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ON THE GEOLOGY OF THE OUTOKUMPU ORE DEPOSIT IN FINLAND

BY

VEIKKO O. VÄHÄTALO

WITH 9 FIGURES AND 13 TABLES IN TEXT, 19 PLATES AND THREE MAPS

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ACADEMICAL DISSERTATION

TO BE PRESENTED, BY DUE PERMISSION OF THE SECTION OF MATHEMATICS AND NATURAL SCIENCE OF THE PHILOSOPHICAL FACULTY OF THE UNIVERSITY OF HELSINKI, FOR PUBLIC CRITISM IN LECTURE ROOM N:o VI, MAY 27, AT 12 NOON.

HELSINKI
1953

Helsinki 1953. Valtioneuvoston kirjapaino

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DEFINITIONS OF MINING TERMS USED

Since geologists must eventually become conversant with mining terminology, perhaps it is well to pause at this point to define the more commonly used terms. Forrester (1947):

BACK. The top or roof of an underground passageway.

BOTTOM. The floor of an underground passage.

BREAST. The end, in unmined rock, of an underground excavation or passage; sometimes called the *FACE*.

CROSSCUT (Xcut). A horizontal underground passage driven in such a way that it intersects, penetrates, or crosses the geologic structure.

DRIFT (Dr). A horizontal underground passage driven along or parallel to some geologic structure.

INTERMEDIATE DRIFT (IDr). A secondary or auxiliary horizontal passage driven between levels in a mine, which may extend from a raise or stope.

RAISE (Rs). Usually a rectangular, although sometimes circular, opening driven upward from a lower level to reach a level above.

SHAFT (Sh). An excavation of limited size, usually rectangular, compared with its depth. Made for finding or mining ore and for permitting access from the surface to underground workings.

STOPE (Stp). An underground excavation from which ore has been extracted, either above (overhand) or below (underhand) a level. Access to stopes is usually by way of adjacent raises.

SUBLEVEL. An intermediate level opened a short distance between the main levels.

PREFACE

This study is based principally on research material collected between the years 1945 and 1950, while the author was employed as a mining geologist at the Outokumpu mine. The evaluation and organization of the material was carried out in part at the same time, with the final revision and compilation taking place in 1950—1952.

The initial impulse to undertake the project came from the executive manager of the Outokumpu Co., Eero Mäkinen, Ph. D., to whom the author owes a debt of gratitude for this as well as for encouragement and support liberally given during all the ensuing stages of the study. I should also like to extend my thanks through him to the Outokumpu Co. for the generous financial aid it has given to bring this work out in print.

To my paternal and inspiring teacher, Professor Emeritus Pentti Eskola, I likewise wish to express my appreciation for the sympathetic interest he took in my work and particularly for the invaluable help he unstintingly gave during its final stages.

To my co-workers at the Outokumpu mine I offer a hearty handshake for their loyal support and many favors. Without forgetting the others, I feel particularly indebted to my colleague Mr. Esko Peltola for his always willing collaboration and help, which made it possible for me to engage in research work even, in part, while carrying out the routine duties of my job.

It gives me real pleasure to add a word of thanks to Mr. Yrjö Vuorelainen for his skilfully drawn illustrations and maps.

Credit is due to Mrs. Irja Lavola for her services as translator and to Mr. Paul Sjöblom for correcting the manuscript, and I want to thank them both.

Outokumpu, January 1953.

Veikko O. Vähätalo.

OUTOKUMPU MINE.
Photo Roos.

INTRODUCTION

The ore deposit of Outokumpu is situated in eastern Finland, in the province of North Karelia, approximately 70 km east-southeast of Kuopio. The geographical situation of the deposit (Central Shaft II at Mökkivaara) is about 60°44′ northern latitude and 29°00′ eastern longitude. From the mine there is a railway connection, through Viinijärvi—Varkaus—Pieksämäki, with the Savo railway, which then leads to southern Finland (Fig. 1).

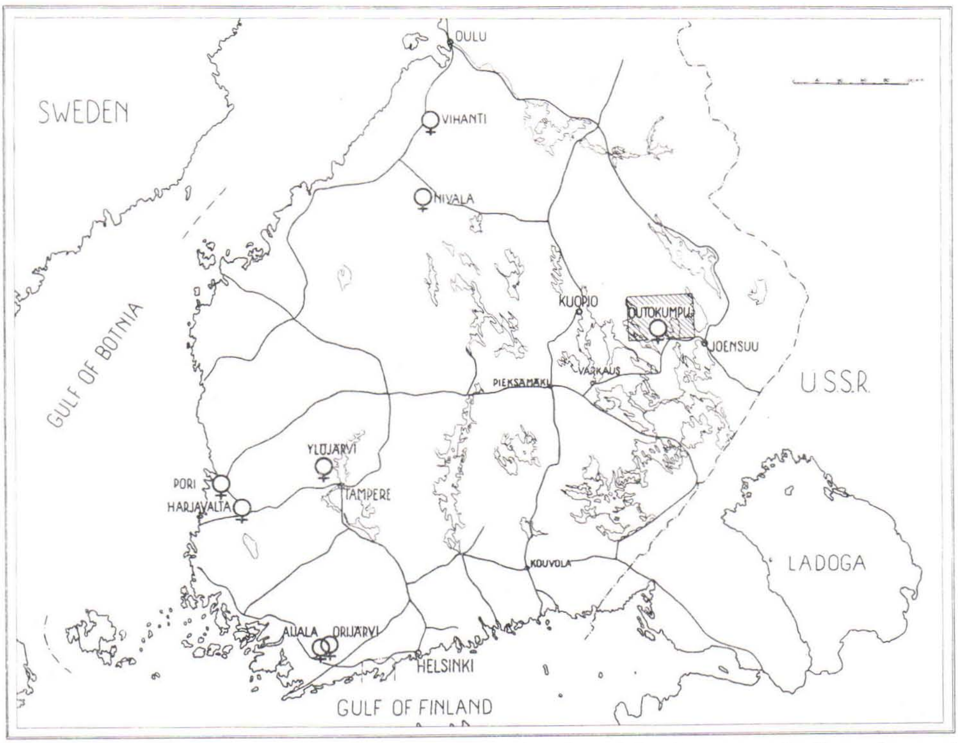


Fig. 1. A map of southern Finland, showing the situation of Outokumpu and other mines and plants owned by the Outokumpu Co. They are: copper, zinc, and nickel mines: Aijala—Metsämonttu, Orijärvi, Vihanti, Ylöjärvi and Nivala, the Copper Smelter at Harjavalta, and the Metal Works at Pori.

The deposit was discovered about 40 years ago as the result of investigations made by the State Geological Survey (then called Geological Office). This work was directed by Otto Trüstedt, Ph. D., a mining engineer, in

1908—1910. The report of the discovery is as follows (Saksela 1948; Sauramo 1924):

While the canal at Kivisalmi in the parish of Rääkkylä (Fig. 2) was being deepened, a boulder 5 cubic meters in size was found on the bottom under a moraine layer about 3 meters thick. A specimen of it was sent to

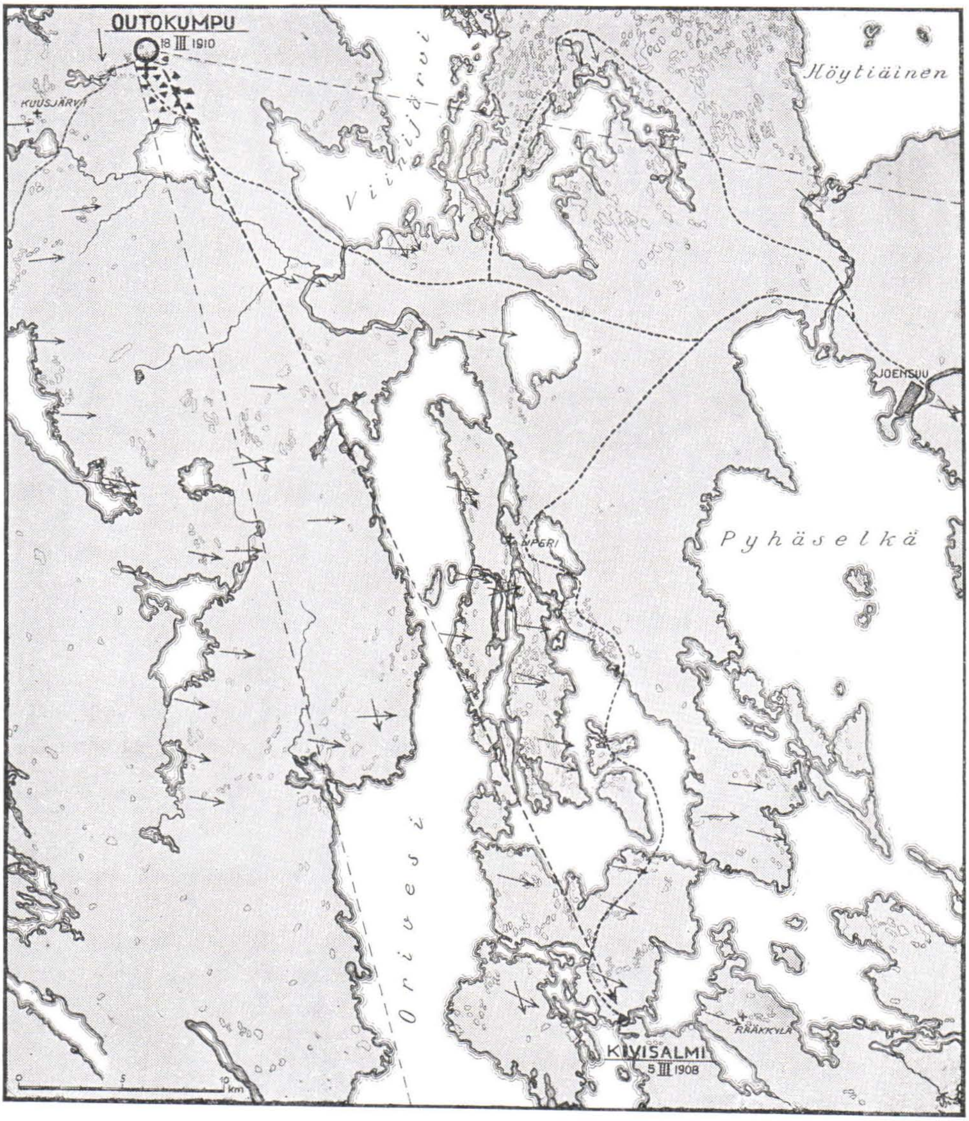


Fig. 2. Discovery of the Outokumpu Ore
▲ Ore boulders, ↘ Moving directions of the glacial land ice, ----- Directions of the exploration works.

Signed by Otto Trüstedt.

the Geological Survey, and there it was found to contain good copper ore. According to the Analysis made by P. Eskola the specimen consisted of:

Cu	3.74 %
Fe	29.85 »
S	33.63 »
Zn	0.11 »
Ni	0.06 »
Insoluble	33.49 »
	100.88 %

In the quartzitic matrix rock of the boulder the sulphides were impregnated parallel to the schistosity. In type it belonged, according to the studies of the geologists (above all, W. W. Wilkman) who have drawn the general geological map, to the so-called »Kalevian» formation [1]. Several zones belonging to this Kalevian formation and containing quartzites are known north and northwest of the site of the discovery. In addition, serpentine- and tremolite-bearing boulders as well as black graphite-bearing schist-boulders, discovered in the close neighbourhood of the ore-boulder, led to the conclusion that the ore must be situated somewhere in the complex consisting of these rocks.

In the light of this knowledge Trüstedt began before long to study the quartzite zones to the north and northwest of Kivisalmi. Thus he gave up the study of the area situated west of the site of the discovery, which had originally been the object of his study. The directions of the striae left by the glacial continental ice sheet showed that the land ice had been moving west-northwest—east-southeast. Only few of the observations show the direction northwest—southeast. According to the earlier geological mapping, no quartzite of the type represented by the boulder had been found in the area west-northwest of the discovery.

After first having studied the quartzites of the area east of Lake Viinijärvi, Trüstedt directed his study to the area of Outokumpu, west of Lake Viinijärvi.

In connection with the field-work in 1899 of Benjamin Frosterus and W. W. Wilkman (1924) a rather long belt containing the rocks in question had been found at Outokumpu in the parish of Kuusjärvi, approximately 50 km northwest of Kivisalmi. In this belt, according to W. W. Wilkman's observations (1899), banded ore-bearing quartzite, which contained some chalcopyrite, was found on the north side of Outokumpu. Now, as Outokumpu had become the object of the investigation, Trüstedt soon, after

[1] The Karelian formations, belonging to the Karelidic orogenic cycle, were earlier divided into Jatulian, Kalevian and Ladogan series, which were believed to represent different age-groups, an opinion that later proved erroneous.

promising preliminary field work, began diamond drilling in September, 1909, and after two unsuccessful drillings ore was found in the third drill-hole (at the present site of Kumpu B) on the 17th of March, 1910[1]. In this hole ore was found at a depth of 29 m. The thickness of the layer was 9 m. O. Trüstedt's monument now stands on this drilling site.

On the basis of the drilling results to the east of Kumpu B an outcrop of ore was uncovered below a swampy moraine layer of about 2—3 m. The length of the outcrop on the surface is about 80 m, the ore being rather weathered on its surface, and the thickness being about 1 m, so that of the original rock material only rather rusty pumiceous quartzitic groundmass remains. In structure the excavated ore is of the same banded impregnation type (Fig. a, Pl. I) as the Kivisalmi boulder, of which well-preserved fragments are still to be seen in the stone covering of the canal bank.

Mining operations began on a small scale after the necessary mining and metallurgic equipment had been procured in 1913, with the landowner, Hackman and Company, and the discoverer, i. e. the State, co-operating. In the beginning the mining did not pay because of the remote situation of the mine and, above all, the bad communications. By 1928, when the mine had built its own railway line, an absolute necessity for any large-scale production, the economic conditions had improved sufficiently to make the mining profitable. Since 1924 the deposit has belonged to the State, which in that year bought the shares of Hackman & Co, and since 1932 the mine has been a state-owned limited company. In recent years the annual output of the mine has been about 500—600 thousand tons of ore.

From the local refining plant the copper-concentrate is transported by rail to the furnace at Harjavalta in western Finland for metallurgic processing. From there the raw copper is transported to the electrolytical refinery at Pori, a town situated on the coast of the Gulf of Bothnia. In connection with the refinery there is a metal works for the preparation of alloys, semimanufactured articles, etc. Sulphur-concentrate is used partly for the preparation of sulphuric acid, partly for acid needed in the preparation of cellulose.

EARLIER STUDIES

Earlier studies dealing with the geology of the Outokumpu area, though there are many of them, are either limited to describing details or superficially touch on the geology of Outokumpu only in connection with regional investigations of larger areas.

[1] According to the documents, which are in the possession of the Outokumpu Company, the discovery of the ore is supposed to have taken place on the 18th of March, since there is the following annotation in the drilling report: »18. 3. 1910 malmförekomstens födelsedag» (18. 3. 1910 the birthday of the ore deposit); and there is also a map by Trüstedt with the same date, 18. 3. 1910. Fig. 2 shows a photograph of this original map.

Borgström in his study (1901) depicts the crystallographic and optical properties as well as chemical composition of chromium-bearing garnet or uvarovite.

Frosterus (1902) describes the geological features noted at Outokumpu in connection with the general geological mapping as well as, together with W. W. Wilkman (1924), field observations made during the same mapping project.

Mäkinen (1919) is the first to give a short general description of the geology of the ore deposit. His study shows that the ore is of epigenetic origin and, leaning on J. H. L. Vogt's (1898) theories about Norwegian sulphide-ores, assumes that the formation of the ore is closely connected with that of the serpentine rock, perhaps originating from it by differentiation.

Trüstedt (1919—21), the discoverer of Outokumpu, regards the neighbouring granite of Maarianvaara as the source of the ore. He draws his conclusions from the clearly epigenetic appearance of the ore and the contact relations between the ore and the pegmatites.

In his microscopical study of the ore minerals from Outokumpu and Pitkäranta, Laitakari (1929, 1931) describes the appearance of pyrite occurring in the ore and especially the replacement phenomena that have taken place, as he has observed, along the fractures in the pyrite.

Eskola (1933) describes in his study of chromium-bearing minerals the appearance and properties of all chromium minerals met with in the deposit. He assumes, too, that the hydrothermal origin of these minerals is closely associated with that of serpentine. Later on (1944) Eskola has shown that the Outokumpu ore, because of its origin, belongs to the group of late magmatic, so-called pneumotectic ores.

Haapala (1936) comes to the conclusion, in his extensive study of the serpentines of North Karelia, that the serpentines in the Outokumpu area have derived through autometasomatism from either primary dunitic olivine rock or pyroxene-peridotite resulting from the influence of magmatic water and silica during falling temperature. The amphibolization belonging to the metasomatic series would have occurred partly because of the change of pyroxene and partly because of silica entering from outside. According to Haapala, the dolomitic carbonate rocks associated with the serpentines have been derived from serpentine as the product of carbonate metasomatism, caused by the influence of bicarbonate-bearing solutions from outside sources. The skarn rocks have evolved as metasomatic replacement skarns.

In his primarily tectonic study of this region, Väyrynen (1939) reaches quite different conclusions from those of Haapala, especially with regard to the dolomites and skarn rocks, considering the former to be metamorphic sedimentary rocks belonging to the so-called Jatul-formation and the latter to be regional metamorphic contact-skarns between carbonate and silicate rocks.

The whole quartzite-serpentine complex of Outokumpu represents, according to Väyrynen, a nappe overthrust from the far northwest into which the ore has been displaced as a true ore-magma. This ore-magma has probably separated from a magma type which has been much more acid in composition than the peridotitic magma.

GENERAL GEOLOGICAL FEATURES OF THE OUTOKUMPU REGION

Before going into a detailed description of the geology of the deposit, a short general description of the relation of the Outokumpu quartzite-serpentine complex to the Karelian schist-formation must be made here.

Map I in the appendix, drawn on the basis of the general geological map, gives a general picture of the geology of the region. The author has supplemented this map of the Outokumpu formation and its immediate neighbourhood with field observations of his own made during the years 1944—50.

The ore-deposit is situated in the western part of the Joensuu depression-area, which belongs to the Karelian schist formation west of the Sotkuma—Vaivio gneissose granite area. The ore field is part of a long belt-like zone, chiefly consisting of quartzite and serpentine rocks. This zone extends northeast—southwest from Polvijärvi to a point near Lake Juojärvi.

The gneissose granite area of Sotkuma—Vaivio belongs to the basement of the Karelian schist formation, which, uncovered by erosion, appears in the schist formation like a »window».

On the boundary of the granite in the west and north, lying against the schist, there is a narrow basal zone consisting of conglomerate zones, breccias, and quartzites. The strike of the zone is parallel to the directions of the contact, the dip being outwards from the granite everywhere, so that the granite occurs in a local culmination below the schist formation.

To the south, west, and north of the contact-zone a rather narrow, slightly metamorphic phyllite-zone occurs, which is bounded by a more strongly metamorphic mica-schist area situated farther to the west. Being due to their different metamorphic grade, the transition zone approximately follows the direction Kuorinka—Solankylä—Rauanlahti—Martovaara.

A complex of numerous serpentine-ophiolites, following the direction Solansaari—Louhiinsalo—Huutokoski—Martovaara, occurs to the west of the phyllite-zone, on the east border of the mica-schist formation.

The mica-schist-formation, in the central zone of which the bow-shaped Outokumpu-zone is situated, is bounded in the west and northwest by an area consisting of micagneisses and tectonic schists. Typical of this area is the injectious influence of the rather wide, oval-shaped Maarianvaara granite, and its apophyses and satellites, which extend to the boundary of the mica-schist-formation. This granite and the pegmatite dikes, which obviously are derived from it, cut the neighbouring schists. Thus the granite obviously belongs to the youngest or late Karelian formation series of the area.

