge in the fault zone. A similar mineralized fault was found in the Elizabeth Mine, Vermont (McKinstry and Mikkola 1954). There has been no noteworthy displacement along the strike faults.

The cross faults are more common and their influence on the mine geology is more important than that of the strike faults. The cross faults generally strike N40W, and they dip steeply to the southwest. Several faults have been intersected in the mine workings, each showing some displacement. It varies from a few centimeters to several dozens of meters. The tendency of the displacement is that the western part has slipped down and south. These post-ore faults are filled with porphyritic plagioclase-hornblende dikes, which in some cases reach the thickness of a few meters. After the deposition of these dikes, some movement still occurred along the same zones, causing fracturing also in the dikes. The fractures are filled with vein material, such as calcite, zeolites, quartz, apophyllite, baryte, pyrite, and some pyrrhotite (Fig. 4).



Fig. 4. Vein material in a post-ore fault. RP-3, 250-m level. Photo A. Mikkola.

The dikes are often broken into pieces when they cut the ore. Fragments are cemented by the ore and the fractures filled either with the afore-mentioned minerals or by serpentine. The faults and the dikes have been recently dealt with by Paulitsch and Hoffman (1960). Their conclusions concerning the two fault systems agree, but the classification of the dike rocks is not in accordance with the field observations.

#### ORE BODIES

The ore is located in a certain horizon in the schist series. The most favourable location for the ore deposition has been the bottom of the dolomite bed. The host rock is most likely tremolite-diopside skarn, but wherever present, the unaltered dolomite and narrow quartzite bands are mineralized, too. The proper controlling factor seems to be a minor folding on the limbs of the main syncline. On the northern limb there are two such folds (as far as is known). In the upper one (along the dip) there is the main ore body, the Ristonaho body, which extends at least 950 m along the strike. To the west the dip flattens and the fold disappears, causing a tapering off of the ore body. The lower minor fold known at the east end of the ore field is probably situated near the bottom of the main syncline. The dip varies greatly, being in places quite gentle. Therefore the vertical thickness of the ore body in this fold, the Lampinsaari body, is rather narrow. Further to the west it takes the same dip as the Ristonaho body.

Some mineralization has been found also on the southern limb of the main syncline. In the same horizon as on the northern limb, it occurs in narrow zones. This is probably due to the lack of minor folding on this limb. The grade, too, is too poor to be worth mining under present circumstances. The ore consists mostly of pyrite and pyrrhotite. Sphalerite and chalcopyrite occur sporadically and some stringers contain galena.

The ore deposition is controlled also by the cleavage but only in a smaller amount. This is to be seen in the necks of the folds. The mineralization continues along the cleavage planes to the footwall quartzite for short distances. The same situation prevails also in the hanging-wall dolomite. There are small lenses of ore outside the favorable horizon though situated along the strike of the same cleavage plane as the main body.

#### MINERALIZATION

In the light of the mineral composition, two different types of sulphide mineralization are to be distinguished. One consists mostly of iron sulphides, the other of base metal sulphides. Only the latter mineralization is of commercial value at present. At first sight it might look as if these types were located separately. This is true to a certain degree, since the mineralization on the southern limb consists mostly of iron sulphides but on the northern limb mainly of base metal sulphides. A more careful examination shows, however, that areally both types belong together. This is best seen in the Lampinsaari ore body. Sphalerite occurs at the eastern end of the body as scattered spots in the upper part of the iron sulphide mineralization. Westwards along the strike the mineralization grades first into sphalerite- and then chalcopyrite-bearing ore. The western end consists again of pyrite and pyrrhotite ore with very little chalcopyrite and almost no sphalerite.

Generally speaking the base metal sulphide bodies are surrounded by a mantle of iron sulphides, which occur either as massive bodies or as a dissemination in the country rock.

#### PYRITE-PYRRHOTITE BODIES

The contacts of the iron sulphide bodies depend largely on the country rock and the type of mineralization. The massive bodies usually have sharp contacts while the disseminated ones show gradational contacts, especially against dolomite and skarn.

Breccia structures have been observed in the contact with the footwall quartzite, especially in the crests of the folds. The quartzite fragments are slightly mineralized in the massive pyrite and pyrrhotite ore. Some of the fragments are angular but mostly they are lenticular with rounded corners. The brecciation was caused by the brittleness of the quartzite during the folding. Bulletin de la Commission géologique de Finlande N:o 205.

The disseminated iron sulphides are usually equigranular, the grain size varying from 1 to 5 mm. The porphyritic texture is, however, rather common in the massive ore. The pyrite phenocrysts are usually 1-3 cm in diameter, showing rather well-developed crystal forms. These are, however, partly destroyed by a later fracturing. The fractures are filled with chalcopyrite, pyrrhotite, and sphalerite. These minerals do not show any considerable corrosion features when filling the fractures, though the replacement textures are common along the crystal faces. The borders of the cracks often completely match, showing that the sulphides mentioned serve only to heal the pyrite phenocrysts. The brittle pyrite was broken down during the later deformation and the more ductile sulphides have moved into the fractures. Ramdohr (1953) calls this a brecciation in situ or a cataclase. In some cases the pyrite crystals contain small grains of skarn silicates and quartz as inclusions. These are surrounded by a narrow rim of pyrrhotite. This texture resembles Ramdohr's (1953, p. 462) description of idioblasts.

Pyrrhotite is another main mineral in the iron sulphide bodies. The relative amounts of pyrite and pyrrhotite vary nearly from one extremity to another. Pure pyrrhotite enrichments are, however, more common than pyrite ones. The mean grain size of these minerals is of the same order, though pyrrhotite does not show a comparable tendency to form phenocrysts. Instead of fracturing the pyrrhotite grains show a platy form, which gives the massive ore a parallel texture, to be seen under the microscope. This texture is parallel to the cleavage of the wall rock.

Pyrrhotite shows replacement textures against pyrite. Both of these minerals vein the skarn silicates along the cleavage planes or fill the fractures independent of the cleavage. The pyrrhotite itself is replaced by sphalerite, chalcopyrite, and galena. The very late fractures have serpentine and calcite filling.

Under the microscope the pyrrhotite grains show a lamellar texture. The lamellae may have a tabular shape throughout the grain, but more often they are wedge-shaped. In this case the lamellae are usually bent slightly, giving a typical flamboyant texture. The number of the lamellae varies greatly from grain to grain. Either only a few lamellae cut the grain while the rest are homogeneous or the whole grain consists of wedge-shaped lamellae. The lamellae are a little lighter and their polishing hardness is a little less than that of the homogeneous part. Their width averages between 0.03 and 0.1 mm.

In dating the formation of the lamellar texture its relation to the fracturing gives some clue. As mentioned earlier the iron sulphides are fractured and the cracks filled by other sulphides. So are the lamellar pyrrhotite grains, too. Chalcopyrite fills the tiny fractures, which are likely to

continue through the flamboyant texture and adjoining pyrite phenocrysts. No corrosion textures are seen along these fractures. It has been observed in the Vihanti ore body that the flamboyant texture is most likely connected to the platy structure of the pyrrhotite. It is conceivable that the origin of the lamellar texture of the pyrrhotite is associated with the deformation after crystallization.

The flame-like texture of pyrrhotite is common and known of old. The difference between the lamellae can be either in their chemical composition or in their crystallographic orientation or in both. A satisfactory interpretation is, however, still lacking. Ramdohr (1960, p. 551) seems to favor alteration in the chemical composition by unmixing. In his view a separation occurs during the alteration. Only a part of the sulphide alters corresponding to the formula FeS, whereas the other part takes the excess sulphur and does not alter. Kouvo and Vuorelainen (1962) have lately studied lamellar pyrrhotites from Outokumpu. According to the results of their X-ray and microscopic examination and chemical analyses, the flamboyant texture is due to the unmixing of stoichiometric FeS in pyrrhotite  $(Fe_{x-1}S)$  or vice versa. The samples studied by them seem to represent a mechanically deformed ore. (In connection with four of the five samples studied, deformation is mentioned). This might mean that the lamellar texture is closely connected with a mechanical deformation as observed in Vihanti. The same situation has been found also by Gavelin (1939, p. 77) in the Malånäs District in northern Sweden.

There are also minor amounts of other sulphides within the iron sulphide bodies. The most common of these are chalcopyrite, sphalerite, galena, arsenopyrite, and cubanite. Only the first two may have economic value, while the others are accessories. The relation of these sulphides to pyrite and pyrrhotite is the same as in the base metal suphide bodies and will be discussed in that connection.

#### ZINC-COPPER-LEAD BODIES

The ore bodies of economic importance consist of zinc, copper, and lead sulphides. In addition there are some silver and gold. The base metal sulphide mineralization is located more consistently in a particular host rock than that of iron sulphides. The favorable ore horizon is a skarn bed in contact with the footwall quartzite.

The skarn minerals are tremolite and diopside partly altered into tale and serpentine respectively. In addition the ore always contains in varying amounts some calcite, quartz, and baryte as waste minerals. The baryte occurs in narrow streaks, giving a distinct bandy structure to the ore (Fig. 5). These streaks are parallel to the cleavage of the country rock and deformed together with it. The baryte is yellowish in color and the grain size averages between 0.7 and 0.8 mm. — The average baryte content of the ore mined in 1956 was 4.5-5.0 per cent.



Fig. 5. Baryte streaks in sphalerite ore. Sp-2, 150-m level. Photo A. Mikkola.

The ore minerals in the skarn form a dissemination, which is rather homogeneous except for the baryte streaks and narrow quartzite bands. Their mineralization is much leaner than that of the adjacent skarn. The ore contains on the average approximately 20 per cent sphalerite, 5 per cent pyrrhotite and pyrite, 1.8 per cent chalcopyrite, and 0.7 per cent galena. The grade of the mineralization varies from a massive ore to a weak dissemination. In each case the ore has a »cleavaged» appearence parallel to the main bedding of the country rock. The sulphides usually replace the silicates, carbonates, and baryte, but they also fill the cracks and cleavage fractures in them (comp. Ramdohr 1960, Fig. 28). Fractures in the ore minerals are filled in turn by vein minerals like calcite, serpentine, zeolites, and baryte.

The mineralization in the quartzite bands differs greatly from the main ore. The bands are mainly disseminated by very fine-grained chalcopyrite and some pyrrhotite (Fig. 6). The grain size of the chalcopyrite varies from 0.01 to 0.05 mm, while the main ore has a grain size ranging from 0.5 to 1 mm. Disseminated quartzite bands in the ore are commonly



Fig. 6. Chalcopyrite dissemination and fracture filling in the pebble quartzite. Polished section,  $\times$  3.5. Photo E. Halme.

broken down. The fractures, varying from several centimeters to a microscopic width, are filled with coarse-grained sulphides as pyrrhotite, sphalerite, and chalcopyrite (Fig. 7).



Fig. 7. Cross fractures in a quartzite band filled with chalcopyrite and pyrrhotite. The width of the band is 0.5 m. Pp-2, 150-m level. Photo A. Mikkola.

Owing to the sulphide content the mineralization in the base metal bodies can be divided into two types. The one, the main type, consists of sphalerite containing chalcopyrite and some galena. In the other the chalcopyrite shows higher enrichment, but quantitatively this type is less abundant. In the latter case the accessory ore minerals are more common than in the former. Galena, the third ore mineral of economic importance is irregularly distributed through the whole body, but it never shows economic concentrations alone.

Interesting is the question whether these minerals show any zoning. Generally speaking the ore minerals are concentrated most abundantly against the footwall. Thus the contact between the ore and the footwall quartzite is sharp. The dissemination diminishes toward the hanging wall and this contact is often gradational. Especially the main ore mineral, sphalerite, occurs in this way. The amount of chalcopyrite, on the other hand, increases from the footwall to the hanging wall, both absolutely and, especially, relatively to the sphalerite. The galena content is so small and irregular that it is difficult to see if it depends on any stratigraphic location. Rather does the occurrence of galena depend on the host rock. It favors a coarse-grained diopside skarn where this occurs in the ore horizon.

As mentioned on p. 19, pyrite and pyrrhotite form a mantle around the sphalerite and chalcopyrite bodies in the east end of the field. Whether this arrangement continues westward along the longitudinal axis is difficult to see yet, since the present mine workings have disclosed only the eastern and upper part of the field. So far the data collected along the longitudinal axis confirm the same arrangement, which could be an original zoning. Some features indicate, however, that it has been locally disturbed during the later history of the ore bodies.

The main sulphides and the accessories will be discussed separately in the following pages.

#### SPHALERITE

The grain size of the sphalerite varies greatly. In the disseminated ore it is mainly from 0.5 to 1.0 mm, but can reach in places up to 5 mm. On the other hand, in the mineralized faultzone it is only 0.03—0.04 mm. The color of the sphalerite is generally dark brown, as is usually the case with sphalerites of Archean deposits. Occasionally the color may change to yellowish brown. The iron content of sphalerites is rather constant (Table II). However, there are exceptions among the iron-poor and iron-rich varieties. The extreme type in the former direction was found on the 150 m level in a small body occurring within the common disseminated ore. The piece

measured circa 2 m in diameter. It consisted of alternating spherical zones of white fine-grained quartz and sphalerite. The galena content increased towards the periphery of the inclusion. At the same time the color of the sphalerite changed from brownish yellow in the center to brown in the outer sphere. The iron content of the yellow sphalerite is only 1.41 per cent (Table II, anal. 11) while the average sphalerite contains 7.15 per cent of Fe. It is noteworthy that in association with the yellow sphalerite there is only pyrite but no pyrrhotite. The gangue minerals are fine-grained sugary quartz, some carbonate and baryte. This is the only case where this kind of sphalerite has been found so far in the mine. In the same part of the mine the sphalerite is occasionally somewhat lighter than generally. Its iron content is 3.75 per cent (Table II, anal. 14), or thus less than the average.