The distance between the nearest known outcrops of Maarianvaara granite and the Outokumpu zone is about 6 km.

In the southwest, in parts of the Juojärvi valley, the mica-schist-zone gradually grades over without any obvious contacts into arteritic vein- and mica-gneisses, which join up with Savo-schists farther away to the west.

GEOLOGICAL FEATURES OF THE MICA- SCHIST FORMATION

It is difficult to form any detailed picture of the tectonic features of the formation because of the rarity of outcrops. Only on the southwest side of the area do outcrops occur richly enough to make possible any description of this nature.

In the northwest against the Maarianvaara granite the general dip is about 30°—45° southeast, the granite lying below the schist formation. In the contact zone mica-schist-granite breccias and rather large mica-schist fragments are found as inclusions in granite, as for instance in the rocks on the northern beach of Lake Saunajärvi as well as in the area of Iivananpuro.

In the schist formation to the southeast of the contact zone (Appendix I, profile) a discountinuous belt of small serpentine-ophiolites occurs in the schist formation in the direction southwest—northeast. The belt extends from Maljasalmi to Teyrivaara and follows the direction of the contact zone. In the same belt there is in the schist formation a synclinal zone which changes into an anticlinal zone. This last-mentioned zone extends southwest—northeast from Maljasalmi to the vicinity of the southeast part of Lake Kaitalampi, passing on the western side of the village of Kuusjärvi.

Another anticlinal zone, parallel with the aforementioned zone but separated from it by a narrow synclinal zone, is situated on the southwest side of Lake Suuri Kuusjärvi. On the southeast side of this anticline, sloping to the southeast, is the southwest end of the Outokumpu zone, comformably following the tectonic features of the mica-schist, so far as any conclusions can be drawn from the few outcrops.

In petrographical structure and mineral composition the mica-schist is surprisingly homogeneous, being consistent in quality and poor in variety all over the area, so that during the sedimentation stage the conditions must have been very uniform.

Megascopical examination reveals that the rock is schistose in structure and that the orientation of the biotite scales is parallel to the schistosity. The dark components consist almost entirely of biotite. Its uneven content produces the only variations in the rock: from rather dark types rich in biotite to pale grey types poor in biotite. Quartz and feldspar occur as light components. Quartz veins, ranging from a few cm to some dm in size, occur occasionally in mica-schist. The veins occur in general in transverse fissures at right angles to the distinct lineation. The lineation is parallel to the pitch of folding of the schist. Another chief plane of veins is approximately the same as the plane of schistosity deviating from it about 5—10°.

Near the Outokumpu zone, or consequently in the middle part of the formation, the schist consists of grains of medium size, but it becomes coarser in grain upon coming nearer to the contact zone of the Maarianvaara granite, and at the southwest part of the formation. Quartz veins and pegmatite dikes, too, become more common in the vicinity of the granite. This is the case in the anticlinal zone of Maljasalmi—Kuusjärvi.

Viewed under the microscope, the mica-schist is evidently a granoblastic, schistose, and even-grained rock. No relict texture remains of the original bedding; on the contrary, the metamorphism has evidently destroyed all the original features.

The main minerals are: quartz, plagioclase, biotite, chlorite and potash feldspar — the accessory minerals being: sericite, apatite, zircon, epidote (pistacite), occasionally almandine, magnetite, as well as sulphide-ore grains and dust-like ore pigment.

Plagioclose, which is mostly without twinning lamellae is usually oligoclase, the maximum extinction angle in the symmetric zone being 5—10°, $n\alpha \sim n_{cb}$ and $n\gamma > n_{cb}$, $n\alpha < \omega_{Qu}$ and $\varepsilon_{Qu} > n\gamma > \omega_{Qu}$. According to Winchell (1951) these values correspond to 20—25 % An-content.

According to the following Analysis by Tomula (Frosterus—Wilkman 1924 P. 96) the chemical composition of mica-schist is:

Table I

	1		2	
	%	1 000 × mol. prop. *)	%	1 000 × mol. prop.
SiO_2	66.66	1 109.9	77.80	1 295.4
TiO_2	0.82	10.3	0.22	2.8
Al_2O_3	14.77	144.9	12.45	122.1
Fe_2O_3	7.03	44.0	2.08	13.0
MnO	—	—	2.02	0.3
MgO	2.56	63.5	0.40	9.9
CaO	2.00	35.7	2.36	42.1
Na_2O	0.98	15.8	2.94	47.4
K_2O	3.96	42.0	1.56	16.6
P_2O_5	0.11	0.8	—	—
S	0.28	8.7 (SO_3)	0.49	6.1
Loss on ign.	0.70	—	0.51	—
	99.87	—	100.83	—

1. Mica-schist, Outokumpu anal. S. E. Tomula, publ. Frosterus 1902).
2. Mica-schist, weathered » » » » » »

*) The molecular proportions here and in the following tables are calculated according to the tables by H. von Philipsborn (1933).

MAARIANVAARA GRANITE

The oval-shaped granite mass of Maarianvaara with its many surrounding satellites and apophyses, which cut the schists, is situated to the northwest of the mica-schist area and gives its own features to the geological picture of the region.

The contacts of the granite with the surrounding schists are mostly sharp, and at many places there are eruptive breccias in which the schist occurs as fragments, while the matrix consists of granite. The schist-fragments in granite are in general large, usually some metres in diameter, and the granite does not seem to have caused any changes in either texture or composition. Only occasionally are there some weak signs of granitization to be seen. From the contact relations the granite of Maarianvaara is obviously younger than the surrounding schists; and its tranquil structure indicates that no greater tectonic disturbances have taken place after the intrusion of this granite.

There are two chief types of granite, which differ in colour and appearance. In the eastern and northern parts of the region, at Kaavi, the granite is mostly reddish and comparatively coarse-grained. It contains richly pegmatitic portions, often with graphic texture. In the western and eastern parts of the region, in the parishes of Kuusjärvi and Tuusniemi, the granite is mostly grey and comparatively even-grained. In places it is cut by coarse-grained aplitic dikes in different directions.

The reddish type contains much quartz and microcline and as minor components plagioclase, biotite, and muscovite in varying quantities. In the grey type the essential minerals are quartz, plagioclase, and biotite, while microcline and muscovite are found in smaller quantities.

In both types apatite, sphene, ilmenite, zircon, and epidote occur as accessory minerals.

The mineral composition of the different types is revealed in Table II.

Table II

Mineralogic Composition of the Maarianvaara Granite

	1 %	2 %	3 %
Quartz	31.3	34.2	40.2
Plagioclase *)	27.9	35.7	29.2
Potash-feldspar	35.1	23.8	2.0
Biotite	4.9	6.2	23.9
Chlorite	—	—	3.0
Accessories	0.8	0.1	1.7
	100.0	100.0	100.0

1. Reddish pegmatite granite Rauantaival, Kaavi, determined by O. Kouvo.
2. » even-grained » » » » » »
3. Grey »post- Kalevian» » Meltusvirta » » » W. W. Wilkman (1924).

*) Plagioclase is oligoclasic in its composition, containing 20—22 % An. Here and there plagioclase is sericitized and in bigger porphyroblasts there is a zonal structure to be observed. Then the inner part of the grain is richer in An, containing 24—26 % An., while the outer part contains only 16—18 % An.

Here and in the following tables the determinations of the feldspar, made according to the Reinhard method (1931) are by O. Kouvo.

The chemical composition of the »post-Kalevian» granite at Meltusvirta is revealed in the following Analysis.

Table III

anal. E. Mäkinen, publ. Frosterus-Wilkman (1924)

	%	1 000 × mol. prop.
SiO_2	71.36	1 189
TiO_2	0.49	6
Al_2O_3	15.25	150
Fe_2O_3	0.34	2
FeO	2.08	29
MgO	0.43	11
CaO	2.16	39
Na_2O	2.98	48
K_2O	3.95	42
H_2O	0.36	20
P_2O_5	0.12	1
CO_2	0.05	1
	99.57	—

QUARTZITE-SERPENTINE ZONE OF JUOJÄRVI—POLVIJÄRVI

A zone chiefly consisting of quartzite-serpentine rocks is situated in the centre of the mica-schist-formation. It extends from Lake Juojärvi to the western part of the parish of Polvijärvi and forms a long, belt-like, narrow zone which distinctly differs from its geological surroundings. This zone is to be subsequently called the Outokumpu-complex, because Outokumpu is situated in the middle part of the zone, which is the best known because of its numerous outcrops, diamond drill-holes, and mine-observations.

The whole length of the zone is about 25 km and its widest breadth in the Outokumpu area is about 1 km. Most of the rock is covered with esker-formations and moraines, so that the geological features of the formation are difficult to outline, especially in the northeastern and southwestern parts of the region. Even at Outokumpu the outcrops are so rare and small that a map drawn on the basis of them would be inadequate.

The map in Appendix II showing the geology of the Outokumpu-complex is drawn on the basis of the outcrop observations and the material gathered during the diamond drilling, mapping of the mine and geophysical explorations in order to clarify the general geological features.

GENERAL TECTONIC FEATURES

The Outokumpu-complex occurs in the mica-schist as a narrow zone, the direction of which is approximately northeast—southwest. Its general dip in the outcrops is between 80° and 45° southeast. The general dip in the deeper horizons known in the central part of the zone according to the mine observations, generally slopes more gently, and varies from 30° to almost horizontal. In its cross-section (Appendix II) the formation is like a curved plate lying in an inclined position in the schist formation, and being conformable to the tectonical features of the country rocks.

At the northeast end of the zone, in the region of Horsmanaho the general strike of the complex is approximately north 25° east and at the southwest end in the parts of Viurusuo about north 60° east. The convex side of this bowlike zone, which is the result of the gradual variation of the strike, is directed towards southeast.

The axial pitch, which appears as a distinct lineation, is at the northeast end of the zone about 25—30° south-southwest, gradually sloping in the southwestern direction and being about 20—15° southwest on the east side of Outokumpu. In the formation on the southwest side of Outokumpu, there is an axial depression, where the axial pitch is approximately horizontal, and only slightly varying in its detailed features along its length of 2 km. From the east side of the village of Kuusjärvi till the region of Viurusuo the axial pitch varies between 5—10° east-northeast.

Thus, at both ends of the Outokumpu-complex the formation gives the impression of rising up into the air, i. e. on the surface incovered by erosion there are horizons which are situated deepest in the plate-like formation and which become thinner as they proceed downwards; but in the middle part of Outokumpu there is a thicker level which corresponds to the upper horizon of the formation.

FAULTS

It was established by means of the mine observations that a rather large fault cuts the formation just on the northeast side of Outokumpu; the strike of the fault plane is about north 25° west and the dip about 80° southwest. The displacement of this so-called Kaasila fault is approximately vertical. This conclusion is drawn from the vertical grooves which occur in the slicken-sides of the fault. Besides, the slicken-sides of the fault zone are vertically undulating, and in its horizontal section the whole known fault zone is like a gentle arch, which entirely excludes the possibility that the movements would have occurred in a horizontal direction.

The displacement of the fault is about 100 m, and the block northeast of the fault, the so-called Kaasila-side is the downthrow side.

It has not been possible to notice the fault on the surface because of the absence of outcrops in the fault zone. On the basis of the mine observations, the fault-direction, which is projected in the surface of the rock, is such that, in the topography of the terrain in the northwest, the Gulf of Luikonlahti lies on the extension of the fault direction. The origin of the Gulf of Luikonlahti, which is about 15 km long but here and there only a few hundred m broad, may be in some way connected with the same tectonical factors as the Kaasila fault.

About 3.5 km southwest of the Kaasila fault, on the east side of the house Naumanen there is another fault zone, nearly parallel with the first mentioned. It had not been possible to determine this fault zone either on the basis of the field observations, but its existence is supported by the geological features, determined by diamond drilling and geophysical explorations. These again are supported by the few outcrops met with in the region. On the basis of the diamond drilling it is ascertained that the Outokumpu-complex continues uninterruptedly to the east side of the house Naumanen. On the west side of the house Naumanen, according to the geophysical explorations, diamond drilling, and some outcrops, the complex continues after a displacement of 550—600 m to southeast in the direction of Ulla Station—Lake Suuri Kuusjärvi. The fault zone, which occurs as a strong transversal electric indication, is like a gently curving S in form, so that here, too, no horizontal movement is possible. In the vicinity of the fault the dip relations are of such a kind that apparently the horizontal displacement of 600 m would correspond to the vertical displacement of about 250—300 m, as follows: the northeast side of the fault would be the downthrow side of the fault, just as at Kaasila.

Along the continuation of the fault, in the direction Kaitalampi—Kolmikanta, there occur tectonical anomalies in the schist-formation, evidently being due to the fault movement. Near the fault zone the strike of the schist curves in the fault direction and follows it. This is due to the bending of the schists, evidently caused by the fault movement. The change of the strike therefore has a direction supporting the supposition that the northeast side of the fault would be exactly the same as the downthrow side of the fault.

The anticlinal zone of Maljasalmi—Kuusjärvi—Kaitalampi, which is situated in the mica-schist formation on the southwest side of the fault, continues in a northeast direction on the northeast side of the fault, a little displaced in the northwest direction from the northeast area of Lake Kaitalampi.

In addition to the large faults here reported there are numerous smaller faults in the formation, where the size of the displacement varies from a few dm to some m. A vertical cleavage plane, approximately transversal to the local pitch, usually occurs as a fault plane.

ROCKS OF THE OUTOKUMPU-COMPLEX

The occurrence of long quartzite- and serpentine-belts is a characteristic feature of the geology of the Outokumpu-complex. As mentioned earlier, the lower parts of the platelike formation occur on the surface at both ends of the complex; these, i. e. the quartzite-serpentine chains, occur in mica-schist as groups of serpentine-plates or lenses farther apart, but in the middle parts of Outokumpu as a uniform lamellar massif about 1 km in breadth.

The m i c a - s c h i s t, which occurs below and above the quartzite-serpentine complex, appears also as separate belts between quartzites and serpentines in the complex itself.

Q u a r t z i t e occurs as thin layers from a few to some dozens of metres in thickness, continuing several hundreds of m, so far as they can be followed on the basis of the outcrops and diamond drilling. They usually follow the strike and dip of the underlying and overlying wall rocks. The share of quartzite is greatest in the outer parts of the formation, while in the central part serpentine mostly dominates.

In intimate combination with quartzites, thin dark p h y l l i t i c b l a c k - s c h i s t layers containing graphite and sulphides are found in abundance. Their association with quartzites is so obvious that, though they may occasionally occur independently, they evidently belong genetically to the same formation series as the quartzites. In the contact-zone of mica-schist and quartzite, black-schist usually occurs as an intermediate formation.

Between the aforementioned schists s e r p e n t i n e-bodies appear in varying forms, sometimes as lenselike massifs, the largest of them being, in their middle parts, hundreds of m thick and several km long. Sometimes they form thin sill-like plates conformable with the schists, in general displaying the usual appearance of basic ophiolitic intrusives.

Closely connected with serpentines, irregular formations rich in d o l o m i t e are met with in the middle parts of the complex. They are seldom pure carbonate-rocks, but they usually contain diopside, tremolite, and serpentine in varying quantities. The dolomite gradually grades over into diopside-tremolite-skarn rocks or into pure serpentine rocks.

A kind of »mixed rock» occurs as a typical formation in the contact-zones of the dolomite and serpentine rocks; in the pale grey dolomitic ground mass of the »mixed rock» there occur numerous plate-like serpentine laths, which give a charasteristic ophitic structure to the rock. Väyrynen (1939) has called the rock »ophicalcite». Because the carbonate-material is dolomitic in its composition, the »field term» ophi-dolomite will be used herein in the later detailed description of the rocks.

S k a r n formations, varying in thickness, occur regularly as »intermediate layers» in the contact-zones of the serpentines and quartzites as well as in quartzite itself. Typical of the Outokumpu skarn is the abundance of green, chrome-bearing skarn minerals. The rock sequence of the contact-zone is, as a rule, rather regular with only small variations: quartzite-, diopside-bearing quartzite, diopside-tremolite-skarn, tremolite-serpentine rock, pure serpentine. In the skarns intercalated with quartzite diopside predominates, while tremolite is connected with the skarns near the serpentine.

In addition to the aforementioned typical rocks of the region, a n t h o p h y l l i t e - c o r d i e r i t e r o c k s occur as occasional formations in the complex. The only outcrop known on the surface was found at Raivionmäki, where the rock occurs near the footwall of the Outokumpu-complex in connection with quartzite- and chromite-bearing dolomite. The same rock was found together with ore on the southwest side of Mökkivaara in the diamond drilling hole K-388 drilled from the mine to the footwall of the ore body. Probably, however, the rock is more common than it would seem on the basis of these two rare outcrops.

During the mining operations some thin p e g m a t i t e- d i k e s were met with in the narrow zone on both sides of the Kaasila fault. The general strike of the dikes is usually approximately perpendicular to the general strike of the complex, the dip being approximately vertical, so that it has been possible to follow the thicker dikes at the different levels of the mine. On the western side of Central Schaft I these pegmatite-dikes are only quite exceptionally met with. Instead of pegmatite dikes quart-veins occur here in the same way.

The o r e b o d y occurs in the form of two plates which form a continuation to each other *en echelon,* being closely connected with the quartzites of the footwall side of the complex. In addition to the actual chief ore bodies, a smaller parallel ore body of a different type was found by means of diamond drilling below the western part of Lake Jyrinlietukka. A detailed description of this ore body as well as of the chief ore body will follow the description of the country rocks.

DESCRIPTION OF THE COUNTRY-ROCKS

MICA-SCHIST

The mica-schist layers occurring in the serpentine-quartzite complex are quite of the same type in character and mineralogic composition as the mica-schist of the neighbouring area. There are no characteristic differences to be noticed between them.

The contacts against the quartzite are sharp and as a rule constantly follow the same strata. The passage from one rock into the other is rapid, the transitional zone being at the most some centimetres in thickness. Sometimes there is a mediating zone or layer consisting of black-schist, the thickness of which varies from a few dm to several m. Thin graphite-bearing black-schist horizons and dark grey mica-schist horizons rich in biotite usually intercalate in this zone; the horizons gradually become more quartzitic, while the proportion of black-schist diminishes. Thus the rock gradually grades over into pure quartzite, which sometimes is so dark and rich in pigment that, without microscopic examination, it is not possible to determine whether it is quartzite at all.

The direct contacts of mica-schist and serpentine are rare, and in places, where they are expected to be found, the rock is covered with drift.

In many cases, according to the mine observations, there is thin quartzite rich in tremolite in the contact-zone, or, when mica-schist and serpentine are in direct contact with each other, a contact-rim rich in biotite and chlorite occurs at the contact; the thickness of the contact-rim is usually a few decimetres.

Structurally the mica-schist is obviously a schistose and even-grained rock, where biotite, as a dark component, lies parallel to the schistosity.

A distinct lineation occurs in the shear surfaces parallel to the schistosity; their surfaces are, because of the secondary folding, slightly crenulated or somewhat wavy. The elongation of the biotite-leaves is parallel to the lineation and with the folding axis of the mica-schist formation.

The microscopic texture and mineral paragenesis are the same as in the mica-schist, which occurs in the extensive neighbouring mica-schist formation and everything already stated in the description of the mica-schist formation holds good here.

QUARTZITE

Quartzite occurs most abundantly as several parallel layers in the marginal zones of the complex. In the central zone of the complex the occurrence of quartzites is not so common. The thickness of the layers varies from a few to several dozens of metres, the length usually being several hundreds of metres. Tectonically the quartzite follows the general structural features of the underlying and overlying country rocks, but because of the influence of the surrounding serpentine lenses many deformations have taken place in the details of the primary structure.

In its appearance the quartzite is always more or less distinctly schistose, and on the slicken-sides a distinct lineation occurs, as well as in the mica-schist, parallel to the axial direction, shown by the crenulation and wavyness caused by the secondary folding.