	S	Zn	Fe	Cd	Mn	Hg	Cu	Pb	Ag	Sn	Ga	$SiO_2$
	%	%	%	%	%	%	%	%	%	%	%	%
			0	0	0	0	0	0	0			0
1	33.61	57.12	8.53	0.2	0.05	0.03	0.04	0.003	0.0005			0.12
2	33.44	57.66	7.93	0.2	0.05	0.03	0.04	0.003	0.0005			0.12
3	33.33	58.18	7.85	0.2	0.1	0.03	0.04	0.03	0.0005			0.04
4	33.33	58.45	7.54	0.2	0.1	0.03	0.06	0.007	0.0005			0.06
5	33.28	58.63	7.52	0.2	0.15	0.03	0.09	0.005	0.0005			0.04
6	33.68	58.89	7.14	0.2	0.01	0.03	0.05	0.003	0.0005			0.10
7	33.34	59.43	6.78	0.2	0.03	0.07	0.06	0.003	0.0005		-	0.16
8	33.20	59.73	6.44	0.2	0.03	0.03	0.03	0.003	0.0005			0.08
9	33.46	59.92	6.13	0.2	0.1	0.03	0.29	0.15	0.0005			0.04
10	33.36	59.63	6.11	0.2	0.1	0.03	0.01	0.03	0.0005			0.06
11	32.70	65.10	1.41	0.38	0.07	0.09	0.02	0.015		0.0005		0.12
12	33.10	58.00	7.15	0.1	0.18	+		0.046	0.0005	0.0002	0.0025	0.51
13	33.10	58.45	6.71	0.1	0.17	+		0.037	0.0001	0.0002	0.0045	0.50
14	_	60.76	3.75		0.05	_		_				
15		56 03	8 62		0.36	-						

Table II. Chemical analyses of Vihanti sphalerites.

1-10 Common sphalerites —10 Common sphalerites
11 Yellowish brown sphalerite } Central Laboratory of the Outokumpu Co.
—13 Vaasjoki and Hyvärinen (1957)
14 Brown sphalerite. Analyst P. Väänänen

15 Black sphalerite.

The extreme type at the iron-rich end is a black sphalerite with an iron content of 8.62 per cent (Table II, anal. 15), or only little higher than the average. This occurs usually with small calcite spots in the ore.

The compositon of some Finnish sphalerites has been studied by Vaasjoki and Hyvärinen (1957), including two samples from the Vihanti deposit. These two represent the main type of sphalerite. All the sphalerites described by Vaasjoki and Hyvärinen are very much alike in their composition, though the Vihanti sphalerite has the highest Zn- and the least Fe-contents. But, as shown in Table II, there are considerable differences

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among the Vihanti sphalerites, too. As for the minor elements, Cd and Hg are concentrated more richly in the iron-poor sphalerite than elsewhere, while the Mn-content varies irregularly. The differences in the Cu- and Pb-contents are largely due to the inclusions of chalcopyrite and galena in the host mineral. It is noticeable that Vihanti sphalerites do not contain any germanium, which is so common in sphalerites occurring in some parts of the world. In comparing the sphalerites from Vihanti with others from the Fennoscandian shield, one can conclude that they largely resemble the sphalerites from the skarn ores of Central Sweden (Gabrielsson 1945). The sphalerites from the Skellefte area show a somewhat higher Fe content, though the last-mentioned region is closer to Vihanti both geologically and geographically.

The minor elements contained in sphalerites have been studied very extensively in all parts of the world. The most complete and up-to-date reference list is given by Fleischer (1955). The quantity and quality of the minor elements depend on many factors, which are not all known yet. Recently Sims and Barton (1961) have concluded that the content is governed by the availability of the element and the ability of the host mineral to accommodate it. The first of these factors depends on the activities of the various components in the depositing solutions. The second is controlled by the crystal-chemical properties of the host mineral. Both factors are influenced by temperature and pressure.

Since Kullerud (1953) showed that the temperatures of formation of sphalerites can be determined on the basis of the FeS-ZnS phase diagram, many new studies have been made and published. In using Kullerud's diagram a necessary condition is that sufficient iron was present during the formation of the sphalerite. The occurrence of pyrrhotite with sphalerite evidences this in Vihanti. According to Kullerud's diagram, which was later revised by Barton and Kullerud (1958) and further modified by Sims and Barton (op. cit.), the estimated temperature of formation of sphalerite in Vihanti was above 380° C (not corrected for the pressure). The vellow sphalerite-pyrite assemblage is an exception, giving the minimum temperature of 210° C. It has appeared that the temperatures derived from Kullerud's diagram vary greatly in one deposit and even in a single sphalerite crystal. In the first case this could mean that the temperatures really changed during the formation of the ore either gradually or that there can be separate generations in the same deposit. In their study on sphalerites from the Star Mine, Idaho, Fryklund and Flecher (1956) demonstrated that much sphalerite in the upper portion of the Star body had formed under a higher temperature than in the lower portion. Their interpretation is that the ore formed from the top downward under decreasing temperature. Benson (1960) concludes from his studies in the New Brunswick area that

the iron content of the sphalerites largely depends on the amount of the iron in the mineral that sphalerite replaces. Temperatures of formation sphalerite-pyrrhotite or obtained from sphalerite-pyrrhotite-pyrite assemblages must be applied with caution. Rose (1961) studied sphalerites from the Central District, New Mexico, and the Bingham District, Utah, in an attempt to demonstrate the complications involved in the use of the iron content of sphalerite to measure temperature. According to him the lack of equilibrium with pyrite or with non-stoichiometric pyrrhotite is believed to be the main difficulty. Other difficulties include the effect of sulphur pressure, exsolution effects, and pressure correction. He suggests that temperatures derived from the iron content of sphalerite be regarded as minimum temperatures, since all the factors mentioned result in a lower iron content than is indicated by the FeS-ZnS solvus for one atmosphere.

In the Vihanti deposit the sphalerites have not been studied systematically enough to determine whether the iron content changes gradually or erratically. In the first case it would mean a change of temperature during the formation — in other words a zoning. In the light of present knowledge, it would seem as if the differences were local and caused primarily by any of the factors discussed or secondarily by deformation. The effect of deformation on the iron content of sphalerites is not dealt in the literature. But on the basis of studies of alloys by metallurgists it is conceivable that even the local deformation must be considered in this respect. Thus the temperatures received from the iron content in deformed sphalerites would not be applicable to indicate the primary temperature of formation.