Approximately perpendicular to this axial direction is a strong joint system (Fig. b, Pl. I) with sharp rectilinear fractures; this jointing evidently corresponds to Cloos' (1936) Q-fractures. Where these joints were developed as open cracks they are filled with loose clay-like material separated from solutions or transported with solutions from the country-rocks. The cracks may be partly filled with ground country rock material, carried by water (Fig. c, Pl. I). In general the filling-mass of the cracks consists of serpentine- or asbestos-bearing amorphous material in which fragments of country-rocks occur as inclusions.

Here and there the normal structure of the quartzite has been rather strongly deformed (Fig. a, Pl. II) by secondary movements. This tectonized quartzite is, contrary to the ordinary type, light-banded parallel to the schistosity and partly glass-like (Fig. d, Pl. I). The light bands appear to the eye as a pure compact vein-quartz-type and even the darker quartzite between the bands is exceptionally compact and gives an impression of being glassy.

In addition to the banded appearance the deformed quartzite are characterized by small faults in different directions, while the faults along the cross-fractures dominate.

Parallel to the schistosity thin zones rich in skarn minerals, or quite pure skarn intercalations free from quartz, are common in the quartzite. The skarn intercalations are often lenticular on their cross-section parallel to the Q-cracks. The thickness of the lenses varies from a few cm to several dm. These lenses are elongated in the axial direction and irregular in form. Skarn intercalations of this type are met with especially in such places where, because of the folding of the quartzite-plate, cracks parallel to the schistosity have opened in the pressure minima and been filled with skarn-material, pressed into them, or with the material from which the skarn had been derived (the »pre-skarn» rock).

Microscopic examination shows the quartzite to be in its texture an even-grained, granoblastic, strongly metamorphic rock. Hardly any signs of its original clastic texture are to be seen.

In a quartzite which occurred as an inclusion in the ore, some traces of the primary texture may be observed microscopically however. The schistosity is parallel to the primary stratification in the form of graded bedding. The photomicrograph taken of the thin section (Fig. b, Pl. II) shows that the quartzite, which is impregnated by sulphides, gradually passes from coarse-grained to fine-grained zones; these in turn are sharply bounded against coarse-grained layers, which, again, grade into fine-grained ones. The phenomenon is repeated a few times in the thin section. This bedding is parallel to the schistosity, observed megascopically, but because of the haphazard position of the fragment no conclusions can be drawn on the basis of this graded bedding as to whether the position of the quartzite plates in the Outokumpu-complex is normal or overtilted.

The quartzite of the purest type is a monomineralic quartz-rock; but in addition to quartz the following minerals may be megascopically noted as accessory minerals in the quartzite of the normal type: diopside, tremolite as well as occasionally green, chrome-bearing mica or fuchsite, and chrome-garnet or uvarovite in the skarn-mineral-bearing zones. Besides these, impregnated sulphide-ore-grains are met with in the quartzite.

In addition to the aforementioned minerals small sericite-lamellae parallel to the schistosity may be observed microscopically as well as occasional carbonate grains, especially in the skarn-bearing layers.

The rock is throughout distinctly schistose and its texture microscopically granoblastic, the size of the grain varying from medium to fine. Coarse- and fine-grained zones alternate, but this alternation is mostly the result of metamorphism (or recrystallization) and not of primary bedding except in the case mentioned.

The undulating extinction in quartz is strongest in the coarse-grained zones; especially in the deformed parts of the quartzite plates the phenomenon is very typical.

Skarn-minerals occur in zones parallel to the schistosity (Fig. c, d, Pl. II) while the intervening zones are almost pure quartzite horizons, poor in accessory minerals. The carbonate grains in the skarn zones (Fig. c, Pl. II) have at least partly altered to tremolite or diopside. In the marginal zones of larger carbonate grains there is a fine-grained diopside-tremolite mass, which seems to replace the carbonate (Fig. a, Pl. III); and as relicts in the aphanitic skarn-mineral mass there are small carbonate grains.

Besides diopside and tremolite, chrome-garnet or uvarovite is met with as solitary crystals, varying in size from about 15 mm to microscopic dimensions, or as aggregates composed of numerous crystals. In connection with uvarovite, chromite appears nearly always as corroded grain clusters, usually with the centre of the uvarovite crystal being rich in chromite inclusions and the marginal zone consisting of pure uvarovite.

As the skarn minerals of the skarn intercalations in the quartzite are similar to those in the actual skarn formations, the detailed description of them will be given in connection with that of the skarn formations.

Chrome-mica, fuchsite, a mineral characteristic of the quartzite type of the Outokumpu-complex, occurs as separate scales or as lens-like aggregates (Fig. b, Pl. III) parallel to the schistosity. In the scale-aggregates the different units may be directed haphazardly, but the elongation of the scale-lens is parallel to the lineation of the quartzite.

Similar scale-lenses occur at the Viitalampi serpentine-quartzite-complex at Polvijärvi. This complex is situated to the northeast of the northeast end of the Outokumpu-complex. Grains of chrome-spinel or picotite are found in the centres of the fuchsite-aggregates (Fig. c, Pl. III), the fuchsite being obviously secondary as a reaction product between picotite and potassium-bearing quartzite minerals. In the Outokumpu-complex picotite is not found to be the core of fuchsite-lenses, but it is possible that the fuchsite is of secondary origin here, too; but the primary picotite or chromite has been exhausted.

The fuchsite has a silky luster. It is a scaly mineral in appearance, megascopically brightly blue-green. A distinct pleochroism may be observed microscopically, $\beta = \gamma =$ yellowish brown-green, $\alpha =$ (at right angles to the basalcleavage) intensely blue green. β and $\gamma > \alpha$. The extinction is straight $(-2V) \sim 10-20°$

$$\alpha = 1.568$$
$$\beta = 1.604$$
$$\gamma = 1.607$$

According to Eskola (1933, p. 30) the Cr_2O_3-content of the fuchsite is 4.90 %, which represents the value of the pure mineral calculated, however, on the basis of an analysis made of impure material.

Quartzite is everywhere more or less sulphide-bearing. The dominating ore-mineral is pyrite, appearing as small idiomorphic hexahedral crystals or as grain clusters. Its occurence is obviously that of an impregnation. It may be microscopically observed that grains of diopside, tremolite and carbonate are occasionally replaced by pyrite; in this case pyrite is more common in such quartzite-zones, where skarn minerals are also met with.

In addition to pyrite, the quartzite contains pyrrhotite, sphalerite, and chalcopyrite, mentioned in order of age, starting with the oldest. They are all obviously younger than pyrite. Their intrusion into the quartzite has occurred along the transverse fissures, from which they have spread sideways along the zones parallel to the schistosity.

The content of sulphides is greatest in the quartzite plates occurring in the vicinity of the ore, though they may exceptionally be found in quartzite-plates far away from the ore, and separated from it by serpentine lenses.

PHYLLITIC BLACK-SCHIST

The black-schist occurs in the formation intimately connected with the quartzites, most frequently at the contact zones of the complex as well as against the mica-schist near the foot-wall and hanging-wall. It may also occur inside the complex either as intervening layers in quartzite-schists or at the contact zones of quartzite and serpentine.

The thickness of the black-schist layers varies from a few metres to some dozens of metres, the length usually being some hundreds of metres, and in thicker layers even some kilometres.

The layers conform with the tectonics of the surrounding rocks, but in such a way, where structural disturbances appear in the wall-rocks, here the tectonization has had an extremely strong influence on the black-schists, which have obviously been least resistant, i. e. least rigid and therefore liable to deformations.

The passage from quartzite to black-schist is usually gradual: at the contact-zones quartzitic and phyllitic zones alternate so that the proportion of the former decreases until the pure black-schist is reached.

In the outcrops on the surface the black-schist is usually strongly weathered and (has become) rusty, which is due to its abundant sulphide content. The alternation of quartz and layers rich in mica-amphibole parallel to the schistosity occurs in the surface outcrops as zonal grooviness caused by weathering.

The rock is usually distinctly schistose, but here and there also slightly schistose or almost massive types are met with.

Quartz, amphibole as thin bands parallel to the schistosity, biotite, as well as pyrite and pyrrhotite grains and grainclusters may be megascopically observed in the black-schist. In some places the pyrite content may be as high as 30—35 %, the pyrite occurring as large hexahedra or pentagon dodecahedra, the size of which ranges from a few mm to 3—4 cm, whereas pyrrhotite occurs as a compact grain mass.

Graphite occurs as an extremely fine-grained, unevenly distributed mass; layers rich and poor in graphite, respectively, alternate parallel to the schistosity.

This rock is of an extremely fine structure and very dark because of its graphite and ore pigment. In addition, the following minerals may be microscopically detected in it: potash feldspar, plagioclase (52—54 % An), andalusite, epidote (pistazite), sphene, rutile, apatite and occasional carbonate grains and magnetite.

The quartz is richly pigmented, and the bigger grains show an undulating extinction.

The biotite, orientated parallel to the schistosity, is slightly pleochroic and almost colourless. Pleochroic halos are almost entirely lacking. The amphibole is tremolite ($\gamma \wedge C = 14—17°$) or hornblende poor in iron.

Andalusite occurs as rows of grains or as rather large crystalloblasts with an hour-glass structure.

Rutile is met with as a rare accessory in small grains.

Polished sections show that, in addition to pyrite and pyrrhotite, some calchopyrite and sphalerite occur in the black-schist. Small pyrrhotite and calchopyrite grains are often regular in form, with rectilinear margins resembling the traces of hexahedron. Sulphides, mentioned in the foregoing, are also met with as thin vein-like filling material in fissures. In all probability pyrrhotite, calchopyrite, and sphalerite are at least partly of secondary origin, replacing the primary pyrite.

In addition to the sulphides, magnetite is met with as idiomorphic but corroded grains or aggregates and as dustlike pigment. Graphite occurs as small, solitary flakes parallel to the schistosity or, most frequently, as scaly aggregates, in which the separate scales may be distinguished only in a polished section with a microscope by using great magnifications and only in polarized light with crossed nicols; by this means the scales can be distinguished because of the extremely strong anisotropy of graphite.

In the scale aggregates the different scales are haphazardly orientated, but the direction of the aggregate follows the schistosity. The rock is closely associated with quartzites, approximating the phyllites in mineral composition and grade of a metamorphism, especially in parts poor in quartz, whereas in the zones rich in quartz it approaches the quartzites in composition.

Genetically the rock most nearly corresponds, perhaps, to the ciastolite-slates derived from bituminous mud sediments (Eskola: 1939, p. 279). A common feature is the andalusite content of the rock and the hour-glass structure of the andalusite crystalloblasts. This structure has developed by orientation of the graphite pigment during the growth of the andalusite crystals.

DOLOMITE AND SERPENTINE ROCKS

The common occurrence of serpentines and associated dolomite rocks is the most characteristic feature in the geology of the Outokumpu-complex. Serpentine follows the general tectonical features of the peridotites occurring as ophiolite intrusives in the schist formation and forming thin lenses (»fishes») which taper out at their ends. The thickness of the lenses ranges from a few metres to some hundreds of metres; the length of the largest, homogeneous, continuous lenses may be even several kilometres.

The predominating rock near the footwall of the complex is quartzite, in which the serpentine forms thin lenses. The central zone consists mainly of serpentines; and the largest serpentine massifs, about 300—400 m in thickness and 3—4 km in length are met with in this zone.

Downwards along the dip (Map, Appendix II, profile) the proportion of serpentines increases, while the quartzite plates near the footwall become thinner. In its cross-section the complex looks as if the intrusion of serpentine along the plane of schistosity between the schist plates had taken place from underneath so as to bring the crests of the serpentine bodies near the present erosion surface.

In tectonic appearance the serpentines conform to the structural lines of the surrounding schist series, though with some exceptions in details.

The general dip and strike of the lenses are the same as in the schists, and the faults observed in them extend in the serpentine, too, though in general as broader zones of differential faults; here the zones are not so distinct as in the schists, because the serpentine is usually traversed by haphazard fracture systems.

A distinct regularity prevails in the contact relations of serpentine and quartzite. The complete transition series from quartzite to serpentine is as follows: quartzite, diopside-skarn, diopside-tremolite-skarn, tremolite-skarn, tremolite-dolomite-rock, dolomite-rock, dolomite-serpentine-rock and serpentine. The thickness between the different members of the series ranges from a few cm to several m. In exceptional instances some member of the transition series may be absolutely lacking, but mostly the series is complete, though the relative thickness of the members is variable.

DOLOMITE

Dolomite generally occurs in the marginal zones of the serpentine lenses as rather long and thin belts with indefinite borders. In its purest appearance the rock is pale grey, homogeneous, and even-grained, but it always contains some tremolite. Determined by the immersing method, the carbonate gives: $1.678 \ll \omega < 1.682$, thus being very pure dolomite. Occasionally, however, coarse-grained carbonate veins 1—5 cm thick and irregularly crossing the dolomite are met with. In them the carbonate is calcite: $1.655 < \omega < 1.664$. These veins are obviously secondary and derived from aqueous solutions in the fissures of dolomite.

Pale greenish-grey tremolite also occurs, in varying amounts: $\gamma \wedge C =$ 12—14°; occasional diopside grain-groups and lumps are met with in addition.

Besides the normal, pale, massive dolomite-type, also darker, somewhat schistose types are infrequently met with. Their darkness derives from the dust-like oxidic ore or graphite-pigment which occur in them. Zones rich in dolomite and tremolite alternate in the rock with richly pigmented bands along the schistosity.

The finely disseminated ore material is mainly either magnetite or pyrrhotite, though occasionally chromite and pyrite are met with. In a polished section, in conjunction with bigger pyrrhotite-grains, pentlandite (Fig. a, Pl. IV) may also be found in the form of idiomorphic grains, distinctly and typically fractured. In some pentlandite grains bravoitization, starting along the cleavage fissures, may be observed.

Chromite occurs as small independent grains and partly as dust-like pigment in the magnetite aggregates. But owing to the intense mixing and the fineness of the oxide-dust they can only with some difficulty be distinguished from each other.

Chromite may rarely occur in the dolomite-rock, taking the form of almost regular octahedral crystals, 5—8 mm in diameter, or as grain clusters brecciated from these (Fig. b, Pl. IV.)

Table IV

Analyses of the Outokumpu dolomite. Analyst: T. Mattila of the chemical laboratory of the Outokumpu mine.

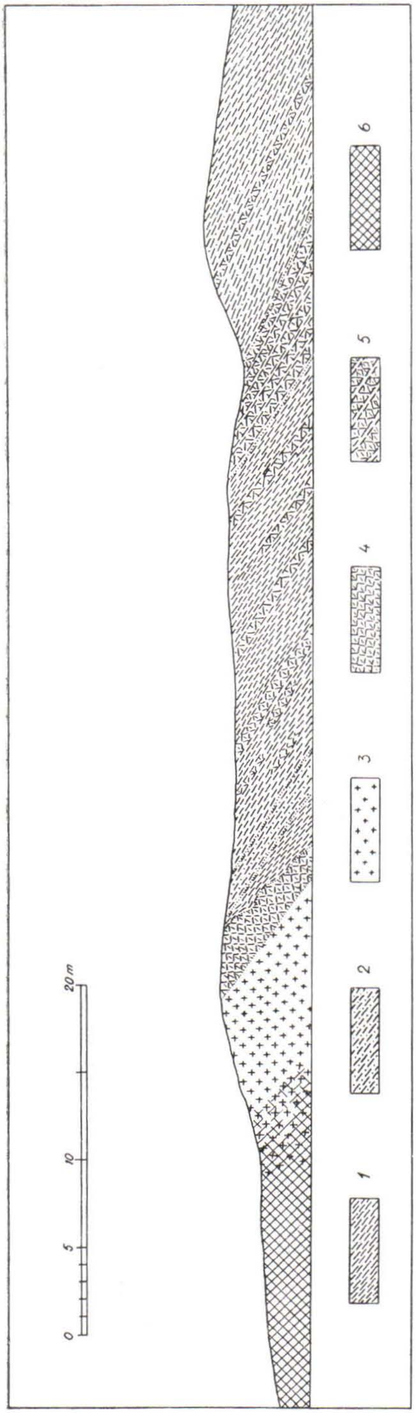
	1.		2.		3.	
	%	1 000 × mol. prop.	%	1 000 × mol. prop.	%	1 000 × mol. prop.
SiO_2	1.67	27.8	1.98	33.0	7.35	122.4
TiO_2	0.00	—	0.00	—	0.00	—
Al_2O_3	0.03	0.3	0.22	2.2	0.23	2.3
Cr_2O_3	0.08	0.5	0.90	5.9	0.26	1.7
Fe_2O_3	0.33	2.1	1.48	9.3	0.57	3.6
FeO	1.38	9.2	3.07	42.7	1.75	24.4
MnO	0.16	2.3	0.08	1.1	0.06	0.9
MgO	21.17	525.1	18.95	470.0	19.26	477.7
CaO	29.94	533.9	26.69	529.4	29.45	525.1
K_2O } Na_2O	0.08	—	0.00	—	0.16	—
H_2O	0.03	1.7	0.05	2.8	0.05	2.8
Ni	0.00	—	0.00	—	0.00	—
Co	0.00	—	0.00	—	0.00	—
FeS	0.85	19.4	0.24	5.5	0.05	1.1
CO_2	44.62	1 014.1	43.17	981.1	40.24	914.6
	100.34		99.83		99.43	
CaO/MgO	1.01		1.12		1.10	

1. Pale, homogeneous and coarse-grained dolomite, railway cut at the Station.
2. Pale grey chromite-dolomite, Raivionmäki prospecting channel.
3. Dark aphanitic dolomite, with some fibrous tremolite, western slope of Sänkivaara.

Such massive dolomite of the pale type rich in chromite, described by Eskola (1933), is met with, for instance, in the prospecting channel at Raivionmäki (Fig. 4). The fragments of chromite grains are capsuled by a fine, scaly chlorite rim, and the chromite is nowhere in direct contact with dolomite. The chromite-dolomite of Raivionmäki is for the present the only known deposit; hence the dolomite of this type is not characteristic of the zone, but only an exception.

In addition to oxide- and sulphide-ore dust in the dark dolomite types, fine graphite pigment in varying quantities is likewise met with, especially in rather strongly schistose zones. Here and there on the slickensides in the deformed zones a thin covering of graphite is also to be observed.

Though dolomite mostly occurs in the marginal zones of serpentine against quartzite, actual quartzite-dolomite contacts are not found, but there is always a transitional zone rich in tremolite whose minimum thickness is only 5—10 cm, though in general it is thicker.



In the dolomite-serpentine of the transitional zone there are two dominating types which, at the same contact-zone, may occur separately or mixed together, as for instance in the railway cut at Outokumpu Station. (Fig. 3.)

In the dolomite lying parallel to the serpentine, there usually begin to occur small serpentine aggregates, indefinite at their borders and unequally scattered, or in clear-cut blebs. As their relative content gradually increases the general colour of the rock turns darker. In such transitional zones small elongated dolomite lumps about 0.5—1 cm in size (Fig. c, Pl. IV) may occasionally be observed. In appearance they resemble rounded fragments, part of them still being angular. The matrix material between the lumps consists of scaly serpentine; and it appears as if the serpentine had capsuled the dolomite blebs, whose grain size and texture are the same as in normal dolomite. Parallel texture is noticeable here and there in the rock, the dolomite blebs being arranged in chains. The axes of elongation of the dolomite blebs are approximately parallel to each other, as if directed by shear movements.

It may be microscopically observed that the dolomite lumps represent normal dolomite in texture and that they are actual fragments surrounded by scaly serpentine material. From this material veinlets of serpentine have intruded into fissures of the dolomite lumps. (Fig. d, Pl. IV). Along these fissures a partial serpentinization of the dolomite has taken

Fig. 3. Cross-section of the railway cut at Outokumpu station. 1. Quartzite, 2. Black schist, 3. Dolomite, 4. Diopside-skarn, 5. Layers rich in tremolite in quartzite, 6. Serpentine.

place. In certain cases the carbonate has been broken along the twinning lamellae and serpentine-material has intruded into the cracks.

Small carbonate grains are found in the surroundings of the bigger carbonate-lumps. Their extinction-position is the same as that of the large grains in the border zone of the lumps. This fact suggests that the small carbonate grains originally were parts of the the big ones but became separated from them during the progress of the serpentinization. In such cases the boundary between the carbonate-grains and the serpentine is not distinct because the carbonate passes gradually over into the serpentine without any sharp grain border as the result of the serpentinization.

In these cases the serpentine is quite obvious younger than the carbonate, occurring as the matrix of a dolomite-breccia crushed by tectonical movements. It is quite obvious that dolomite has been replaced by serpentine, at least partially, in addition to which tremolite has formed as a reaction product. In the serpentine-mass tremolite occurs as unorientated prisms with distinct amphibole-cleavages.

At the contact zones of serpentine and dolomite another general transition type, though not so common as the one mentioned, occurs as local formations measuring 2—3 m in maximum thickness. In the dolomite of normal type, dark serpentine plates occur as a network, the thickness of the plates varying from 1 to 10 mm and the diameter from 1 to 10 cm. In such a case the serpentine plates are thinner and smaller in diameter in the parts of the contact zone against the dolomite, while the dimensions of the plates become larger towards the serpentine.

On the cleavage faces of dolomite the cross-sections of the plates in general taper out towards the ends. Superficially examined, they give the rock an ophitic appearance; hence the name: ophi-dolomite. A more detailed examination, however, shows that serpentine occurs in plate-like formations, whose measurements vary within the limits just mentioned. It clearly resembles breccia in structure, the fissures of the crushed dolomite being filled with serpentine material, which again is further crushed here and there. Therefore it is quite difficult to decide whether serpentine or dolomite has formed the primary material of certain parts of the alteration zone (Fig. a, Pl. V). As can be easily observed in some parts of the alteration zone the serpentine plates are nearly parallel or slightly *»en echelon»*, as if caused by the shearing movements; but in general no orientation can be observed.

The dolomite material between the serpentine plates is of normal type, but always more or less tremolite-bearing. When the serpentine plates are thick and numerous, the tremolite content is greater than normally.

It can be microscopically observed that the serpentine plates in general become thinner at their ends. In dolomite, on the continuation of the plate, a slight crush structure is noticeable.

In the centre of the thicker serpentine plates olivine relicts are usually met with. They are serpentinized in their margins and along the netlike crack system. The thinner plates are free from olivine so that it looks as if the primary plate material had been olivine, later partly or wholly serpentinized.

In the contact-zone of the serpentine plates tremolite prisms are usually found. In general they are unorientated but sometimes like teeth of a sawblade directed outwards from the serpentine (Fig. b, Pl. V).

From the mutual relations as well as from the contacts between the serpentine and dolomite in this type of dolomite it is most likely that the serpentine is younger than the dolomite.

In such a case the ophidolomite would represent a breccia originating at the contact zone of the rocks. This formation might possibly be a preliminary stage for the dolomite-serpentine-breccia, previously described, and have come about under circumstances where the movements or other factors responsible for the crushing of the dolomite had not yet produced any effect strong enough for grinding, but only a crack system had resulted, into which the serpentine, probably still in the form of dunite, had been pressed.

The photograph (Fig. c, Pl. V) taken of the tailings of the Outokumpu concentration plant shows that a cleavage system of the type mentioned may result from other causes than movements alone. The jointing, which quite clearly resembles the jointing type of ophi-dolomite, has in this case been brought about by the influence of the contraction phenomenon when the somewhat damp tailing has frozen.

SERPENTINE

In his study of the serpentines of North Karelia, Haapala (1936) has given a detailed description of the serpentine types connected with the Outokumpu-complex. The present author, who has nothing to add to the part of the study concerning the serpentines, will in the following only refer to the main points and results of the said study.

In its main type serpentine in the Outokumpu-complex is massive in appearance, more or less granular, and only rarely are aphanitic or schistose types met with. In colour it ranges through all the shades of green, from almost black to pale green. The rock is very resistant to weathering. In some cases, however, it behaves quite contrariwise, rapidly disintegrating when exposed into a fine powder.

The serpentinization is in general almost complete, and only in the types with a darker granular structure are relicts of premetamorphic rocks found.

Haapala divides the serpentines into three main types, within which varieties without any structural bounds are met with.

The regional distribution of the different types is not distinct, but they are more or less haphazard mixed together, and the completely serpentinized types make up the great majority. The best preserved parts are situated in the proximity of the contact-zones, whereas the parts most altered, in which relicts of premetamorphic structures or minerals are scarcely to be found, make up the centre of the massifs.

The Dunitic Type

Dunitic olivine-rock has been dominant in the premetamorphic stage. A granular texture and unaltered olivine are to be discerned as relicts of its primary structure in the thin section.

The rock has originally been almost monomineralic. In addition to olivine, amphibole has occurred here and there, as pseudomorphs of serpentine after amphibole are met with. The serpentinization of olivine has begun at the margins of the crystals and along the cracks, and at the same time magnetite has precipitated. Magnetite in general is powder-like dust distributed throughout the serpentine or occurring as aggregates and strings along the cracks of the primary olivine. These strings, marking pseudomorphically the cracks and the grain boundaries of the primary olivine, are often preserved, showing the granular texture of the dunite. In addition to magnetite there occur coarser grains of chrome-bearing magnetite either as octahedral crystals or irregular grains.

Chrysotile of a net-like structure occurs as serpentine mineral and, in addition, as accessory secondary minerals, there are chlorite, talc, and carbonate, which, according to Haapala, is entirely of secondary origin.

In the serpentinous pseudomorphs after amphibole, most likely originally anthophyllite, the forms of the amphibole prisms have been preserved completely unchanged. These pseudomorphs may be found both in the dark varieties, in which olivine still may be present, and in the paler ones, where the original composition is more difficult to decipher.

There seems to be no doubt that the serpentinization of olivine and amphibole has occurred practically simultaneously. Serpentine and magnetite at least have not been present prior to the formation of amphibole. The mineral sequence was: olivine, amphibole, serpentine, magnetite.

The dunitic type, of which Analysis 1. is given in Table V, is the most monomineralic and distinct type, while the others are more varying both in their structure and mineral composition. The accessory minerals—chromite, talc, carbonate — and the mode of their occurrence will be described later in connection with other types containing the same components in larger proportions.

The Saxonitic Type

This type is characterized by its mottled appearance. In the most altered varieties the mottles are not so distinct, because enstatite, which causes this mottled appearance, has been replaced by brownish green serpentine and the dark magnetite-dust is more evenly distributed throughout the serpentine mass. The original features are therefore noticeable only when viewed under the microscope. In comparison with the dunitic type the saxonitic variety more frequently contains unaltered anhydrous silicates, though the amount is always small.

The following minerals can be recognized: olivine, enstatite, anthophyllite, tremolite, chrysotile, bastite, chlorite, kaemmererite, talc, carbonate, chromite, magnetite, and pyrrhotite.

Olivine has been the major component in the premetamorphic rock; enstatite has occurred rather sparsely as short prisms.

The texture is poikilitic. The small rounded inclusions of olivine are well preserved when protected by enstatite. When enstatite has been replaced by bastite, the forms of the olivine grains are to be seen as »windows» of mesh-structure serpentine in the bastite flakes. The hydration of enstatite has always occurred with complete preservation of the original pyroxene form as a relict.

Amphibole is of minor importance in the saxonitic type. It is always altered into hydrated silicates. The serpentine formed in this way is distinguishable from that derived from olivine only by the absence of the magnetite powder.

Talc is common in connection with enstatite and bastite. In places a zonal arrangement is noticeable. The core may still consist of enstatite, bordered by bastite, which is followed by a zone of talc. Here and there talc may have originated at the expense of serpentine or amphibole.

Chlorite is present nearly everywhere, though in quite small amounts. It appears in conjunction with bastite serpentine and in cracks of chromite, around which it also occurs as fine-scaled rim-mineral.

Chromite is in general rather rare, though found in the saxonitic type more frequently than elsewhere. It seems likely that the crystallization of chromite ended before the formation of enstatite.

The mode of occurrence of magnetite is similar to that of other types described before. The enstatite- and bastite-bearing types are free from the pigment-like magnetite powder.

Pyrrhotite occurs as filling material in cracks, being obviously the latest member in the mineral sequence. The present author has observed pentlandite in association with pyrrhotite by means of microscopic examination of a polished section.

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In Table V Analysis 2. represents a completely serpentinized specimen containing: bastite and chrysotile, and, as accessory minerals, talc, chlorite, carbonate as well as chromite and magnetite. The content of chromite is higher than usual.

The Porphyritic Type

Characteristic of the porphyritic type is the occurrence of elongated olivine crystals or their serpentinous pseudomorphs in a paler ground-mass, which consists mainly of material rich in carbonate, amphibole or talc.

The mineralogical composition is as follows: olivine, tremolite, anthophyllite, chrysotile, dolomite, talc, chlorite, chromite, magnetite, and sulphides.

Three varieties can be distinguished among the mottled, partly hydrated rocks: amphibole-, carbonate- and talc-bearing rocks. The latter occurs separately, while the other two are more intimately associated.

The olivine is comparatively well preserved, especially when associated with carbonate or amphibole. Its serpentinization has occurred in the usual way along the cracks and the borders of the crystals. In close connection with amphibole, the olivine is better preserved. Olivine occurs partly in poikilitic intergrowth with amphibole, being preserved comparatively unaltered. The hydration has commenced in the cracks, forming magnetite powder at the same time. The borders of the crystal against serpentine are in general regular and sharp; the serpentine round the crystal is yellower than normally and its birefringence is higher than in the normal serpentinous pseudomorphs after olivine.

Anthophyllite and tremolite occur as long laths or fibrous units penetrating into olivine. The serpentinization of amphibole is general except in the types rich in carbonate, in which the amphibole is well preserved. The serpentine produced is similar to that derived from olivine but free from magnetite powder.

The porphyritic type of Haapala, rich in carbonate, is similar to that previously described by the author in connection with the dolomite rock as the contact formation of serpentine and dolomite. According to Haapala this type represents the result of the metasomatism of serpentine-amphibole rock. Here, according to Haapala, carbonate penetrates into the serpentinous pseudomorphs after olivine and amphibole (Haapala p. 41), though he adds: »The carbonate grains have, then, the exact form of fragments, some of which may still have been left unchanged.»

According to Haapala, carbonate has replaced both amphibole and serpentine, but not olivine directly, the process probably being selective to some extent.

As already mentioned, the porphyritic type rich in talc occurs more independently and contains amphibole and carbonate to some extent.

The serpentinization has been complete, having been followed by the formation of talc, while the distinct, occasional serpentinous pseudomorphs after olivine are surrounded by flakes of talc. Magnetite dust is completely lacking.

Chromite occurs in the general manner. The grains are more like groups of small, strongly corroded crystals, the spaces between the crystals being separated from other minerals by blades of chlorite. Occasional relicts of olivine are found in connection with chromite.

Table V

	1		2		3		4		5	
	%	1 000 × mol. prop.	%	1 000 × mol. prop.	%	1 000 × mol. prop.	%	1 000 × mol. prop.	%	1 000 × mol. prop.
SiO_2	37.26	620.4	35.92	598.1	35.04	583.4	40.48	674.0	40.08	667.3
TiO_2	—	—	—	—	—	—	—	—	—	—
Al_2O_3	0.48	4.7	1.47	14.4	1.26	12.4	0.32	3.1	0.40	3.9
Fe_2O_3	6.32	9.6	5.27	33.0	1.61	10.1	1.17	7.3	0.96	6.0
Cr_2O_3	0.28	1.8	1.05	6.9	0.47	3.1	—	—	—	—
FeO	2.56	35.6	2.63	36.6	8.31	115.7	1.34	18.7	2.23	31.0
MnO	—	—	—	—	0.15	2.1	0.14	2.0	0.08	1.1
MgO	38.11	945.2	35.77	887.2	35.90	890.4	41.60	1 031.8	40.06	993.6
CaO	—	—	1.45	25.9	tr.	—	tr.	—	0.80	14.3
Na_2O	—	—	—	—	tr.	—	tr.	—	0.22	3.6
K_2O	—	—	—	—	tr.	—	tr.	—	—	—
P_2O_5	—	—	—	—	—	—	—	—	—	—
H_2O+	12.95	718.8	12.20	677.2	12.90	716.1	13.80	766.0	13.76	763.8
H_2O-	0.91	—	1.27	—	0.82	—	1.28	—	1.48	—
S	0.63	19.7	0.21	6.6	4.29	133.8	0.28	8.7	0.48	15.0
NiO	0.24	3.2	0.28	3.8	0.24	3.2	—	—	0.07	0.9
CoO	—	—	—	—	0.05	—	—	—	—	—
CO_2	—	—	2.26	51.4	—	—	—	—	—	—
	99.74		99.78		101.04		100.41		100.62	
—0					1.07		0.07		0.12	
					99.97		100.34		100.50	

1. Completely serpentinized dunitic serpentine, Mine, level +130 anal. P. Haapala (1936, p. 34).
2. Bastite-serpentine, Outokumpu, anal. P. Haapala (1936 p. 37).
3. Massive dark serpentine, below the footwall of the ore, Mine, Sh I, +285 level, anal. O. v. Knorring.
4. Fibrous serpentine, Mine, Sh I +285 level, anal. O. v. Knorring.
5. Dense, aphanitic, microscopically almost isotropic serpentine, Mine, Sh I +285 level, anal. O. v. Knorring.

In the summary of his study (Summary p. 79—80) Haapala comes to the following conclusions:

In the serpentine complex either the dunitic olivine rock or, in exceptional cases, pyroxene-peridotite have formed the pre-metamorphic rock. The original rock has undergone several successive metasomatic changes, viz.:

amphibolization, serpentinization, carbonatization, and the development of talc.

The amphibolization is supposed to be due partly to the conversion of pyroxene and partly to the accession of silica from outside sources. The serpentinization presumably took place as an autometamorphic change caused by the action of magmatic water and silicic acid contained in the rock itself. Carbonatization and the formation of talc appear to have been caused by hydrothermal solutions. The former process has resulted in the formation of genuine dolomites subsequent to the carbonatization, when a new silicification occurred during which the skarn rocks were formed.

Accordingly, Haapala concludes, the dolomite- and skarn-rocks would be metasomatic replacement products.

SKARN ROCKS

Characteristic of the contact zones of quartzite and serpentine or dolomite is the occurrence of skarn of varying thickness along the contacts.

Likewise, skarn formations are met with as intercalations or »intervening layers» in quartzite. Characteristic of them all is the occurrence of green chrome-bearing calc-silicate-minerals.

As mentioned the following variety of mineral assemblages dominates, almost without any exception, in the contact zone of quartzite and serpentine: quartzite, diopside-skarn, diopside-tremolite-skarn, tremolite-skarn, tremolite-dolomite-skarn, dolomite-serpentine rock, serpentine. In regard to the relative thickness of the different components, however, some local variations occur. The whole transition series from quartzite to serpentine is in general only a few metres thick.

The skarn occurring as intercalations in quartzite is mainly diopside skarn, and the thickness of the layers varies from some cm to two or three m. They regularly occur in a thin lenticular form, elongated in the axial direction of the quartzite. The tendency seems to be for them to occur in quartzite horizons, where, owing to the folding, cracks parallel to the schistosity have opened in pressure minima. The »protoskarn» has intruded into these openings and, later on, altered into skarn.

DIOPSIDE SKARN

Alongside the quartzite, the skarn zone consists mostly of diopside. In addition to quartz there occur other components: tremolite, uvarovite, carbonate, grossularite, chromite, and sulphide ores.

D i o p s i d e is in general coarse, occasionally forming prisms with a distinct cleavage, 10—15 cm in size. The colour varies from dirty greenish grey to intensive green. Occasionally there occur quite translucent chrome-green units with almost complete crystal faces. The optical properties vary within the following limits:

	α	β	γ	γ-α	$\gamma \wedge C$
1.	1.673 ± 0.002	1.678 ± 0.002	1.692 ± 0.002	0.019	38.5°
2.	1.665 ± 0.002	1.673 ± 0.002	1.686 ± 0.002	0.021	42°

According to Winchell (1951) a hedenbergite-content of about 0—15 % corresponds to the optical properties here mentioned.

According to an Analysis by L. Lokka the chemical composition of the diopside is as follows:

Table VI

Grass-green chrome-diopside-crystal, Outokumpu, anal. L. Lokka (1943).

	%	1 000 × mol. prop.	At. n.	
SiO_2	52.88	8 805	Si 8805	9055 = Z = 4 × 2264
TiO_2	0.00	—	Al 250	
Al_2O_3	1.27	125	Cr 70	4672 = Y = 2 × 2336
Cr_2O_3	0.53	35	FeIII 72	
Fe_2O_3	0.58	36	FeII 125	
FeO	0.90	125	Mg 4405	
MnO	0.09	13	Ca 4535	4548 = X = 2 × 2274
MgO	17.76	4 405	Mn 13	
CaO	25.43	4 535	OH 422	
H_2O+	0.38	211	Formula $X_2\ Y_2\ Z_4\ (0,\ OH)_{12}$	
H_2O-	0.09	—		
	99.91	specific gravity 3.302		

Owing to the variable chrome-content the green colour of diopside is not always even. In exceptional instances crystals may be met with in which the colouring is zonal, so that bright grass-green and pale grey zones alternate along the crystallographic directions (Fig. a, Pl. VI). The boundaries of the zones are sharp and parallel to each other. The intensity of the colour is constant in the same zone but varies in different zones.

Thus it is obvious that the chrome content of the rock has rhythmically varied during the growth of the diopside crystals.

The large diopside crystals are in general free from pigment, whereas the fine-grained diopside mass is, almost without any exception, clouded by ore pigment. When there are larger lumps of sulphide ore in diopside-skarn, the diopside in the immediate proximity is clear and free from pigment, as if the ore had absorbed all the pigment particles in its neighbourhood (Fig. b, Pl. VI).

T r e m o l i t e generally occurs in diopside-skarn as occasional laths or groups of laths, being, however, small in amount. Tremolite, too, is usually greenish in colour. Occasionally transparent, intensely green tremolite prisms, 4—5 cm in length and 2—4 mm in thickness, are met with.

Carbonate is dolomitic in its composition. It occurs as occasional coarse-grained lumps. Viewed under the microscope, it may be observed that the formation of diopside and tremolite has taken place at the expense of carbonate (Fig. a, Pl. III).

A study of uvarovite was carried out by Borgström as early as 1901, when the Outokumpu ore was still unknown.

Uvarovite occurs partly as well-formed solitary crystals, a few mm in size, but always more or less fractured, or partly as aggregates of microscopically small, irregular crystals. Occasionally units may be found which are 15—20 mm in diameter, almost of ideal crystal form and intensely emerald-green.

It may be noted microscopically that chromite frequently occurs in conjunction with unvarovite. In such cases the core of uvarovite consists of a fine-grained chromite mass, while the outer parts are of pure uvarovity (Fig. c, Pl. VI). It seems probable that uvarovite had formed secondarily as the reaction product of chromite and calc-silicate-minerals.

v. Knorring (1951) has come to the same conclusion in his study of uvarovite.

When uvarovite occurs in skarn rock rich in carbonate, it is often surrounded by a thin, paler green contact-rim (Fig. d, Pl. VI) which microscopically appears to be of a fine-grained diopside-uvarovite-carbonate mass. In this case secondary reaction products, developed at the contact of primary uvarovite and carbonate, are involved.

The chemical composition of uvarovite is revealed in the following analyses: Table VII.