In relation to the other ore minerals sphalerite shows many similarities to pyrrhotite. The earliest sulphides, pyrite and arsenopyrite, are either corroded by sphalerite or it fills the fractures in them together with pyrrhotite and chalcopyrite. The relations to pyrrhotite itself are mutual. The replacement of pyrrhotite by sphalerite is common with »island and sea» or with »bay» textures. Sphalerite contains also pyrrhotite as rod-shaped inclusions, which often run rather parallel, showing a clear orientation (Pl. I, Fig. 1). According to Ramdohr (1953, p. 449) similar features in the Rammelsberg deposit are caused by mechanical deformation and recrystallization. But pyrrhotite also shows an exsolution pattern when the inclusions follow crystallographic directions in the sphalerite. The rim texture is the third pattern between sphalerite and pyrrhotite. The sphalerite grains are surrounded by a tiny rim (0.001 mm) of pyrrhotite and/or chalcopyrite. The same minerals fill the deformation fractures of the same order in sphalerite without any replacement or corrosion (Pl. I, Fig. 2). The rim textures are due to the easy removability of pyrrhotite and chalcopyrite (Marmo 1960).

In a disseminated ore, the sphalerite is replaced by chalcopyrite, showing intruding veinlets and other textures of that kind (Pl. II, Fig. 1). Chalcopyrite occurs in sphalerite as inclusions. Some of these are arranged parallel to the crystal directions. They form either rodshaped or spotted rows. The grain size of the blebs varies greatly even in the same sphalerite crystal. The biggest are of the order of 0.01 mm while the finest ones form »dusty» clouds in the sphalerite (Pl. II, Fig. 2).

The relations of chalcopyrite blebs in sphalerite have been studied extensively. Concerning the abundance of the blebs Baker (1960) has concluded that in a pyrometasomatic deposit it is roughly proportional to the amount of chalcopyrite in the immediate area or bed of sphalerite. The pattern of the blebs and the mode of their formation has been of much greater interest than their abundance. The exsolution of chalcopyrite by cooling is the mainly accepted view. Ramdohr (1953, pp. 440—443) has shown after studying the Rammelsberg deposit that there are five different possibilities to form textures of this kind. They can be divided into two groups, viz. primary and secondary.

The primary textures include crystallization from a mixed ZnS-CuFeS, gel and from a solution. In both cases chalcopyrite and sphalerite form a rhythmic intergrowth, the ratio of the minerals being greatly variable. The third primary texture is the exsolution pattern. In this case sphalerite may contain up to 10 per cent chalcopyrite as blebs in crystallographic directions. In the formation of the secondary textures, metamorphic processes have played a dominant role. Easily mobilized minerals can infiltrate in a deformed sphalerite grain along twinning lamellae or glide planes. The texture developed in this way largely resembles the exsolution pattern with the exception that the rows are not straight but slightly bent. An infiltration can be caused also by increased temperature. Chalcopyrite can diffuse from outside in sphalerite and deposit as small blebs along the borders and fractures when the temperature decreases again. In such a case the center of the grain is clean. Jancovic (1957) has stated that the increased temperature during metamorphism also causes the exfiltration of chalcopyrite, and naturally pyrrhotite, too, from a sphalerite grain.

The mechanism of discontinuous unmixing by increased temperature in a Cu-Cd alloy has been studied by Sulonen (1957) and Jansson (1962). They have shown that the unmixing starts on the crystal borders and continues into the parent crystals as a film of a liquid phase. The film breaks down discontinuously, resulting in bent rows of rounded exsolution crystals. Similar unmixing textures result also through tension. The final texture of a discontinuous unmixing completely resembles the chalcopyrite exsolution pattern in sphalerite. The observed mechanism and the reasons for its development may be applicable in studying the textures in ore minerals.

In the sphalerite of Vihanti no rhythmic intergrowths are observed. Pyrrhotite, chalcopyrite, and occasionally galena are situated either in tiny fractures (Pl. III, Fig. 1) or arranged in rows. In some cases the rows occur in crystallographic directions and point to a primary exsolution texture, but often they are in real fractures, continuing across the grain boundaries, or the rows are situated in any direction, pointing to in- or exfiltration during deformation.

Sphalerite grains often show lamellar twinning. This can be seen in certain cases without etching by one nicol as a difference in hardness. With crossed nicols the lamellae are visible through the color difference. According to Edwards (1954) the twinning is due to shearing forces during the crystallization. A similar texture can be caused also by a mild deformation after the crystallization. A stronger deformation causes a breaking of grains and finally recrystallization, as in Meggen, Westfalen (Ehrenburg at al. 1954, p. 123). This is seen in Vihanti, too, especially in the post-ore fault zones, where the sphalerite was mechanically crushed and finally recrystallized.

#### CHALCOPYRITE

The occurrence of chalcopyrite depends largely on the host rock. In quartzite bands and pre-ore dikes it forms a very fine-grained dissemination, mostly alone or with some pyrrhotite. Sphalerite occurs in this connection very sparingly. The grain size of this kind of mineralization is only 0.01 mm (Fig. 6). In the skarn rock, on the other hand, chalcopyrite occurs with sphalerite, the grains measuring up to 3.0 mm in diameter. In this type of ore some galena and sulphosalts often occur. Besides the paragenesis there is a difference also in texture. Replacement patterns and a certain sequence are common in the quartzitic ore while the ore minerals in the skarn ore exhibit mutual patterns and relations. In the mineralized quartzite the coarse-grained ore fills fractures. They join, forming wider veinlets, which seem to be infiltrations from the ore outside the bands and dikes. The phenomenon could be interpreted as two generation. But, considering the grade of the metamorphism, one may assume that the ore minerals in the skarn rock have been easier to remobilize than in the fine-grained quartzite. Originally they may well have been from the same source.

In relation to the other minerals, the chalcopyrite shows different patterns. Replacement textures like »island and lake» and veinlets are most common. In a typical pattern corroded pyrite and pyrrhotite grains (Pl. III, Fig. 2) are surrounded by sphalerite and chalcopyrite. The last-mentioned minerals show mutual patterns, but most commonly the chalcopyrite, however, replaces the sphalerite (Pl. II, Fig. 1). As mentioned in the foregoing sphalerite is commonly the host for chalcopyrite inclusions. But the contrary occurs, too, although not as commonly. In the latter case sphalerite inclusions usually have the often described star shape (Pl. IV, Fig. 1). The size of the stars only occasionally exceeds 0.01 mm in diameter.

Chalcopyrite quite often contains pyrrhotite inclusions arranged in rows or lamellae, which are parallel to some crystallographic planes of the host mineral. The rows and lamellae consisting of fine-grained pyrrhotite grains do not show any replacement textures against the chalcopyrite. They may extend through the whole chalcopyrite grain, but they do not continue in the surrounding minerals except in galena along cleavage planes. If the chalcopyrite grain is surrounded by pyrrhotite the rows continue along the border, forming a rim texture. When occurring with cubanite the pyrrhotite rows intersect it (Pl. IV, Fig. 2). This shows that the pyrrhotite has deposited after the cubanite exsolution. Occasionally the pyrrhotite stringers may occupy about 50 per cent of the primary chalcopyrite grain (Pl. V, Fig. 1). A rim texture also occurs in between the chalcopyrite and fine-grained disseminated quartzite fragments in the ore (Pl. V, Fig. 2). The rims consist solely of fine-grained pyrrhotite. Their thickness is about 0.01 mm. The rim may branch out as veinlets intruding the coarsegrained chalcopyrite and sometimes the pyrrhotite, too. If the chalcopyrite contains cubanite lamellae these are intersected in the same way as mentioned in the foregoing. Thus the rim is of the same age as the stringers in the chalcopyrite. In pyrrhotite the branches extend only a short distance, ending as a fine-grained recrystallization in the original pyrrhotite. The location of the branches is not along the crystal boundaries but in fractures.