Table VII

	1			2			3		
	%	1 000 × mol. prop.		%	1 000 × mol. prop.		%	1 000 × mol. prop.	
SiO_2	35.88	597.4		36.79	612.6		37.31	621.2	
Al_2O_3	1.13	11.1		1.93	18.9		5.34	52.4	
Cr_2O_3	27.04	177.9	204.4	27.54	181.2	202.7	22.60	148.7	205.0
Fe_2O_3	2.46	15.4		0.41	2.6		0.30	1.9	
MnO	0.03	0.4		—	—		0.15	2.1	
MgO	0.04	1.0	595.4	0.50	12.4	595.7	0.25	6.2	619.0
CaO	33.31	596.0		32.71	583.3		34.25	610.7	
ign.	0.18		—	—		—	0.10		—
	100.07			99.99			100.30		
(Ca, Mg, Mn) O: ($Al, Cr, Fe^{III})_2O_3$: SiO_2		2.95: 1.02: 2.94		3.02 : 1.0 : 2.94			3.03 : 1.0 : 3.02		
Sp. gr.		3.75		$3.772^{15°}$			3.809		
n-green		1.8467		1.8552			1.821—1.829		

1. Uvarovite, from uvarovite-tremolite-tawmawite-dike. Kumpu B, Outokumpu, anal. L. Lokka, Eskola (1933).
2. Uvarovite in quartzite, Outokumpu, anal. Borgström (1901).
3. » » » » » v. Knorring (1951).

Locally uvarovite may occur in skarn rocks so abundantly that the expression »uvarovite rock» is justified; the uvarovite mass, consisting of fine crystals, forms the chief mineral, while diopside and tremolite occur as minor components.

In his study of chrome minerals, Eskola (1933) has described some rare vein formations that cut the quartzite. In them uvarovite, together with tremolite, tawmawite, and pyrrhotite, occurs as an actual vein-forming mineral, and, according to the description, resembles the chromite in chromite-veins, to be described later.

The uvarovite-tawmawite-pyrrhotite veins described are met with in the mine, in the eastern region of the fault zone of »Kumpu B». They contain, in addition to accessory minerals, chrome-diopside, pyrite, chalcopyrite and chromite. As the parts of the mine in question have been inaccessible because of cave-ins during the time the author has held his post, and, as the veins referred to are not found elsewhere, it has not been possible for the author to study them.

Occasionally grossularite-garnet is found in diopside-skarn as small pale greenish units, yellowish along the margins (Fig. b, Pl. VI). Characteristic are the habit of a garnet crystal, high refringence, and anomalous birefringence.

C h r o m i t e normally occurs as occasional grains or grain groups, and when their occurrence is rather abundant, the green colour of the skarn minerals is more than usually intense. Solitary chromite grains are strongly corroded, irregular, and somewhat rounded in form. Megascopically they are dark, almost black-brown in colour, and in polished section under the microscope blood-red internal reflections are noticeable.

There are some chromite dikes cutting in the diopside skarn in the mine in the Kaasila area that make the mode of occurrence of chromite a remarkable feature. The skarn formation, about 2 m in thickness, is situated below the footwall of the ore at the contact-zone of quartzite and serpentine. In the wall of the drift made in the skarn rock there is a network of thin, irregular intercrossing chromite dikes. The thickness of the dikes varies from 1 mm to 15 mm. The enclosed photograph (Fig. a, Pl. VII) is taken of a hand specimen taken from the wall of the drift, where the dikes are 1 cm thick. The dikes border sharply against the wall-rock (Fig. b, Pl. VII) while occasionally some thin apophyses of these dikes penetrate into diopside skarn.

Microscopically examined the contact is likewise sharp and in the dike may be distinguished small fragments of the wall-rock parallel to the dike.

The dike material is almost exclusively of chromite, in addition to which some uvarovite and diopside as well as occasional quartz grains are met with. The chemical composition of the dike material separated quantitatively from the wall-rock is given in the following Analysis:

Table VIII

Chromite dike, contains some uvarovite, Kaasila, + 250 raise, sublevel 6. anal. O. v. Knorring

	%	1 000 × mol. prop.
SiO_2	4.90	81.6
Al_2O_3	8.20	80.4 } 456.0
Cr_2O_3	57.10	375.6 }
FeO	22.20	309.0
MnO	3.30	46.5 }
MgO	2.56	63.5 } 113.6
CaO	0.20	3.6 }
H_2O-	0.44	24.4
Mo...............	0.32	} as Molybdenite
S	0.30	}
	99.52	

The chemical composition of pure chromite, calculated from the Analysis above by subtracting the components entering into the uvarovite, starting from the SiO_2-percentage, is as follows:

$$\begin{aligned} Cr_2O_3 &= 62.92\ \% \\ Al_2O_3 &= 9.31\ » \\ FeO &= 26.18\ » \\ MgO &= 1.52\ » \\ \hline & 100.00\ \% \end{aligned}$$

The relation of the components of uvarovite is taken in the calculation as: (Mg, Ca, Mn) O : (Al, Cr, Fe^{III}) : SiO_2 = 3 : 1 : 3.

The specific gravity of chromite when separated with Clerici-solution was found to be 4.60.

The skarn rock in the close vicinity of the dike contains small chromite grains and uvarovite in rather large amounts. In the contact zone of the dike and skarn some flakes of molybdenite scales with strong reflection pleochroism may be distinguished.

The occurrence of chromite as an actual dike-forming mineral shows that there is no necessity of its being a primary mineral separated at the beginning of the differentiation, but chromium may also migrate in rocks.

The occurrence of sulphide minerals is rather characteristic of skarn rocks. The skarn formations next to the ore body and especially in its contact zones contain considerable amounts of sulphides. Sulphides occur between skarn minerals or squeezed into their cracks. As inclusions in larger lumps there occur tremolite prisms and rounded diopside grains, which give the impression of being corroded (Fig. c, Pl. VII).

It seems likely from the mutual contact relations between the skarn minerals and the sulphides that the ore is younger than the skarn rock, and at least partly replaces it. In addition to sulphides solutions have intruded into the skarn rock. By their influence the diopside has partly altered into a talc-tremolite mass along net-like structures (Fig. d, Pl. VII).

Pyrrhotite is the most general sulphide mineral, while rarer components are chalcopyrite, pyrite and sphalerite. In addition, valleriite occurs in conjunction with chalcopyrite. A certain white Co-Ni-mineral, probably belonging to the linnaeite group, is found associated with pyrrhotite in the form of the result of unmixing in the solid state. The amount of this Co-Ni-mineral and the size of its grain are so small that it has not been possible to ascertain its properties. The mode of occurrence and combinations of all these ore minerals is similar to those in the main ore.

TREMOLITE SKARN

In its mode of occurrence the tremolite-skarn follows the same lines as the skarn rocks rich in diopside. The difference between them is the occurrence of tremolite as a dominating mineral instead of diopside. Tremolite-skarn is commonest in those parts of the contact zones of quartzite and serpentine that are next to serpentine, especially if the serpentine is dolomite-bearing.

The contact against quartzite is in general sharp and conformable with the schistosity of quartzite. Skarns rich in tremolite are occasionally met with also as intercalations in quartzite.

Besides tremolite dolomite in remarkable amounts generally occurs in conjunction with serpentine in the zones next to serpentine.

Minor mineral components are: diopside, anthophyllite, quartz, chlorite, biotite, uvarovite, chromite, and sulphide ore minerals.

T r e m o l i t e generally occurs as coarse prisms or fine fibres, which in some cases are arranged radially as »suns», together with anthophyllite. The colour of tremolite varies from white to chrome green, the last-mentioned being especially intense in the chromite-bearing skarn zones, where also uvarovite occurs in the same manner as in diopside skarn.

The optical properties of different tremolite types, measured by the immersion method, vary as follows:

	α	β	γ	γ-α
1.	1.604±0.002	1.621±0.002	1.634±0.002	0.030
2.	1.612 »	1.626 »	1.636 »	0.024
3.	1.621 »	1.633 »	1.643 »	0.022

$\gamma \wedge C = 15$—$18°$

1. White tremolite at the contact of ore and serpentine, Sh. I +285 level, Rs. 9.
2. Pale green tremolite in the footwall of ore. Sh. I +250 level, help Rs. 1.
3. Intensely green tremolite in ore. Kaasila +250 level, Rs. 1 sublevel 2 W.

The pleochroism of the paler varieties is extremely weak, but of the green ones distinctly visible: α = faintly greenish yellow, β = yellowish green, γ = intense green.

The chemical composition is given in the following Analysis:

Table IX

	1		2	
	%	1 000 × mol prop.	%	1 000 × mol. prop.
SiO_2	55.76	928.4	57.74	961.4
Al_2O_3	0.62	6.1	2.35	23.1
Cr_2O_3	—	—	0.64	4.2
Fe_2O_3	0.60	3.8	—	—
FeO	2.76	38.4	2.75	38.3
MnO	0.11	1.6	—	—
MgO	23.84	591.3	22.38	555.1
CaO	13.24	236.1	14.04	250.4
Na_2O	—	—	—	—
K_2O	—	—	—	—
P_2O_5	—	—	—	—
H_2O+	2.50	138.8	0.38	21.1
H_2O-	0.10	—	—	—
S	0.90	28.1	—	—
Ni	—	—	—	—
Co	—	—	—	—
Cu	—	—	—	—
	100.43		100.28	

1. White monominerale tremolite rock, anal. O. v. Knorring, the same sample being used to determine the value 1. by immersion, in the foregoing.
2. Green chrome-tremolite, anal. S. E. Tomula, publ. Frosterus-Wilkman (1924).

The values in the analyses given show that the composition of tremolite greatly varies in its chrome-content. The variation in composition appears in the variation of the optical properties as well.

In its properties and mode of occurrence, d i o p s i d e resembles to that in actual diopside skarn. The size of the grains is generally smaller than in diopside skarn.

A n t h o p h y l l i t e occurs as slender prisms or fibres mixed with tremolite.

C h l o r i t e appears as occasional, almost colourless, slightly pleochroic scales or scale groups. Solitary scales have an almost right extinction and weak birefringence.

Another chlorite type, faintly rose-reddish in colour, may occasionally be met with. The pleochroism is weak, but yet noticeable, // C nearly colourless and ⊥ C faintly reddish. Birefringence is weak with anomalous interference-colours. In composition this variety represents the slightly chrome-bearing chlorite described by Eskola (1933) in connection with the anthophyllite-cordierite rock. In view of its faint shade, the Cr_2O_3-content of the chrome-bearing chlorite, met with in the Outokumpu formation, is probably much smaller than that of the kaemmererite or actual chrome-chlorite.

Biotite is met with in certain zones parallel to the schistosity in tremolite skarns. Biotite is coarse-scaled. It approximates phologopite in shade and has a tint of golden yellow.

Uvarovite and chromite appear in the same way as in diopside skarn. In certain chromite-uvarovite aggregates a rhythmical zonal texture is microscopically noticeable: the central portions of the aggregate consist of chromite surrounded by an intervening uvarovite covering, while the outermost zone consists of a fractured chromite mass. In connection with chromite grains tiny translucent blood-red picotite crystals are occasionally met with; they have a fractured texture similar to that of chromite.

In exceptional cases small quartz or tremolite inclusions may also be met with in chromite.

Sulphide ore minerals occur in the same manner as in diopside skarn, the sulphide material, however, being evidently younger than the skarn. The most common sulphide mineral is pyrrhotite, in which small linnaeite grains may be noticed microscopically. They occur as irregular equidimensional grains or as elongated units, lath-like in form and fringed along the borders. It is very likely that they have separated from pyrrhotite by unmixing. Such lath-like units are usually parallel to some crystallographic direction of pyrrhotite (probably 0001), orientated parallel in the whole pyrrhotite crystal.

As in diopside-skarn, chalcopyrite, pyrite, sphalerite and valleriite associated with chalcopyrite occur as other sulphide minerals.

CORDIERITE-ANTHOPHYLLITE ROCK

In the prospecting channel at Raivionmäki a pale, cordierite-anthophyllite-rock rich in pyrrhotite and composed of coarse prisms is met with. It occurs in quartzite, sharply adjoining it as a conformable intervening layer, the thickness varying from 2 to 3 m (Fig. 4).

During the first prospecting operation at Outokumpu, it was assumed that the occurrence at Raivionmäki was the extension of the ore plate in the upper ridge. This conclusion was drawn from the remarkable ore mineral content of the formation.

Later on, however, it was ascertained that the cordierite-anthophyllite-rock formation is situated in a horizon which lies considerably higher in the complex than the ore. The formation is parallel to it, and has probably no direct structural connection with it.

Associated with ore, a cordierite-bearing rock of the same type is, however, directly encountered in a drilling-hole, dug in the lower portion of the mine, in conjunction with cubanite-bearing ore on the level +285.

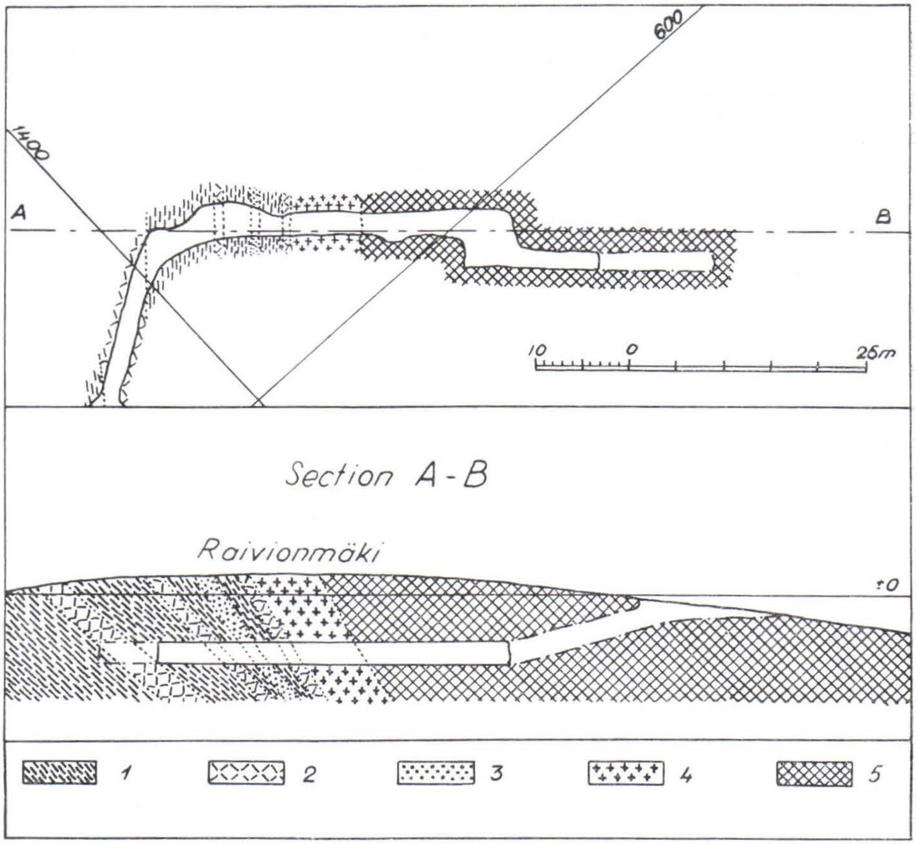

Fig. 4. Prospecting channel at Raivionmäki, Outokumpu. 1. Quartzite, 2. Skarn rock, 3. Anthophyllite-cordierite rock, 4. Dolomite, 5. Serpentine.

The cordierite-anthophyllite-rock of Raivionmäki was very minutely described by Eskola (1933). Megascopically the rock consists of coarse prisms. Anthophyllite, radially or in sheaf-like groups, occurs as a major component; the solitary prisms may be as much as 5 cm in length. The matrix material between the amphibole prisms is made up of bluish grey xenomorphic cordierite with a fatty lustre and sulphide ore, which occurs in abundance.

In addition, a varied collection of accessory minerals (Fig. a, Pl. VIII) may be observed microscopically: small yellow-brownish rutile crystals, small ilmenite rhombohedra, irregular xenomorphic staurolite crystals, which here and there occur together with cordierite in symplectitic intergrowth, as well as roundish almandite crystals and brownish-red, faintly translucent chrome-spinel, picotite-octahedra, and a reddish brown chlorite-mineral, kaemmererite.

Characteristic of the cordierite rock, found in connection with the ore, is the strong pinitization of the cordierite (Fig. b, Pl. VIII) as well as the covering which surrounds the pseudo-hexagonal cordierite grains and is dirty from the effects of the alteration products.

Sulphide-ore associated with cordierite-anthophyllite rock is chiefly made up of pyrrhotite and chalcopyrite, and occasionally of pyrite and sphalerite.

Pentlandite, with its typical cleavage and crystal form, appears, microscopically observed, in conjunction with pyrrhotite at Raivionmäki. Incipient bravoitization along the cleavage system is distinctly noticeable.

Associated with cordierite rock the chalcopyrite has in all cases proved to be cubanite-bearing. Present accessory minerals in chalcopyrite are strong reflection-pleochroic valleriite, found as a filling in deformation cracks and cleavages, and small star-like sphalerite skeletons. Examined in polarized light with crossed nicols, an internal lamellar twinning texture occurs in chalcopyrite.

PEGMATITE DIKES

In the northeastern parts of the mining field, especially at Kaasila and in the area of Kumpu B as well as rarely in the more western parts, in the area of the Central Schaft I, there occur some quartz-plagioclase-pegmatite dikes. Their general strike is perpendicular to that of the quartzite-serpentine complex, the dip being always steep and almost vertical. Strike and dip are rather the same as in the Q-fracture-system observed in quartzite.

In the surface outcrops no pegmatite dikes are met with in the formations, which are connected with the actual Outokumpu complex, excepting the dikes cutting the footwall of the mica-schist. The nearest pegmatite dikes are exposed in the mica-schist, on the eastern side of Lake Suur-Särkilampi. Farther on, near the Maarianvaara granite, the pegmatite dikes are very common.

In the mine the thickness of the dikes ranges from about 2 m to a few centimetres. Several dikes may, owing to their vertical dip, be followed through different levels of the mine. By virtue of their pale colour and the structure cutting the general length direction, they are easily distinguishable.

The contacts against the wall rock are sharp and the passage from one rock to another is distinct. Occasionally thin breccias may be noticed at the contact. In these formations the wall rock occurs as fragments and the pegmatite as matrix.

When pegmatite penetrates serpentine, a contact rim rich in biotite — a so-called black-wall appears on both sides of the dike. The rim is followed by a zone rich in chlorite. It passes gradually over into normal serpentine. The thickness of the whole contact zone varies from 5 to 50 cm, depending on the thickness of the pegmatite-dike, so that the thinner dikes are bounded by a thinner contact rim and contrarywise.

The contact of quartzite and pegmatite is generally sharp, and even microscopically there are no apparent alterations to be seen, excepting that at the contact-zone the quartzite is brecciated and contains more sericite than normally. The small oval quartzite fragments at the contact are in general parallel to the contact.

A common feature of such pegmatite dikes which penetrate the country rocks is furthermore their relative wholeness and rectilinear continuity.

In the ore the pegmatite dikes occur somewhat more haphazardly. Over short distances their thickness varies greatly and local apophyses, quickly thinning out, may shoot into the ore. In places pegmatite occurs in the ore as intermittent chains of dike fragments, the fragments being separated from each other by the ore as in a breccia. The contact of pegmatite and ore is always sharp and in the contact zone small ore fragments may be noticed in the pegmatite dike. The pegmatitic character of the dikes is in general quite distinct and even megascopically the possibility that the pegmatite might be older than the ore seems to be out of question.

Megascopically the following minerals may be observed: quartz, feldspar, muscovite and, occasionally, sulphide minerals.

Microscopically the feldspar proves to be partly plagioclase and partly microcline. Plagioclase is strongly sericitized and the twinning lamellae are only weakly visible. The composition is oligoclase, 20—25 % An. Microcline and plagioclase occur as coarse grains, from 2 to 3 cm in size, while quartz makes up the ground mass. Muscovite is met with in abundance as scales measuring at most 2 or 3 cm in diameter. Biotite occurs occasionally as solitary scales, and never in more than small amounts.

An integration-table determination of a fine-grained pegmatite dike shows its mineral composition to be as follows:

Pegmatite dike, Kaasila +250 level, determ. by O. Kouvo.