Ramdohr (1960, p. 495) has mentioned two possibilities for the occurrence of pyrrhotite stringers in chalcopyrite. They can be direct exsolution products from a high temperature chalcopyrite or they can be relics of altered cubanite lamellae. In Vihanti the exsolution can hardly be the only explanation, since chalcopyrite cannot contain excess iron to the extent that about 50 per cent of the original chalcopyrite could be replaced by exsolution pyrrhotite. On the other hand, the alteration of cubanite lamellae cannot be applied, either. Why would some of the cubanite lamellae alter while others do not? The author believes that, in the same way as chalcopyrite invades sphalerite, pyrrhotite invades chalcopyrite. The reason for this is the increased temperature and stress during deformation. Chalcopyrite itself forms rims around sphalerite and tetrahedrite, especially when these minerals occur together with galena (Pl. VI, Fig. 1).

Like sphalerite, chalcopyrite shows some secondary textures. Slight banding and crushing and, especially, a distinct translation twinning are the most common ones. The last-mentioned is shown by the gliding across

the twinning lamellae. The latest fractures in chalcopyrite are filled mostly with calcite and serpentine. But in certain cases there are also pyrrhotite grains with well developed crystal planes. Their grain size is about 0.001mm. The pyrrhotite belongs to the same vein material as calcite and serpentine (see p. 16).

#### GALENA

The third mineral to be concentrated in Vihanti at present is galena. It occurs irregularly without forming concentrations of any significance. Most likely it occurs in the diopside skarn, forming a disseminated ore with sphalerite and chalcopyrite. These minerals fill fractures and replace silicates along cleavage planes. But, on the other hand, the galena seems to be concentrated with chalcopyrite in the zones of cross faults. The grain size of galena is usually about 0.2-1.0 mm, but in some cases really giant crystals can be found. They measure up to 4 cm in diameter. These grains contain numerous carbonate inclusions, which are arranged parallel to the crystal planes.

The galena exhibits a distinct replacement pattern against sphalerite and chalcopyrite (Pl. VI, Fig. 2). It borders and intrudes them, forming »island and lake» and »bay and cape» textures. Similar textures are common also against tetrahedrite. On the other hand, galena and chalcopyrite may form a rim around tetrahedrite and sphalerite. But in some cases tetrahedrite occurs as narrow stringers in between the galena grains, or there is a graphic intergrowth of tetrahedrite, chalcopyrite, sulphosalts, and gudmundite. In the fault zone the galena grains have streaks of chalcopyrite and pyrrhotite. These minerals are deposited in the cleavage fractures.

Of interest is the relation of galena to the plagioclase-hornblende dikes. As a result of the latest movements, these dikes are broken down and fragmented in the ore. The fragments, generally having sharp edges, are cemented by sulphides (Fig. 8). Some fragments are slightly mineralized on the margins. The sulphides intrude them along tiny fractures and even replace the silicates. The intruding sulphides consist primarily of galena and some chalcopyrite and pyrrhotite, the first-mentioned having intruded farthest in the fragments. At first glance, this would suggest that the dikes are of a pre-ore age. But since the ore itself occurs as fragments in the dikes, this is not plausible. The other possibility is that there is a second post-dike generation of sulphide mineralization. There certainly is, but not of a kind to cement the fragments of the dikes. The only sulphides in the post-dike vein material are pyrite and tiny pyrrhotite grains (see p. 16). Considering the mineral composition and the structure of the ore around the dikes, i.e., in the fault



Fig. 8. Fragments of porphyritic plagioclase-hornblende dikes in the ore. Polished section,  $\times$  3.3. Photo E. Halme.

zones, the possibility of remobilization is to be considered. It was during the post-dike movements, which caused the fragmentation of the dikes, that the ore was remobilized, the galena, chalcopyrite, and pyrrhotite, among the main constituents, being most sensitive to such a process.

#### ACCESSORY ORE MINERALS

The Vihanti ore contains many accessory ore minerals. Some of them are common in any Archean copper-bearing sulphide mineralization. Included are cubanite and valleriite. The first-mentioned occurs commonly as lamellae in chalcopyrite up to 0.5 mm in width. The amount of cubanite is very irregular. In places there is no cubanite in the chalcopyrite, but sometimes a great part of a chalcopyrite grain is occupied by cubanite lamellae. Usually the chalcopyrite contains sphalerite inclusions (stars) together with cubanite. Except in lamellae, cubanite may occur occasionally as single rounded grains around chalcopyrite. These are about 0.2 mm in diameter.

Valleriite is rather common in some parts of the mine. It occurs in chalcopyrite usually along cleavage fractures, which are generally parallel to the crystal planes. It forms either narrow stringers or single grains in these fractures (Pl. IV, Fig. 1). In this case the grain size may reach up to 0.01 mm. Sphalerite stars are a common occurrence in association with valleriite, but no cubanite is observed in the same chalcopyrite grain.

In one instance tetrahedrite contained minute inclusions of chalcopyrite and of a mineral which, according to the microscopic observations could be bornite. This came to light in the fragment consisting of yellow sphalerite, quartz, and galena (see p. 24).

In addition to the afore-mentioned accessories, the Vihanti ore contains arsenopyrite, molybdenite, magnetite, rutile, and graphite, like most of the Archean sulphide deposits. Arsenopyrite is one of the earliest minerals in the sequence. It occurs so sparsely that it can be detected only under a microscope. The study of polished sections shows that arsenopyrite is concentrated in the galena-rich mineralization. Originally euhedral grains were corroded and replaced by later sulphides. The fractures are often filled by pyrrhotite, sphalerite, and chalcopyrite with a slight replacement. But when occurring with galena, the corrosion has been stronger. The grain size of arsenopyrite varies greatly — the range being up to 1.0 mm in diameter. Molybdenite is also an early member of the sequence. Tiny molybdenite flakes often occur as inclusions in pyrrhotite, sphalerite, and chalcopyrite. Magnetite, graphite, and rutile do not necessarily belong to the ore mineralization. They occur also in the surrounding schists anywhere.