Quartz	44.44 %	
Plagioclase	50.19 »	20—25 % An
Potash feldspar	2.22 »	
Muscovite	3.15 »	
	100.00 %	

Apatite, epidote, rutile, and zircon may be microscopically observed as accessory minerals.

The grain size of the pegmatite minerals becomes evidently smaller from the central portions to the border, while the marginal zone near the contact is micropegmatitic in texture (Fig. c, Pl. VIII). At the intrusion stage of the dikes the wall rock (i. e. the ore) has obviously been already cooled. Quick cooling has caused a micropegmatitic texture at the margin of the dike, whereas the more slowly cooled central zone has become coarser-grained during the slow crystallisation.

The pegmatite dikes undoubtedly penetrate the ore (Fig. 5), which, on the basis of the foregoing arguments must be assumed to have already

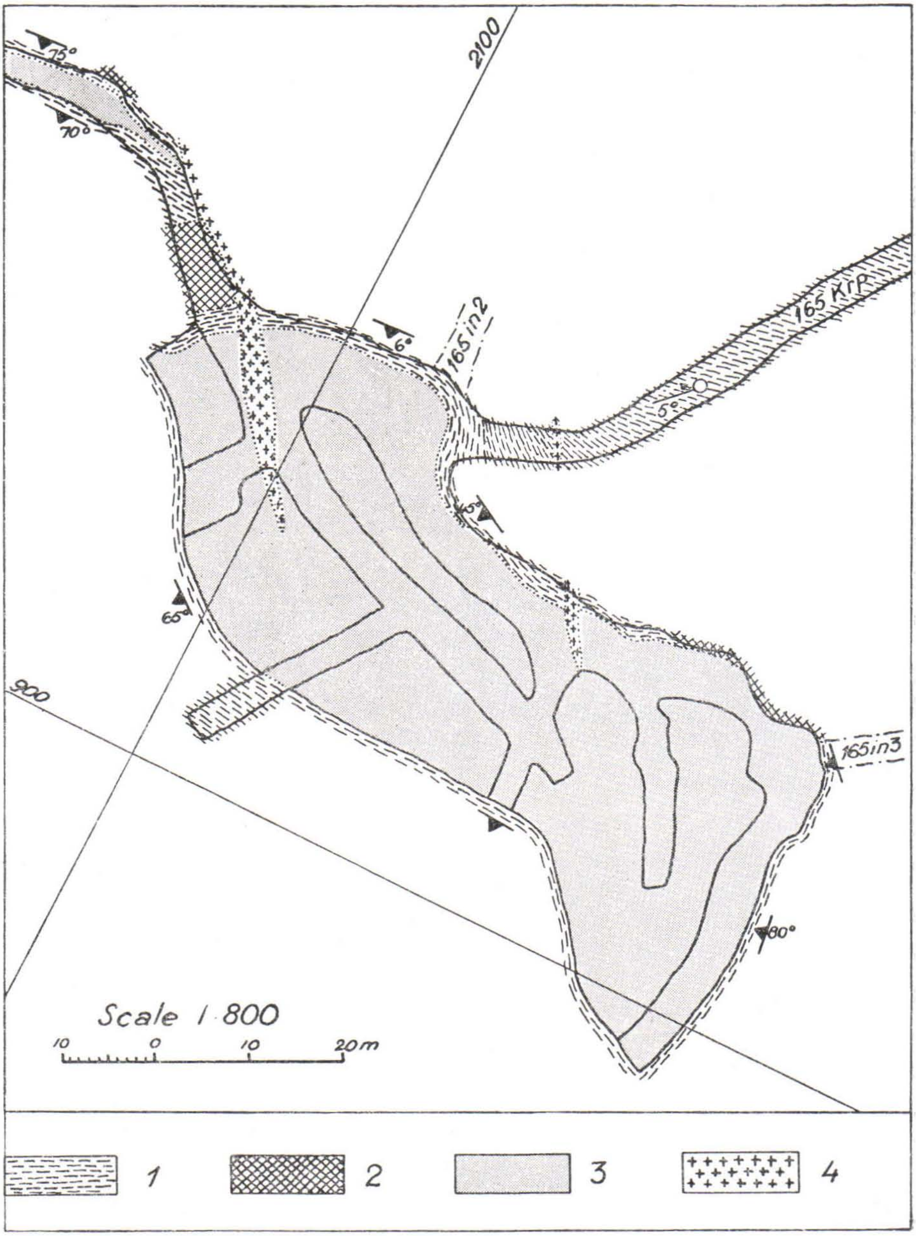

Fig. 5. Pegmatite dikes cutting ore and its wall-rocks. 1. Quartzite, 2. Serpentine, 3. Ore 4. Pegmatite dikes. Kaasila +165 level, Dr. 1 E,

been relatively cooled when the pegmatite intruded into it. Though this be the case, the pegmatite contains ore minerals, which evidently were derived from the ore and are especially common in the marginal parts of the dikes.

Thin ore veinlets, one or two mm in thickness or quite microscopically fine shoot from the ore into the pegmatite. They fill the cracks in the crushed zones occurring in the pegmatite. The ore minerals appear in the pegmatite as separate grain groups or separate disseminated grains without any obvious connection with the wall rock.

The ore mineral composition in pegmatite is the same as in the actual ore body, excepting that pyrite is absent or extremely rare.

Chalcopyrite occurs as the most common sulphide mineral and small star-like sphalerite skeletons are met with. Pyrrhotite is of normal type, containing small flame-like linnaeite laths.

In conjunction with sphalerite, as in the normal ore, small stannite grains appear at the borders of the sphalerite grains. Estimated with the eye the proportion of stannite to sphalerite is, however, greater than in the main ore.

Cubanite is absent in the pegmatite dikes.

The occurence of ore minerals in pegmatite as secondary components derived from the main ore implies that part of the sulphides of the ore deposit have still been in motion after the intrusion of pegmatite, viz., the youngest ones: pyrrhotite, chalcopyrite, and sphalerite, together with the minerals associated with them. They have intruded, probably as solutions, into the cracks of pegmatite, which have developed during the latest movements of the ore formation. The chains of pegmatite dikes in broken sequence or aforementioned fragment-like pegmatites have developed as a consequence of these latest movements.

In the light of the facts presented, the time between the *mise-en-place* of the ore and the intrusion of the pegmatite has been relatively short.

ORE DEPOSIT

GENERAL TECTONIC FEATURES

In its tectonic features the ore deposit of Outokumpu follows the general structure of the quartzite-serpentine complex. The deposit (Map Appendix III) consists of two orebodies in the form of plates or »rules» following each other »*en echelon*» in an inclined position. The easternmost of the so-called Outokumpu plates is by the Kaasila fault, which, as has been mentioned, is divided into two separate orebodies Fig. 6.

The orebody of the deviation side, northeast of the fault, is called the Kaasila orebody and the part southwest of it the Kumpu orebody. Another

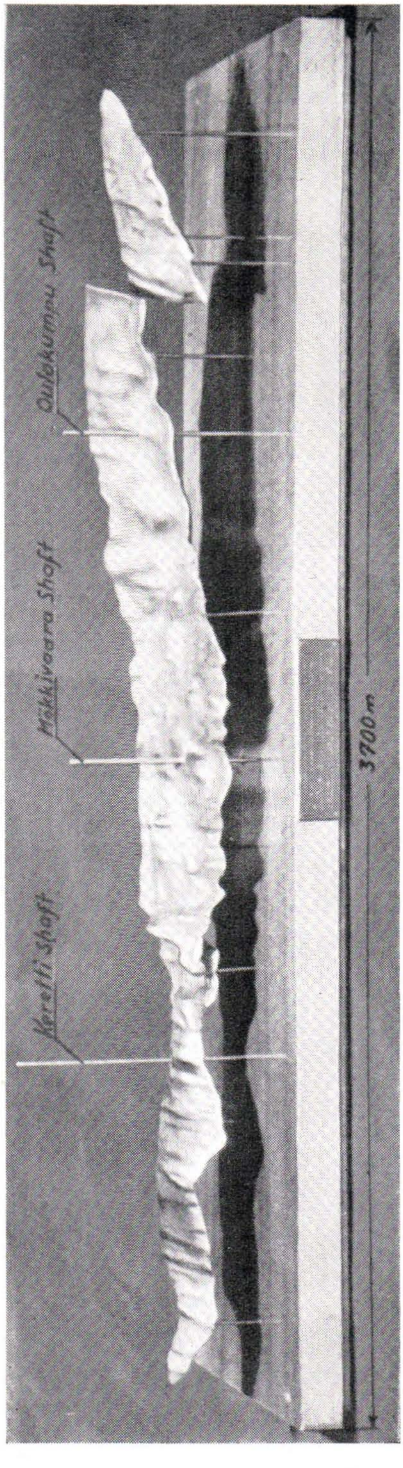

FIG 6. THREE-DIMENSIONAL MODEL OF THE OUTOKUMPU ORE BODIES.

Photo Roos

main plate extends »*en echelon*» from the lower portion of the southwest end of the last- mentioned orebody. Because of its situation almost wholly under Lake Jyrinlietukka, it is called the Lietukka orebody.

The plate group of ore is situated near the footwall of the quartzite-serpentine complex in the part of the complex dominated by quartzite, conforming with the tectonic features of quartzite. The general strike, followed by the ore plates, is in the part of the complex in question approximately northeast—southwest. The dip varies within wide limits, being on the upper ridge of the ore plate 60—30° southeast, gradually grading down towards the lower portion, being there about 20—0° southeast. In places in the lower portion the dip may even be 0—15° northwest.

The axial pitch, which is about 25—15° southwest at Kaasila, remains the same in the Kumpu orebody in the area near Central Shaft I; then it gradually grades and becomes nearly horizontal in the central part of the Kumpu orebody. From there it extends horizontally to the southwest end of the Lietukka orebody, folding only quite locally.

Owing to the axial pitch and the Kaasila fault, the ore deposit has two outcrops in its northeast part: one at Kaasila, where the ore seems to »rise up into the air» and another at Kumpu B, bordering the fault. It was precisely at Kumpu B that the ore was discovered and exposed for the first time. The loose boulders, which had been transported by the glacial ice sheet, had been detached from these outcrops, leading to the discovery of the deposit. The outcrop of Kaasila, having already been dug out, is filled up at the present, but at Kumpu B (Fig. a, Pl. I) the same ore type is exposed, which, for example, is represented by the Kivisalmi boulder.

The breadth of the ore plates in the dip direction varies from 250 to 400 m, the average thickness being about 7—9 m. The total length of the plates is about 3.8 km.

According to the last estimates the original ore resources were about 25 million tons, with the remaining ore resources being valued at 16 million tons (in 1952).

The average metal content is, according to the analysis of the 290 diamond drill-hole samples:

Cu	3.71 %	
Fe	28.19 »	
S	24.75 »	
Zn	1.07 »	Au 0.6 g/t sp.gr. 3.60
Ni	0.11 »	Ag 8.9 »
Co	0.20 »	
Insolubles	41.97 »	(of which SiO_2 40.34)
	100.00 %	

The average mineral composition of the ore, calculated in the above table, is as follows:

Chalcopyrite	$CuFeS_2$	10.7 %
Pyrite	FeS_2	21.0 »
Pyrrhotite	$Fe_{12}S_{13}$	24.6 »
Sphalerite	ZnS	1.5 »
Silicates		42.2 »

FAULTS

As mentioned, a detailed mapping and study of the fault cutting the Outokumpu complex on the northeast side of Kumpu B has been possible in connection with the mining operations.

The fault, the strike of which is about north 25° west and the dip about 80—85° southwest appears as a »sköl» filled with loose and ground material of the wall rock, the thickness of the »sköl» being about 0.5—1.5 m. Somewhat rounded fragments of serpentine, quartzite and ore, too, may occasionally be observed in the ground »sköl» material, while the material for the most part consists of ground clay-like serpentine material. According to the observations by the author, the fragments vary in size: they may be as large as a human head or only as small as a fist. The ore fragments are strongly polished with shining faces. Signs of polishing are likewise to be noticed at the ends of the ore plate adjoining the fault.

The cross-section of the ore plate, so far as an exact mapping of the slicken-sides in the stopes has been possible, is almost identical at the ends of the ore bodies, situated on different sides of the fault. The slip of the fault is about 100 m.

In the author's opinion there cannot be any doubt about the fact that the fault would not be younger than the ore. Besides, the displacement has taken place along the transversal joint plane, which is approximately perpendicular to the general axial pitch of the formation.

Another fault, though considerably smaller than that of Kaasila, is met with on the southwest side of Central Shaft II cutting the region of +250 Rs. 14 and +285 L. Rs 2. The strike of the fault is here about north 25° east, the dip about 75° southeast and the slip about 5—6 m; and the deviation side is the east side, like that of the fault at Kaasila. The thickness of the fault »sköl» varies from 0.1 to 1.5 m, the »sköl» material consisting of loose serpentine-chlorite-graphite material, full of gleaming slickensides.

In addition, several smaller faults, of less than 2 m displacement but with distinct slips, occur in the mine. The fault plane is in general a transverse fracture plane, approximately perpendicular to the general axial pitch of the formation. All these small faults are younger than the ore, as can easily be ascertained.

CONTACT PHENOMENA BETWEEN ORE AND WALL ROCKS

Below the footwall of the ore there occurs a quartzite layer of varying thickness; in appearance and structure it corresponds to the normal quartzite type of the formation. Quartzite of the same kind, though thinner than that of the footwall, occurs in general above the hanging wall of the ore. The occurrence of quartzites as the wall rock of the ore is most general in the northeastern parts of the deposit at Kaasila and in the area of Central Shaft I, whereas, in the central and southwestern parts, other rocks may be in contact with the ore.

The contact between ore and quartzite is normally sharp and rectilinear, following continually the same schistosity horizon of quartzite (Fig. d, Pl. VIII). Only occasionally are contacts met with where the passage from one rock to the other is gradual and where in the mapping of the mine an economical limit is to be used instead of a geological boundary.

In places the contact surface has served as a shear plane for small tectonic movements. In these cases there occurs a thin, damp clay-like rim of serpentine-chlorite-graphite-material, at most a few cm thick. In this so-called »separator» the signs of movement are visible as grooves and an orientation of chlorite caused by the shear. The surface of the unbroken ore lying against the shear rim likewise often has a fine polish.

In spite of the general regular renquillity and rectilinearity of the contacts, there may occasionally occur contacts in which vein-like ore apophyses shoot from the ore into the cracks of the adjoining quartzite: Such contacts are met with e. g. directly on the eastern side of Central Shaft I on the + 250 level, where apophyses, about 30 cm in thickness and nearly 1 m in length, intrude from the ore into the vertical cracks of the tectonized quartzite below the foot wall.

A formation of another type than that just mentioned, but obviously similar in its origin, is met with on the southwest side of Central Shaft II in the stoping area of +250 M-Rs. 12 a. Here a plate-like, parallel orebody has intruded into a crack. The orebody is about 200 m in length, 40—50 m in breadth, and 0.2—0.8 m in thickness. The crack has opened in the quartzite, which forms the foot wall of the main orebody, parallel to the schistosity (Fig. 7). According to mining and diamond-drilling observations the developed orebody has a direct connection with the overlying main orebody.

In the southwestern parts of the Kumpu orebody and especially in the area of the Lietukka orebody, the ore more and more frequently directly adjoins serpentine or skarn rocks. The quartzites in the foot wall and especially in the hanging wall, if still present, are extremely thin, sometimes measuring only a few cm.

The contact of ore against serpentine is considerably more irregular than against quartzite. The contact surface is uneven, rough, and in the

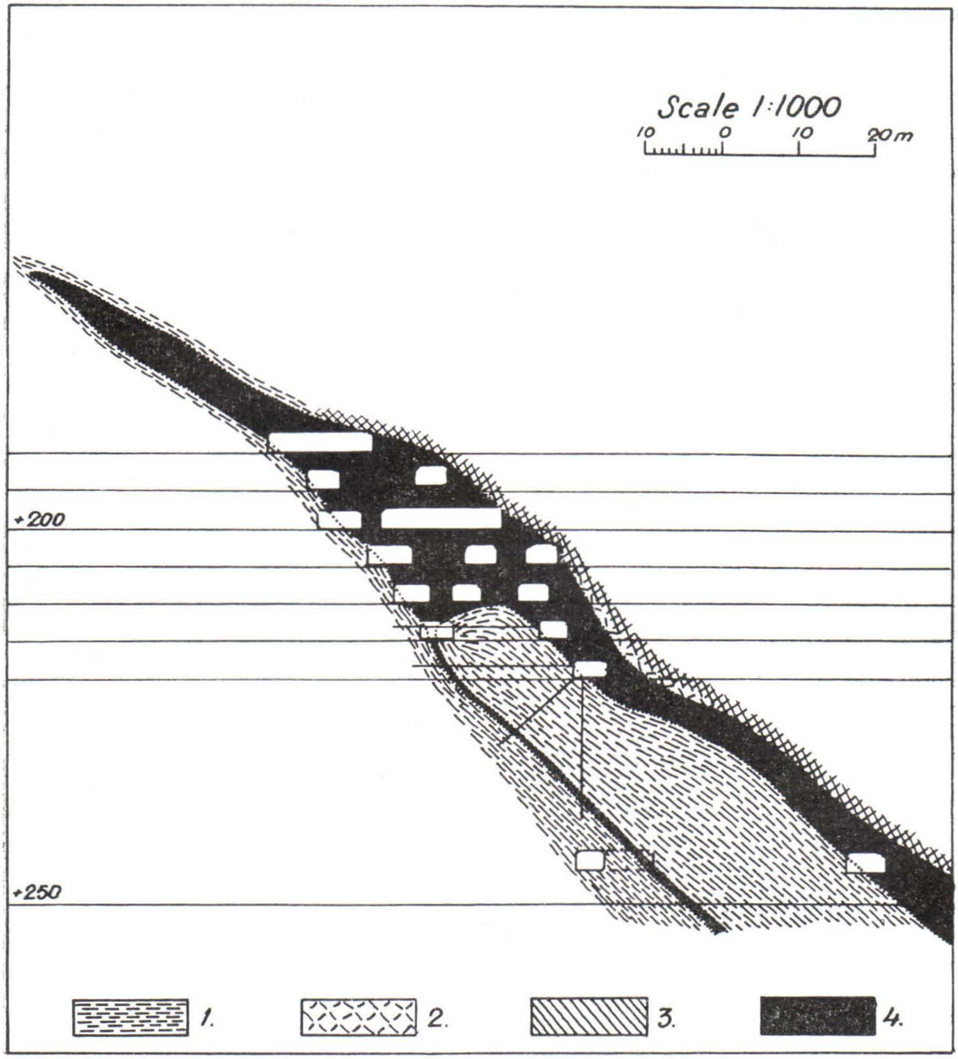

Fig. 7. Cross-section 52—20, showing the displacement of the ore between quartzite layers 1. Quartzite, 2. Skarn, 3. Serpentine, 4. Ore.

contact-rim there is nearly always a loose, thinner or thicker serpentine-talc-chlorite »sköl». The serpentine next to the contact-rim is furthermore full of gleaming slicken-sides and pale, dike-like, fibrous serpentine-talc-formations, the rock being extremely apt to cave in.

The almost white tremolite-skarn layers, a few dm thick, are quite typical of the contact zones of ore and serpentine. They are, contrary to the usual tremolite-skarns met with in the quartzite-serpentine contacts, generally free from green, chrome-bearing skarn minerals. Analysis 1., in Table IX, is made of a tremolite-skarn specimen taken from just such a contact between ore and serpentine.

The contact zone of ore next to serpentine often contains small serpentine inclusions, the size of which varies from a few cm in diameter down to microscopic dimensions. Usually they are less than 1 cm in size. Analysis 4, Table X, is made of such a sample rich in serpentine inclusions, taken from the contact zone of ore. Its abnormally high MgO-content, 7.74 %, implies that about 21 % of the serpentine material is contained in it as inclusions.