Typical of the Vihanti ore deposit is a Sb-As-mineralization, which is connected with the galena enrichments. As mentioned, these in turn are located around the cross faults. Tetrahedrite is the most common of these minerals. It occurs with galena, chalcopyrite and/or sphalerite. The granular tetrahedrite may reach the grain size of 0.2 mm. It can be detected even by the naked eye. Under the microscope the grains show corroded but smooth margins against galena. Often the grains have a half-moon shape, the straight line bordering chalcopyrite or sphalerite. The rim textures are rather common. Tetrahedrite may be rimmed by chalcopyrite and/or galena (Pl. VI, Fig. 1). The thickness of the rim is about 0.01 mm. Chalcopyrite may fill the fractures in tetrahedrite in the same ways as in sphalerite (see p. 27), or it may occur as tiny inclusions in it. Graphic intergrowths are common between tetrahedrite and galena, or tetrahedrite and chalcopyrite, or tetrahedrite, pyrrhotite, and gudmundite. The first-mentioned of these is an original replacement texture but the others may be developed either by exsolution or by decomposition as mentioned by Ramdohr (1960, p. 178). Thus fahlerz minerals may decompose into chalcopyrite + gudmundite  $\pm$  pyrrhotite  $\pm$  arsenopyrite or pyrrhotite + gudmundite.

Tennantite is by far less common than tetrahedrite but is to be seen nevertheless, in several polished sections. When occurring together, these minerals are easy to distinguish by their optical properties. Tennantite is a lighter grey, with a bluish tinge, than tetrahedrite and its polishing hardness is slightly less than that of tetrahedrite. Tennantite is seen only in connection with galena.

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Gudmundite occurs nearly as abundantly as tetrahedrite in the galenarich portion of the ore. The occurrence of gudmundite is described from many localities in Fennoscandian shield (Gavelin: Bjurliden and Ö. Högkulla; Ödman: Boliden; Saksela: Ylöjärvi and Seinäjoki). Detailed descriptions are also given from many other areas by several authors (e.g., Ramdohr, Maucher). In Vihanti, gudmundite occurs in connection with galena and pyrrhotite or it is closely associated with tetrahedrite and other Sbbearing sulphosalts. Most commonly it replaces pyrrhotite along the galena contacts or pyrrhotite inclusions in galena and chalcopyrite. In this case the gudmundite and pyrrhotite form graphic intergrowths (Pl. VII, Fig. 1). The intergrowths usually occupy the whole pyrrhotite grain and nothing more. Galena does not have any inclusions. But in connection with chalcopyrite there is an interesting rim texture. The pyrrhotite contains no gudmundite inclusions in a zone about 0.02 mm wide against the chalcopyrite. The galena on the other side of the pyrrhotite has a zone full of tiny holes (less than 0.001 mm) (Pl. VII, Fig. 2). This gives the impression that the intergrowth front proceeds from galena to chalcopyrite. When occurring with tetrahedrite, the gudmundite intergrowths can be complicated, consisting of boulangerite, pyrrhotite, tetrahedrite and chalcopyrite. This intergrowth may be caused by the decomposition of tetrahedrite, as mentioned earlier. Gudmundite may occur also as single crystals (Pl. VIII, Fig. 1), which sometimes have well-developed crystal faces. In the intergrowths the grain size of gudmundite is only on the order of 0.001 mm, but single crystals may reach 0.3 mm in diameter.

Boulangerite ranks next in abundance among the Sb-minerals. It occurs in connection with tetrahedrite and galena as needle-shaped crystals. Occasionally it may form graphic intergrowths with galena. The grain size varies up to 0.05 mm, but usually it is much less. Thus determination by optical methods is difficult, but the identification was confirmed by the X-ray method in the laboratory of the Outokumpu Co. In a few cases another mineral may be observed which closely resembles boulangerite. On the basis of microscopical determinations this might well be jamesonite, though the small grain size prevents definitive identification.

In addition to the afore-mentioned Sb-bearing minerals, pyrargyrite is identified with certainty (by microscopic and X-ray methods). It is seen in several galena-rich sections occurring with other Sb-minerals, and most commonly with tetrahedrite. The grain size may occasionally reach 0.1 mm, when the pyrargyrite can be distinguished also with the naked eye, owing to its high red reflection. The red internal reflection is a good indicator under the microscope, too.

In connection with the sulphosalts, three other minerals have been observed. Unfortunately they occur in such small quantities that identifi-

cation was not possible with certainty. One of these occurs as an inclusion in tetrahedrite. Its optical properties are identical to bournonite and comparison with a known material confirms this observation. The other two may well be freibergite and berthierite. Both of these minerals are not uncommon in sequences like this one.

Besides the Sb-minerals, one As-mineral has been observed in the same sequence. Niccolite occasionally occurs as inclusions in pyrrhotite. It may occur either as separate grains or it forms graphic intergrowths with pyrrhotite. A sphalerite grain surrounded by pyrrhotite is shown in Pl. VIII, Fig. 2. Around the sphalerite there is a zone in the pyrrhotite, about 0.02 mm in thickness, wich contains niccolite grains. The identification of niccolite was made by microscopical and X-ray methods.

The mill feed contains on the average circa 0.5 g/t Au and 30 g/t Ag. Both of these metals are associated with lead- and copper-bearing ore, while the pure sphalerite ore is rather barren. Silver is mostly contained in pyrargite and tetrahedrite, but metallicsilver, too, is to be seen under the microscope. It occurs as separated grains in connection with galena, tetrahedrite, boulangerite, and pyrargyrite. The grains are 0.05 mm in diameter at the maximum, though usually only a tenth of it. Gold belongs to the same mineral composition. The presence of galena and tetrahedrite or some sulphosalts seems to constitute a favourable condition for the occurrence of gold. On the other hand, gold may be associated with arsenopyrite occurring with chalcopyrite. The grain size may reach 0.05 mm in diameter but usually it is much less.

A very similar paragenesis is described by Gavelin (1936) from northern Sweden. He has been able to distinguish two generations in the sulphide mineralization. Pyrite, pyrrhotite, and sphalerite, which are the main minerals, belong to the first stage. From the residual liquids arsenopyrite and stannite crystallized first. They were followed by antimony-bearing minerals and chalcopyrite. Galena was the last to be crystallized. In the Vihanti deposit it is not possible to establish a similar sequence. There the iron sulphides have a strong tendency to deposit in separate bodies, which contain some chalcopyrite and sphalerite. These may grade into bodies consisting chiefly of base metal sulphides. In the last-mentioned ones, pyrite and arsenopyrite are crystallized first, being followed by pyrrhotite, sphalerite, chalcopyrite and galena. Some of the accessories are contemporaneous with these minerals, some are of later origin. All these minerals originally derived from the same sources and crystallized successively, but behaved differently during the later history of the ore deposit. Though the leadantimony minerals are concentrated around the cross faults, there is no reason to think that these minerals would be of another generation and the fault zones would have formed channels for the parent solutions. In

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and around the fault zones, which extend into the country rocks, these minerals occur only inside the ore bodies. The vein material in the faults consists of calcite, serpentine, zeolites, apophyllite, pyrite and, in rare cases, pyrrhotite. The only sulphide minerals in the vein material, pyrite and pyrrhotite, are of distinctly later origin than the sulphides in the ore bodies. In addition, the galena has a tendency to deposit in the diopside skarn and even form lens-shaped concentrations, which are conformable with the country rock and iron and zinc sulphide bodies. One such lens has been intersected by diamond drill holes on the southern limb of the syncline. The explanation for the concentration of chalcopyrite, galena, and some accessories (especially the antimony minerals) around the fault zones can be found in their easier remobilization during deformation than that of sphalerite and iron sulphides.

#### SUPERGENE SULPHIDES

The upper part of the ore bodies shows a slight supergene alteration, which extends about 50 m in depth, though in the fault zones much deeper. The alteration was undergone only by the pyrrhotite and thus it is most common in the pyrrhotite ore. The minerals of the alteration are pyrite, marcasite, limonite and, rarely, chalcocite.

The alteration of pyrrhotite under superficial conditions is discussed by Ramdohr in his textbook (1960, pp. 556—559). He describes different alteration patterns, three of which are well developed in Vihanti. Similar textures are depicted by Marmo (1960) in Finnish sulphide schists.

The most common pattern in Vihanti shows a lamellar texture, in which the altered lamellae are composed of fine-grained pyrite and marcasite. Each of these minerals occurs in alternate lamellae. Marcasite is often oriented perpendicular to the lamellae.

The second type of alteration has a typical bird's eye pattern, in which pyrite and marcasite form concentric ellipsoidal rings. In the center of these ellipsoids is a primary pyrite grain, around which new pyrite replaces the surrounding pyrrhotite. The rings are composed of pyrite and marcasite separated by vuggy black zones. The zones measure about 0.02 mm and 1/10 of that width respectively.

The third type is a veining pattern, in which supergene pyrite forms narrow rims along the fractures or margins of pyrrhotite grains. The rims have a zonal structure similar to that in the bird's eye type. Between the unaltered pyrrhotite and the supergene pyrite there is always a zone of black powdery material, which reveals the first step in the alteration.

Under the microscope the supergene pyrite shows some differences from the primary pyrite. In oil immersion it is either pure white or slightly bluish white while the primary pyrite has a creamy white color. It also exhibits a weak anisotropism, which, according to Ramdohr (1960, p. 745), may be caused by an intergrowth of fine-grained marcasite or by a small arsenic content. Limonite is always associated with the secondary pyrite. It fills the center of fissures bordered by supergene pyrite. In silicates it only fills the fractures.

Chalcocite is quite rare. It occurs with supergene pyrite as minute grains, which are detectable only by means of oil immersion.

#### SUMMARY AND DISCUSSION

The Vihanti ore deposit is located in a rather small schist patch of sedimentary origin in a large area of mainly granitic rocks. The granites are the youngest rocks in the area, with the exception of some dikes. They cut the ore, too. Structurally the schists form a synclinal fold, which, however, is displaced along several cross faults. The axis of the fold strikes roughly N 70 E and plunges about  $10-15^{\circ}$  to the west. The axial plane dips southward, varying from nearly vertical at the east end of the field to  $40-45^{\circ}$  at the west end. The fold itself is slightly overturned to the north. Both limbs have a southern dip. The sequence from the bottom to the top is mica schist, then cordierite-mica schist, quartzite, pebble quartzite, black schists — all in the same horizon — and dolomite on top. The last-mentioned has altered to tremolite-diopside skarn, especially close to the contacts of the silicate rocks.

The ore deposit consists of several bodies, which are located: first, in a certain horizon, viz., in the skarn adjacent to the stratigraphically underlying quartzite, and, second, in minor folds on the limbs of the main syncline. This is true, indeed, on the northern limb which is drag folded. In the light of present knowledge, the southern limb is more straight-lined. There the ore is located in the same horizon but consists mostly of pyrite and pyrrhotite. Nor is the thickness of the body of the same order as on the northern limb.

The ore bodies seem to pinch out to the west with the flattening dip. Whether there are any other controlling factors in the localization of the ore is not yet known. One possibility is a pre-ore strike faulting.

The ore bodies can be divided into two types. Pyrite and pyrrhotite form concentrations which seem to be separated from the zinc-copper ore. But closer examination reveals that they are situated in the same structural position as the zinc-copper ore. The two types grade into each other as seen in the Lampinsaari body. The commercial ore bodies consist of sphalerite and some chalcopyrite and galena. In addition they contain pyrite, pyrrhotite, and several accessory ore minerals, among which antimony-

bearing minerals are common. Tetrahedrite, gudmundite, several sulphosalts, and pyrargyrite are to be identified in polished sections. Arsenopyrite, tennantite, and niccolite represent arsenic-bearing accessories. The copper minerals include cubanite, valleriite, and bornite.

The mineral composition is rather typical of this kind of ore in the shield areas. The original crystallization sequence is disturbed by a later deformation. Thus several minerals show mutual and contrary patterns in relation to each other. But judging by the observations made during microscopic and field work, pyrite and arsenopyrite are the first minerals to have crystallized, followed by pyrrhotite, spalerite, chalcopyrite and tetrahedrite-tennantite in one group. Galena belongs to this group, too, but it shows replacement patterns against those minerals. It has itself been corroded by sulphosalts and gudmundite. All these minerals belong, however, to the same sequence and generation. A second generation is represented by pyrite and pyrrhotite in the post-ore faults as vein material. Pyrite and marcasite occur as secondary minerals in the supergene alteration zone.

The ore shows several features which point to a deformation. It has a banded structure. Baryte and chalcopyrite form streaks in the sphalerite ore parallel to the cleavage of the country rock. Pyrrhotite occurs as platy grains which show a cleavage texture. Under the microscope the most conspicuous features are the granulation and the recrystallization of some ore minerals, fracture fillings and inclusions, rim patterns and graphic intergrowths. The mutual patterns between ore minerals in one and the same generation can be explained by differences in their ability to sustain the deformation agents. Some minerals, like pyrite and arsenopyrite, are crushed; some like sphalerite and pyrrhotite, are recrystallized; some, like galena, chalcopyrite, and pyrrhotite, are remobilized. The exsolution textures (emulsion and rim patterns), fracture fillings, and flamboyant pyrrhotite are probably produced by the same agents. The mechanism of the formation of these textures among the minerals is not fully understood. Recent investigations with metal alloys prove that similar textures are produced via the liquid phase by stress and temperature changes. This might be applicable to ore minerals, too.