Microscopical study discloses that the small serpentine inclusions have almost wholly altered into a fine-scaled talc mass and the bigger ones in their marginal zones (Fig. b, Pl. IX). In addition, the inclusions have mechanically become rounded or lenticular.

Microscopic study of polished sections reveals that there is pentlandite in connection with pyrrhotite in the serpentine inclusions.

The serpentine is obviously more resistant to jointing than the quartzite. Therefore apophyses of the kind mentioned, intruding into the wallrock from the ore, are quite rare. However, an apophysis of this kind is met with in serpentine on the southwest side of Central Shaft II on +285 level cutting the drift of the Ventilation Shaft. This outjutting apophysis is about 20 m in length, 0.5—0.8 m in thickness, and begins at the arched end of the Kumpu orebody. Its contacts against serpentine are sharp and relatively rectilinear; and in the homogeneous ore rich in pyrrhotite, which forms the dike material, small, rounded serpentine inclusions appear in abundance.

The contact phenomena between skarn rocks and ore correspond in character to those of the ore-serpentine contacts described in the foregoing.

ORE TYPES

Structurally, three main types may be observed in the ore body:

1. Disseminated ore type
2. Structural normal ore type
3. Brecciated ore type

In respect to mineral paragenesis two main types are to be observed:

A. Paragenetic normal type
B. Cubanite type

All the main types of structural division are represented in the paragenetic normal type, whereas the occurrence of the cubanite type is chiefly associated with the structural normal type. Only occasionally is the cubanite paragenesis found in association with the brecciated or disseminated ore type.

The different structural ore types are not confined to different parts of the ore field but are mixed together with gradual transition zones, where the brecciated ore type dominates.

The general tendency is, however, for the disseminated ore type to occur in the contact zones of the ore against the foot wall and hanging wall quartzites as well as near the upper ridge. The normal type occurs as a dominant type in the central zones of thick orebodies and nearer the hanging wall, while the brecciated type appears as an intervening formation in the transition zone of both the said types. Cubanite ore occurs almost exclusively in the parts near the lower cant of the ore plate.

1. THE DISSEMINATED ORE TYPE

As mentioned, the disseminated ore type occurs mostly in the contact zones of ore adjoining the foot wall or hanging wall of quartzite, and in the parts of the upper ridge of the ore plate. The contact against the quartzite forming the wall-rock is in general sharp and continuously in conformity with the same schistosity horizon, while the quartzite is practically free from ore minerals.

Megascopically viewed the structure of the normal quartzite of the Outokumpu formation is totally intact. The transverse jointing noticeable in the quartzite continues undisturbed into the ore; also the faults occurring along them continue in the ore.

Dark, glass-like »layers» rich in quartz alternate parallel to the schistosity with light, more distinctly granulated ones rich in sulphide. This kind. of ore therefore appears striped and the name »convict's cloth»[1] used by the miners is vividly descriptive of the most typical disseminated ore. In normal disseminated ore the stripes vary in breadth from a few mm up to some cm. Occasionally, however, there are also dark glass-like quartzite horizons nearly free from sulphides and measuring 1 or 2 m in thickness. On the other hand, there may occur horizons with an exceptionally high sulphide content, horizons in which the relict texture of the quartzite is visible only microscopically.

In addition to quartz, which is the dominating siliceous mineral, there occur tremolite and diopside, concentrated in bands parallel to the

[1] Convicts in Finland wear striped uniforms.

schistosity or as accessory minerals in the disseminated ore just as in the normal quartzite. The grain size of quartz varies between 1.5 and 0.02 mm.

Pyrite of varying grain size occurs as the principal ore mineral, disseminated between quartz grains or as chains of aggregates parallel to the schistosity (Fig. c, Pl. IX). The pyrite grains vary in size from 1.5 to 0.01 mm, measuring in general the same as the quartz grains. Aggregates or bands comprising idiomorphic pyrite crystals of coarser grain are, however, occasionally met with.

Other ore minerals are: pyrrhotite, chalcopyrite and sphalerite, with their associated accessory minerals. In addition, magnetite grains or grain groups, ranged parallel to the schistosity, are occasionally met with. The occurrence of these ore minerals is less uniform than that of pyrite. They are found chiefly as a filling of transversal fissures or cracks of the crushing zones (Fig. a, Pl. X). They may also appear as compact sulphide aggregates (Fig. b, Pl. X). Magnetite, on the other hand, seems to belong, at least partly, as a relict to the primary quartzite.

Under the microscope tremolite and diopside occasionally appear as ragged relicts (Fig. c, Pl. VII) partly replaced by ore in zones rich in ore minerals, whereas the quartzite stripes poor in pyrite are nearly free from lime-silicate minerals. It seems likely that in its primary stage the sulphide mineralization took place at least partly at the expense of the lime-silicate minerals.

On the other hand, in the disseminated ore there are crushed zones in which sulphides have intruded during the shearing movements; nevertheless, under megascopic examination the quartzite appears to have preserved its normal texture (Fig. d, Pl. XI).

2. THE NORMAL ORE TYPE

As has been pointed out, the normal ore type is chiefly met with in the central parts of the ore plate and nearer to the hanging wall, separated from the disseminated ore by the brecciated ore type. In addition, normal ore may occur in immediate contact with the wall rocks, brecciated and disseminated ore being quite absent.

Where quartzite forms the wallrock, the contacts against the wallrocks are sharp and rather rectilinear, while the contact continuously follows the same schistosity horizon. Occasionally, however, features cutting the structure of quartzite may be met with in the contact zone (Fig. 8). Such are also the small ore apophyses which shoot into quartzite (Fig. 9). As mentioned, quartzite fragments in ore (Fig. c, Pl. XI) and brecciated contacts are occasionally found (Fig. a, Pl. IX). In general, however, the contact relations are rather distinct and undisturbed.

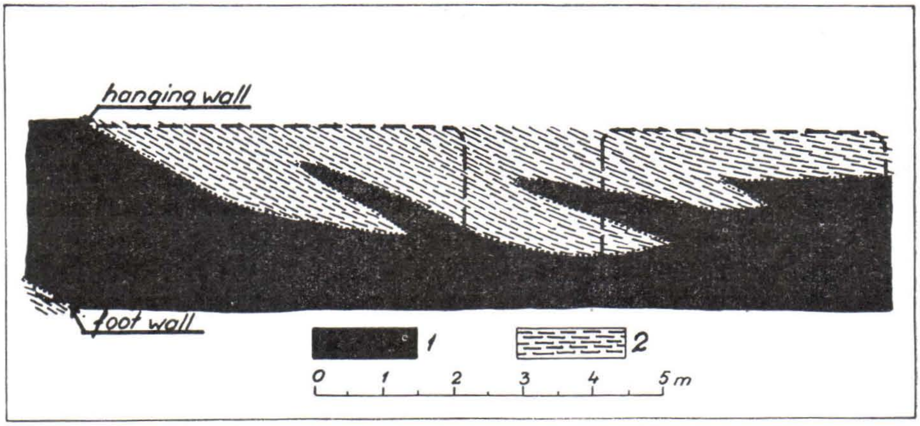

Fig. 8. Intrusion of ore into opened cracks parallel to schistosity in quartzite. 1. Ore, 2. Quartzite. Mökkivaara +250 level, Rs. 13 a. sublevel +214 E.

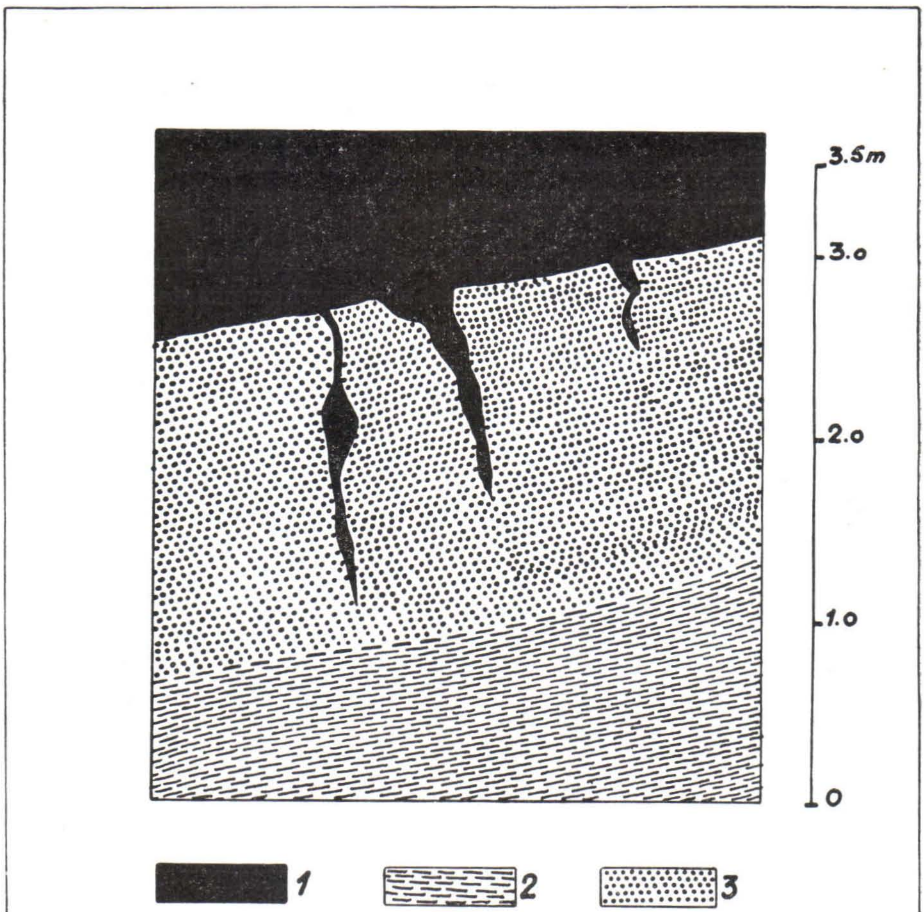

Fig. 9. Ore apophyses in quartzite below footwall. 1. Ore, 2. Quartzite, 3. Quartzite impregnated with pyrite. Mökkivaara +285 level, Dr. 1W.

In the transition zone between disseminated ore type and normal ore there usually occurs a zone of brecciated ore varying in thickness. But occasionally normal ore borders on disseminated ore with sharp contacts. This is quite distinctly visible on the southwestern side of the Mökkivaara Shaft on the + 285 level near the lower margin of the Lietukka ore body. According to the observations made during the drift mapping and diamond drilling, a disseminated ore zone, about 1 or 2 m in thickness, occurs in the footwall of ore against the underlying quartzite. A massive, rather homogeneous ore of normal type adjoins this disseminated ore zone and partly cuts its schistosity with sharp contacts. At a certain place in the lower part of the + 285 Lietukka-raise four irregular ore dikes, varying in thickness, nearly perpendicularly traverse the preserved schistosity of the disseminated ore (Fig. d, Pl. XI).

The normal type, from which the said dikes begin, is in this region richer than usual in chalcopyrite and pyrrhotite. The disseminated ore differs from its common type in containing chiefly disseminated chalcopyrite instead of pyrite, while the structure otherwise is similar to that of the pyritic type.

Structurally the normal ore type is in its most characteristic form a homogeneous and unorientated massive mixture of sulphides and quartz, the relative abundance of sulphide minerals varying within wide limits. The essential ore minerals are: pyrrhotite and pyrite. On the average, they occur in equal amounts, though their quantitative relations may vary locally to an appreciable extent. In addition, chalcopyrite and sphalerite are met with as minor components. Microscopically the following ore minerals may be detected as accessories: in pyrrhotite two sulphide minerals belonging to the linnaeite group, as well as valleriite and stannite. Occasionally some magnetite- and chromite-grains as well as very rarely galena, pentlandite and gold may be met with as well.

Quartz occurring in ore appears unequally distributed as small glass-like grains, varying between 1.5 and 0.1 mm in diameter or sometimes as large groups of grains or lumps.

In conjunction with normal ore a certain variety extremely rich in chalcopyrite-pyrrhotite is met with, in which quartz occurs as somewhat rounded blebs in the homogeneous compact sulphide mass. Quartz blebs, varying in size from 5 cm to a few mm, are always distinctly rounded or oval in their cross-section.

Microscopic examination shows that the quartz blebs are quartzitic in texture. The quartz in general shows a strong undulatory extinction. A complete series of quartz blebs may be noticed, from pure quartzite to completely recrystallized and unorientated quartz lumps, which are very common in the normal ore type.

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The preliminary stage of the blebbed type (Fig. d, Pl. IX) represents crushed quartzite, between whose fragments ore material has intruded, while some of the fragments are somewhat rounded and surrounded by an »archipelago» made up of small quartz grains. At more advanced stages of the process (Fig. a, b, Pl. XI) quartzite occurs as separate, rounded blebs, strongly corroded along their margins, in the fine-grained sulphide mass, most of which is made up of pyrrhotite in conjunction with fine-grained chalcopyrite and sphalerite. Part of the quartz blebs are impregnated by pyrite, but because of the fine grain of the disseminated ore, it is rather difficult to conclude whether fragments of primary disseminated ore or secondary impregnations of quartzite fragments are in question.

It is obvious that the blebbed type just described represents an intrusion of an extremely concentrated sulphide material either into quartzite crushed and ground up by shearing movements or into poor disseminated ore.

The corroded margins of the blebs suggest that the sulphide material has at least partly replaced quartz.

In the most common normal ore the origin of the quartz is not so definitely traceable, but it seems probable that the quartz has likewise derived, at least partly, from ground- up quartzite; but it is so strongly metamorphozed that no relicts from the original structure are left.

On the other hand, the sulphide material itself must have contained certain amounts of silicic acid solutions. This conclusion may be drawn from the fact that the serpentine fragments, which have remained as inclusions in the ore, have in their outer parts turned into a talc-tremolite mass (Fig. b, Pl. IX). This is also indicated by the tremolite skarn at the contacts of ore and serpentine. They are obviously reaction skarns caused by the ore solutions.

The same non-metallic minerals occur in ore as in the wall-rocks: tremolite, diopside, and occasionally uvarovite, dolomite, and chlorite, though usually in small amounts. The MgO + CaO-content of the ore resulting from them is in general of an order of magnitude less than one per cent. This implies that the proportion of calcium-magnesium-silicate minerals is about 1 %.

As previously described sulphides at least partly replace silicate minerals in such skarn formations as adjoin the ore (Fig. c, d, Pl. VII). The same is true of the skarn minerals in the ore itself. Rounded and corroded calcium-magnesium-silicate minerals (Fig. a, Pl. XII) or pseudomorphs after them may microscopically be met with in ore. The original crystal form of the silicate crystals may be well preserved in them, but the silicate material has partly been replaced by a fine-grained sulphide material (Fig. b, Pl. XII).

The replacement has usually commenced at the outer margins and cracks of the crystal and then advanced towards the centre, but occasionally relicts are met with in which the replacement process has been most advanced in the central part of the crystal (Fig. b, Pl. XII).

In the ore a distinct parallel jointing may be noticed, the direction of which joins approximately to the transverse fracturing, which is distinctly visible in the quartzite of the wallrock. In cases where this is stronger and open cracks have developed, fine fibrous tremolite is met with as filling material of the cracks. The fibres of tremolite are perpendicular to the cracks, or the filling of the crack is made up of a massive, almost aphanitic serpentine material. It is obvious that a secondary silicate mineralization, caused by water solutions, is here involved.

Table X

Analyses of Outokumpu ore, anal. O. v. Knorring

	1 %	2 %	3 %	4 %	5 %	6 %
SiO_2	54.56	57.08	36.30	18.76	16.60	14.32
TiO_2	—	—	—	tr	—	tr
Al_2O_3	0.20	0.66	0.56	1.84	0.72	1.12
Cr_2O_3	—	tr	tr	0.03	tr	0.05
MnO	0.05	0.10	0.14	0.28	0.08	0.03
CaO	0.10	0.70	0.06	1.16	0.10	0.67
MgO	0.22	0.64	0.30	7.74	0.12	1.36
K_2O	tr	tr	tr	tr	tr	tr
Na_2O				0.10		0.63
H_2O+	0.12	0.12	0.10	1.46	0.16	1.48
H_2O-	0.10	0.12	0.10	0.30	0.10	0.12
P_2O_5	—	—	tr	tr	—	tr
CO_2	—	tr	—	0.20	tr	0.50
S	20.60	15.35	29.34	25.58	30.40	28.40
Fe	22.15	17.90	26.97	37.10	34.62	29.80
Cu	1.84	6.60	1.91	5.17	13.50	17.68
Zn	0.44	0.80	4.35	0.30	3.38	3.36
Ni	0.07	0.07	0.05	0.18	0.22	0.11
Co	0.06	0.05	0.05	0.12	0.10	0.06
Pb	tr	tr	tr	—		
Cd		tr			tr	tr
Bi	—	—	—	tr		
Sb		—	tr	—	—	—
As	tr	tr		tr	tr	tr
Sn			—		tr	
Se	—	—		—	—	—
Te						
	100.51	100.19	100.23	100.32	100.10	99.69

1. Normal disseminated ore, Mökkivaara +250 level, Rs. 16. sublevel 3.
2. Crushed disseminated ore, Sh. I +285 level, Rs. 6. underhand drift.
3. Typical normal ore, Mökkivaara +285 level, Dr. 1 W.
4. Normal ore from the contact with serpentine, Mökkivaara +285 level, Dr. 2 W.
5. Normal ore, zuartz-blebbed variety, Sh. I +250 level, Rs. 9 a.
6. Typical cubanite ore, Sh. I +285 level, Dr. 1 W.

3. THE BRECCIATED ORE TYPE

As mentioned earlier the brecciated ore type usually occurs as a mediating formation in the transition zone between the disseminated and normal ore. The different types of ore pass gradually one into the other without any distinct zone borders and their general areal distribution is not regular in other respects either.

A distinct brecciated structure (Fig. a, Pl. I) is characteristic of the said type of ore. Fragments of disseminated ore of varying size are embedded in a matrix of massive nonhomogeneous normal ore. The size of the fragments varies from some dm up to two or three m. The smallest fragments are in general non-orientated, while the large ones approximately follow the direction of the contact of the ore and the wall-rocks. As the shapes of the fragments are mostly plate-like, owing to the structure of the disseminated ore, they have not in general had room enough to rotate and the only possibility to move has been sliding in the direction of the contacts.

In structure and composition the fragments correspond to the normal disseminated ore type, where the sulphides occur impregnated parallel to the schistosity in the quartzitic rock. Pyrite is the dominant ore mineral, while pyrrhotite, chalcopyrite and sphalerite are minor components. The accessory minerals are the same as in the normal disseminated ore.

The matrix material between the fragments corresponds to the normal ore type in structure and mineral composition. As the dominant ore mineral in the matrix there occurs pyrrhotite, in addition to which an abundance of pyrite as well as an appreciable amount of chalcopyrite and sphalerite are present, while the accessory minerals are again the same as in the normal ore type.

A. MINERAL PARAGENESIS OF THE NORMAL ORE TYPE

P y r i t e, as one of the two chief components, together with pyrrhotite, occurs in the ore in the form of regular equidimensional grains or grain clusters. Among them are numerous idiomorphic cubic crystals or aggregates formed by these. Occasionally there may occur cubes up to 30 × 30 mm in size and, because of deformation, somewhat rounded in their corners, which is also typical of the Sulitelma ore in Norway. The grains are usually more or less fractured, either with irregular crack systems or, as is more usual, following the natural (100) cleavages. The fracturing is strongest in the surface parts of the grains and especially in the corners of the cubes (Fig. c, Pl. XII). In the cleavage cracks chalcopyrite and pyrrhotite as well as, occasionally, sphalerite may be detected as secondary minerals. The most frequent filling mineral of the cracks is chalcopyrite, often intruded along the cracks through the whole individual crystal. Replacement of pyrite by chalcopyrite starting from the cracks has proceeded either from the margins of the crystal towards the centre or, in exceptional instances, advancing outwards from the centre (Fig. d, Pl. XII). Though the fracturing is mostly microscopic in size, it is possible that the copper content of pyrite owing to the intrusion of chalcopyrite into the fractures, may be quite considerable.