The deformation of the Vihanti deposit is partly regional, partly local in character. The shape and the structure of the bodies, the recrystallization and infiltration of chalcopyrite, galena, and pyrrhotite into fractures are regional features caused by regional metamorphism. The crushing and local recrystallization of some minerals, the concentration of galena and chalcopyrite towards the cross faults, and some microtextures are of local character. The deformation agents are divided in a long time interval and propobly are repeated time after time. Thus the ore minerals show mutual and discrepant patterns difficult to interpret. Considering what has been said in the foregoing it is hazardous to make very definite conclusions concerning the origin of the Vihanti ore. Many features point to an epigenetic origin and some of these are hydrothermal. In the footwall there occasionally occurs a 10-cm-wide zone of a weakly bleached quartzite (Table 1). The plagioclase shows stronger sericitization than elsewhere and all the micas have altered to sericite. In addition the zone contains plenty of apatite. The alteration zone is met with only in a very few places. It is so weak, however, that it is not enough to explain the increase of Na, K, and  $H_2O$  typical of any hydrothermal alteration. In the hanging wall skarn, tremolite and diopside show a slight alteration to talc and serpentine respectively. This is, however, a regional feature and thus hardly connected with the ore deposition.

The occurrence of the cordierite gneiss in the footwall points to a concentration of Mg and Al (cordierite and corundum). In the same rock biotite shows a gradual alteration into phlogopite and chlorite. The end product is a light brown or greenish mica. Its composition varies from phlogopite to chlorite according to X-ray determination. This certainly means a Mgenrichment. But that it could be caused by Mg-metasomatism associated with ore deposition is hardly plausible. In the Orijärvi region (Tuominen and T. Mikkola 1950) the Mg — Fe enrichment is caused by regional metamorphism.

The ore contains some gangue minerals which could be of hydrothermal origin. Tourmaline occur in quantities as small patches both in the ore and in the adjacent skarn and granite dikes. The skarn tourmaline is deep brown while in the ore and granitic dikes it is black. The relation of the tourmaline to the ore minerals is the same in both cases. The tourmaline is broken down and its fractures filled and corroded by sulphides. Baryte, too, could be considered as a hydrothermal mineral while apatite is common in all the schists. The increase of SiO<sub>2</sub> in connection with the ore deposition would serve as evidence of a hydrothermal origin. There are, indeed, different kinds of quartz in the ore. Close to the footwall of the ore, the glassy and coarse-grained quartz occurs in bands which are remnants of the original quartzitic beds in the host rock. In the baryte-rich ore the quartz is disseminated and fine-grained. It does not show an undulating extinction like the quartz in quartzite. Towards the hanging wall the quartzitic bands are less abundant. There are only streaks of fine-grained (0.1 mm) white quartz. These are often less than 1 cm wide and only a few dm long. These veinlets are broken and bent and irregularly located in the ore. The quartz associated with the sphalerite abnormally low in iron (p. 25) has a similar appearance both megascopically and microscopically. This kind of quartz occurs only in the ore and may have originated from the hydrothermal silica.

Totally considered, the possible hydrothermal features are weak, as in

many occurrences in the shield areas. But this is explicable if the post-ore deformation is accepted. Deformation was undergone by both the gangue minerals in the ore and in its immediate surroundings and by the ore minerals.

Another possible explanation for the origin of the Vihanti deposit is that advanced for the Rammelsberg and Meggen deposits, i.e., the metals were produced by volcanic exhalations at the bottom of a sea. They were precipitated by  $H_2S$ , which likewise, according to Ramdohr (1953, p. 491), seems to originate from exhalations. The metal content, in general, and the geological setting in Vihanti are highly similar to those in Rammelsberg and Meggen. There are significant differences, too. Baryte, a typical and abundant constituent of those deposits, is inconsiderable in Vihanti. Moreover, no volcanics occur in the immediate surroundings of the deposit. Regionally, volcanics occur in the schist formation. The main difficulty in explaining the origin of the Vihanti deposit in this way is the lack of primary textures, which have been disturbed by a much stronger and longer metamorphism than in the German deposits.

New light is shed on the discussion of the origin of the sulphide mineralization in Finland by absolute age determinations. The isotopic composition and hence the age of Finnish galenas was recently discussed by Kouvo and Kulp (1961). The Vihanti galena belonging to the Karelian group (according to Kouvo) has the model age of 2100 m.y. on the average, while the Svecofennian model age is only 1800 m.y. According to the authors the isotopic ages indicate that neither of these ages precludes a prior and possibly different history for these belts. The results obtained by the present author are in accordance with the metamorphic history. With regard to the origin of the ores in the Svecofennian and Karelian belts, Kouvo and Kulp (op. cit.) conclude, on the basis of the sulphur isotope composition, that they are derived from metasedimentary sources rather than from the mantle of the depths of the earth's crust. This suggests that the Vihanti deposit is somewhat similar in origin to those of Rammelsberg and Meggen.

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Fig. 1. Pyrrhotite inclusions in sphalerite.  $\times$  290. Photo A. Mikkola.



Fig. 2. Fractures in sphalerite filled with chalcopyrite and pyrrhotite.  $\times$  140. Photo E. Halme.

### BULL. COMM. GÉOL. FINLANDE N:0 205



Fig. 1. Sphalerite corroded by chalcopyrite in contact with galena.  $\times$  140. Photo E. Halme.



Fig. 2. Chalcopyrite inclusions in sphalerite.  $\times$  550, oil. Photo A. Mikkola.

### BULL. COMM. GÉOL. FINLANDE N:o 205



Fig. 1. Pyrrhotite grains forming rows in sphalerite.  $\times$  100. Photo A. Mikkola.



Fig. 2. Fractured and corroded pyrite grains surrounded by chalcopyrite and sphalerite in the skarn ore.  $\times$  57. Photo E. Halme.



Fig. 1. Sphalerite star and valleriite stringers in chalcopyrite.  $\times$  770. Photo E. Halme.



Fig. 2. Cubanite lamella in chalcopyrite intersected by pyrrhotite stringers.  $\times$  235. Photo E. Halme.

### BULL. COMM. GÉOL. FINLANDE N:o 205



Fig. 1. Pyrrhotite stringers occupying chalcopyrite along cleavage planes and fractures.  $\times$  770. Photo E. Halme.



Fig. 2. Pyrrhotite rim bordering chalcopyrite in the contact with quartzite.  $\times$  100. Photo A. Mikkola.



Fig. 1. Chalcopyrite and some galena rimming sphalerite and tetrahedrite.  $\times$  100. Photo A. Mikkola.



Fig. 2. Galena replaces sphalerite in the skarn ore.  $\times$  82. Photo E. Halme.

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Fig. 1. Gudmundite intergrowths with pyrrhotite in the galena-rich ore.  $\times$  220. Photo E. Halme.



Fig. 2. Unoccupied front of pyrrhotite between chalcopyrite (left) and pyrrhotite-gudmundite intergrowth. Galena (upper corner, right) borders the intergrowth with vuggy rim.  $\times$  490. Photo E. Halme.

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Fig. 1. Gudmundite crystal in tetrahedrite. Sphalerite in upper left corner.  $\times$  770. Photo E. Halme.



Fig. 2. Niccolite-pyrrhotite intergrowth around a sphalerite grain.  $\times$  1500, oil. Photo E. Halme.