An Analysis was made of a pyrite crystal, almost a hexahedron in form and 20 × 23 × 25 mm in size, which megascopically seemed to be quite pure and faultless. The analysis (Table XI) shows its copper content.

Table XI

Analysis: Pyrite crystal, Sh. I +250 level, Rs. 9, anal. O. v. Knorring

	%		%
SiO_2	0.48	Fe	46.60
S	49.10	Cu	3.31
Se	—	Zn	0.31
Te	—	Ni	0.20
As	tr	Co	0.07
Sb	—	Mn	0.02
Bi	—	Au, Ag	no (quantitatively)
			100.09

Pyrrhotite occurs in the same manner, replacing pyrite (Fig. a, Pl. XIII). But sphalerite is met with only in the cracks near the surface of the pyrite grains. The replacement process between pyrite and sphalerite cannot be determined with certainty.

The more advanced replacement process is represented by such relict structures of pyrite, where pyrrhotite occurs as regularly formed aggregates, the outlines of which are typical sections of hexahedron. Part of the aggregate may still contain more compact pyrite, but it is, however, strongly fractured. Pyrrhotite material surrounding and penetrating the pyrite aggregate occurs as a filling of the cracks.

Relict structures, somewhat different in type but indicating a more advanced replacement process, may be represented by rather regularly formed pyrrhotite grains. Haphazard crossing and stripe-like chains of small pyrite grains resembling the cleavage net of pyrite may be observed in pyrrhotite grains. These grains are bordered by pyrite like strings of pearls. These relicts are of such a fine structure that they can be observed only with the help of very great magnifications (Fig. b, Pl. XIII). Schouten (1937) and Grondijs (1937) have described such pyrite relicts of »Atoll» texture, mentioned previously in their studies on the Mount Isa deposit in Australia.

Separate chalcopyrite and pyrrhotiye grains displaying regular cross-sections, either square or otherwise resembling the crystal forms of pyrite, are occasionally met with as relicts of completely altered pyrite crystals in quartzitic gound mass. Because e. g. chalcopyrite has never been found in the Outokumpu ore as idiomorphic crystals, the occurrence or such grains, which have rectilinear surfaces and, as far as can be concluded from the sections, are cubical in form, may be explained only as relicts of primary pyrite crystals.

Large separate, idiomorphic pyrite crystals, somewhat roundish and deformed in their faces, are often met with in the ore in addition to the dominant type of pyrite, which is fine-grained and obviously belongs to the disseminated ore generation. They occur especially in the compact parts of the orebody rich in pyrrhotite and chalcopyrite and seem to be of somewhat later origin thus belonging to the younger pyrrhotite-chalcopyrite generation. The deformation of the pyrite crystals in some cases resembles the deformations observed in the pyrite crystals from Sulitelma ore, Norway, samples of which the author has seen in the collections of the Institute of Geology, University of Helsinki.

Replacement phenomena similar to those described earlier are microscopically to be observed also in the grains obviously belonging to this younger pyrite generation. This pyrite generation would likewise be older than the pyrrhotite and chalcopyrite, though it would belong to the same mineralization with them in its primary phase.

P y r r h o t i t e, together with pyrite, is one of the two chief ore minerals forming unequally distributed massive grain groups, or irregular lumps and vein-like fissure-fillings. It is distinctly younger than the pyrite, having at least partly developed as the result of its alteration, as previously described. In separate grains the texture of pyrrhotite is generally undisturbed, but infrequently an irregular lamellar texture may be detected microscopically (Fig. c, Pl. XIII). It is partly visible in unpolarized light, owing to reflection pleochroism, but is quite distinct in polarized light with crossed nicols. Each of the lamellar components is obviously of the same composition and the crumpled structure is caused by transformations under pressure (»Zerknitterungstruktur», according to Schneiderhöhn 1931).

Small roundish grains of linnaeite or a newly discovered variety of this mineral may microscopically be observed as minute inclusions in pyrrhotite, apparently as products of unmixing from this mineral. They occur as narrow laths, fringed at their ends, in parallel orientation and obviously following a certain crystallographic direction in the pyrrhotite grain.

The occurrence of c h a l c o p y r i t e in the ore is similar in appearance to that of pyrrhotite. It varies in abundance in the different parts of the orebodies and in detailed features within great limits, as is evident from the variation of the copper content in the analysis of Table X. In general chalcopyrite forms aggregates consisting of small grains or lumps and irregular vein-like formations intimately associated with pyrrhotite. They seem to be approximately simultaneous in origin, the chalcopyrite, however, being in general younger, for it occurs in pyrrhotite as thin veinlets, while the latter occurs as inclusions in chalcopyrite. Here and there almost myrmekitic intergrowths or whirly flow-structures may, however, be observed. From such phenomena it may be concluded that pyrrhotite has been at least partly in a mobile state together with chalcopyrite.

Fine lamellar texture is to be noticed even with the naked eye in lumpy coarse-grained chalcopyrite aggregates, and microscopically, using polarized light, this phenomenon is distinctly visible everywhere. In old polished sections the lamellar texture becomes visible even in unpolarized light and the different lamellae get a different tint of »aging colour» on account of the slow surface oxidation.

Small sphalerite skeletons of varying form, either being star-like or resembling »ice-flower» structures, are met with as accessory minerals associated with chalcopyrite. They vary from 0.01 to 0.3 mm in diameter and occur independent of chalcopyrite lamellae and cutting them (Fig. d, Pl. XIII). Valleriite and occasionally stannite are found as other accessory minerals associated with chalcopyrite.

S p h a l e r i t e occurs in the ore usually as brown-black polygonal grains, less than 1 mm in diameter or as aggregates and lumps formed by these. It is distributed almost everywhere in the ore and closely associated with chalcopyrite. Occasionally fine-grained portions rich in chalcopyrite and sphalerite occur with almost myrmekitic structures. Usually, however, chalcopyrite and pyrrhotite may be observed as irregular inclusions in sphalerite, or *vice versa*, sphalerite as veinlets in pyrrhotite. In this case a thin chalcopyrite rim is often noticed between sphalerite and pyrrhotite (Fig. a, Pl. XIV). Microscopically the age succession in these sphalerite apophyses can be definitely ascertained: pyrrhotite-chalcopyrite-sphalerite.

Besides the previously described sphalerite, which belongs to the primary crystallization, small sphalerite skeletons varying in appearance, usually being star-like or resembling the »ice-flower» structure, are to be noticed in chalcopyrite. They seem to have developed as the result of unmixing of the sphalerite, which had earlier existed in solid solution in chalcopyrite. In some skeletons the small silicate inclusions, which had remained in chalcopyrite, have served as the cores of crystallization (Fig. b, Pl. XIV). The crystallization of sphalerite skeletons seems to have occurred at a time when the twinning of chalcopyrite already had developed, as the unmixing skeletons cut the lamellar structure of chalcopyrite (Fig. d, Pl. XIII).

Small stannite grains in connection with primary polygonal grains and secondary sphalerite skeletons separated by unmixing are met with as accessory minerals associated with sphalerite.

In chemical composition sphalerite is iron-bearing, as is also indicated by its dark colour. The enclosed Analysis (Table XII) is made from somewhat impure tremolite-bearing material.

Table XII

Analysis: Compact sphalerite, containing some tremolite prisms, Outokumpu mine, Sh. I +285 level Rs. 9, anal. T. Mattila

	%	%[1]	1 000 × mol. prop.	Note:
SiO_2	2.05	—	—	as tremolite
CaO	0.32	—	—	
MgO	0.88	—	—	
Fe	8.71	9.01	161.4	
Zn	55.25	57.12	873.7	
Cu	0.02	0.02	0.3	as inclusions
Mn	0.34	0.35	6.4	
Co	0.08	0.08	1.4	
S	32.32	33.42	1 042.4	
	99.97	100.00		

[1] After subtraction of CaO, MgO and SiO_2 contained in tremolite, and the remainder recalculated to 100.

From mol. proportions Zn : Fe : S ∼ 11 : 2 : 13; and formula $Zn_{11}Fe_2S_{13}$.

L i n n a e i t e I occurs usually in pyrrhotite, but occasionally also in chalcopyrite as small, roundish, nearly equidimensional grains visible only under the microscope (Fig. c, Pl. XIV and Fig. b, Pl. XV). The grain varies between 0.5 and 0.01 mm in diameter, being on an average 0.1—0.05 mm. The polishing hardness is about the same or a little greater than that of pyrrhotite and it takes a good polish. The colour is white with a yellowish tint, being distinctly paler than that of pyrrhotite. The difference in colour is, however, so slight that, when the minerals occur apart from each other without common boundaries, it is difficult to distinguish them. The reflectivity is good. The anisotropy in polarized light with crossed nicols is exceedingly weak, the mineral being probably isotropic. The anisotropy cannot be determined with absolute certainty owing to the great magnifications needed because of the fine grain and, especially, the strong anisotropy of the adjoining pyrrhotite interferes with the observations.

The staining test with chromic acid ($CrO_3 + HCl$) according to Gaudin (1935) does not give any iridescent colour reaction characteristic of pentlandite, but the mineral is wholly inactive against oxidation, remaining a bright white (Fig. b, Pl. XV). In examining the powders, the distinguishing of linnaeite from pyrrhotite is expressly based on this test, as the pyrrhotite turns dark very quickly under the influence of the oxidation reagent.

Linnaeite I dissolves with difficulty in diluted hydrochloric or nitric acid, even when boiled. The small size of the mineral grains prevents obtaining a pure sample for microchemical or spectrographical analysis. Microscopically examined, a sample taken with a dental bore contained, according to calculations from the observed grain size and the holes made by the bores of 0.5 mm in diameter, about 10 % linnaeite I, and according to spectrographic determinations it proved to contain 4 % Co and 1 % Ni. Calculated from these values the linnaeite I contains about 40 % Co and 10 % Ni.

Linnaeite II. Intimately associated with the pyrrhotite there occurs another Co — Ni mineral resembling the former in its optical character and hardness, but essentially differing from it in its mode of occurrence. This mineral will be here called Linnaeite II. It always occurs in pyrrhotite resembling the unmixing texture, apparently orientated parallel to the crystallographic (0001) direction as narrow laths (Fig. d, Pl. XIV) or as rather large fringed skeletons, which all have the same direction in the same pyrrhotite grain. Occasionally hexagonal sections with 120° angles are noticeable (Fig. a, Pl. XV).

Linnaeite may rarely occur as vein-like segregations in pyrrhotite (Fig. d, Pl. XV). From the margins of the veins typical laths of linnaeite II shoot into pyrrhotite without any visible border between the compact vein and the apophysis-like linnaeite II skeletons shooting into pyrrhotite.

The hardness of linnaeite II is approximately the same or somewhat greater than in pyrrhotite and it takes a good polish. The colour is white with a tint of yellowish brown and the reflectivity is higher than in pyrrhotite. The anisotropy in polarized light with crossed nicols is especially weak or wholly lacking, while the strong anisotropy of the neighbouring pyrrhotite mineral disturbs the observations.

The lath-like mode of occurrence, fringed at the ends and resembling unmixing textures is almost like the »pentlandite flames in pyrrhotite» described by Schneiderhöhn (1931), but the oxidation test according to Gaudin does not even in this case give any iridescent colour characteristic of pentlandite; the mineral is inactive against the oxidation reagent, remaining a bright white like linnaeite I. Pentlandite, from which it differs in character, is apparently not the mineral concerned. Linnaeite II like linnaeite I dissolves with difficulty in diluted hydrochloric and nitric acid.

The separation method for the chemical enrichment of the minerals, evolved by Tatu Mattila, M. A., at the chemical laboratory of the Outokumpu mine, is based on this property.

Two samples of ore rich in pyrrhotite were chosen on the basis of a microscopic examination for separation of linnaeite I and linnaeite II, of which the one contained mainly linnaeite I and the other linnaeite II.

The ground samples were first treated by boiling with hydrochloric acid in order to destroy the pyrrhotite and sphalerite. After boiling, the part which had not dissolved was roasted in 350—450°C and after that boiled again with hydrochloric acid. This method was chosen because experiments had proved that in the temperature in which chalcopyrite, pyrite, and pyrrhotite begin to decompose, the Co-mineral still remains unchanged. The roasting and hydrochloric acid treatment mentioned earlier was repeated several times in succession.

The quartz and the silicates which had remained unchanged by the treatment described were removed by evaporating the roasting residue with hydrofluoric and sulphuric acid until it became dry and by boiling it once more with hydrochloric acid. At this stage the Co-mineral was considerably dissolved, as appeared inter alia in the changing of the colour of the solution.

One kilo samples yielded 3.8 g of linnaeite I concentrate and 2.4 g of linnaeite II concentrate.

A microscopic examination indicated that the concentrates were rather pure. In the linnaeite I concentrate some pyrrhotite grains and occasional linnaeite II-prisms could be noticed. In the linnaeite II concentrate colourless translucent grains were found as an impurity, which was dissolved into the mixture of hydrochloric acid and nitric acid during the process of analysis when determining the insoluble part. Because apparently no sulphide mineral was involved and as only a small amount of the concentrate was available for analysis, it was not considered necessary to determine the quality of this impurity. The considerable deficit in the sum given by the analysis of linnaeite II is probably mainly due to this fact.

Table XIII

Linnaeite concentrates from Outokumpu ore, anal. T. Mattila

	Linnaeite I			Linnaeite II		
	%	1 000 × mol. prop.	—Fes *)	%	1 000 × mol. prop.	—Fes *)
Ni	16.54	281.8	} 972.5	26.91	458.5	} 886.9
Co	40.71	690.7	—	25.25	428.4	
Fe *)	2.51	45.0	—	2.30	41.2	
S	39.96	1 246.4	1 201.4	37.54	1 170.9	1 129.7
Indissoluble	0.10	—	—	2.64	—	
	99.82			94.64		
(Co, Ni) : S	= 4 : 4.92			(Ni, Co) : S = 4 : 5.09		
Chemical formula	$(Co, Ni)_4S_5$			$(Ni, Co)_4S_5$		

*) The Fe is probably due to the pyrrhotite that was present as an impurity in the analysis. material. When this Fe, calculated as FeS, is subtracted, the analysis leads exactly to the chemical. formulae given above.

Brinckman (1924), Rückert (1925) and Shannon (1926) have come to the same linnaeite-formulae in their studies. If, however, we consider the possible small analytical errors, the possible impurities in the analysis material and the possibility that minerals during the long and rather »rough» treatment may have partly changed, which, to be sure, could not be determined microscopically, the present adjusted formula $R^{II}R_2^{III}S_4$ (Ramdohr 1950) of the linnaeite group may be rather confidently accepted. This is especially indicated by the fact that during the hydrochloric acid treatment some elementary sulphur was precipitated, which may have been set free mostly from the pyrrhotite, but may also have been the result of an alteration of the »surface film» of the linnaeite grains. The slight deviation of the chemical composition from the theoretical formula of the linnaeite-group is perhaps due to the aforementioned facts. Also on the basis of their optical and other properties, these minerals would most nearly correspond to the linnaeite-group.

Mr. Fruch (Department of Geology, the University of Chicago) has made Debye-Scherrer-diagrams of the concentrates. The calculated dimensions of the unit cell are the same as in the linnaeite-group.

All the results obtained consequently indicate that there are two minerals of the linnaeite-group in question of which linnaeite I would correspond most closely to the Co-sulphide or the linnaeite proper $(Co, Ni)_3S_4$ and linnaeite II to the Ni-Co-mineral of the same group, or siegenite $(Ni, Co)_3S_4$.

Valleriite $(Cu_3Fe_4S_7)$ is commonly met with as an accessory component associated with chalcopyrite. Most generally it occurs as narrow, sharp scales, bent at its ends or as thin scale aggregates (Fig. c, Pl. XV) in the cleavage cracks of chalcopyrite, the most general of which is the cleavage along (111). Valleriite often occurs also in the contact zones of pyrrhotite and chalcopyrite shooting into the last-mentioned as pointed projections, being apparently younger than chalcopyrite. The length of the scales is in general less than 0.25 mm and the breadth 0.002—0.004 mm. Because of its fine scaly appearance and colour nuances resembling those of chalcopyrite and sphalerite, owing to the strong reflexion pleochroism it is difficult to detect valleriite in unpolarized light. But because of its extremely strong anisotropy, valleriite can be easily observed in polarized light with crossed nicols. Its optical properties and hardness are in other respects too the same as in Schneiderhöhn's (1931) »unbekanntes Nickelerz», which Ramdohr and Ödman (1932) later discovered to be a nickel-free copper mineral corresponding to the aforementioned composition.

Stannite $(Cu_2Fe\,Sn\,S_4)$ occurs most generally in sphalerite as small equidimensional grains, but may be occasionally met with also in chalcopyrite as grain groups or veinlets (Fig. a, Pl. XVI). Some stannite grains have been rarely observed in pyrrhotite, too (Fig. c, Pl. XVI).

The grain size varies between 0.01 and 0.05 mm, the polishing hardness being a little higher than in chalcopyrite but lower than in sphalerite. The reflectivity almost corresponds to that of sphalerite, though a trifle paler in colour, the tint being somewhat greenish. Because of the small size of the grains large magnifications are necessary for examination, and therefore the anisotropy is weakly apparent. For the same reason pure samples of the mineral cannot be obtained for microchemical determination, but spectrographically a considerable amount of tin was found in a sample rich in chalcopyrite, which was taken with the help of a dental bore under the microscope. Thus the diagnosis made on the basis of the optical properties may be considered as confirmed.

Stannite is younger than sphalerite, often occurring as fine veinlets in the cracks of sphalerite grains or as narrow aggregates bordering the grains against chalcopyrite. Stannite is also to be observed in conjunction with the secondary sphalerite skeletons in chalcopyrite. The sphalerite stars seem to have acted partly as crystallization centres for the stannite, since the latter adjoins certain parts of the star-like skeletons here and there (Fig. b, Pl. XVI) in the same manner as the stannite borders the silicate grains in certain cases described earlier.

G a l e n a appears megascopically in rare cases as grain groups only a few mm in diameter.

Microscopically it may be detected as occasional grains in the parts of the orebody rich in sphalerite. It is at least younger than the chalcopyrite, because the apophyses shooting from it cut the latter. The deformed cleavage cracks revealed by the triangular grinding spalts typical of galena indicate that late movements have taken place in the ore after the crystallization of the galena (Fig. d, Pl. XVI).

G o l d. According to the drive analyses the average gold content of the Outokumpu ore is from 0.6 to 0.8 gr a ton. It is at least partly metallic in occurrence, since part of the gold content of the ore can be dressed from the mill-tailing on a corduroy-cloth over which the tailing runs at a suitable speed. This part may, however, include only the roughest grain category, varying between 0.4 and 0.05 mm in size. The grains are flat and plate-like in form and apparently deformed during the grinding process. There is no statistically reliable observation material on how or in what minerals gold occurs in the ore; for, in spite of careful microscopical searching, only in a few polished ore sections could tiny gold grains, varying in size between 0.1 and 0.05 mm, be discovered, although more than 500 polished sections have been examined (Fig. a, Pl. XVII). In such cases gold occurs in conjunction with grains of sphalerite enclosed in chalcopyrite. Therefore, it is quite possible that gold is associated either with sphalerite or chalcopyrite. The latter alternative seems to be more probable, because most of the gold in the ore follows copper in the flotation and metallurgical process and gathers in the copper electrolysis into the anode mud, from which it is metallurgically separated.

Pentlandite associated with pyrrhotite is found in the ore as an especially rare accessory mineral in the parts of the contact zones of ore and serpentine (Fig. b, Pl. XVII). Typical of these contact formations is the occurrence of small serpentine inclusions in the ore, and it seems likely that the pentlandite met with originates from serpentine mixed with ore, where it occurs together with pyrrhotite, as previously described. The pentlandite presents a weak bravoitization which has started from the cleavage cracks. Pyrrhotite associated with pentlandite differs so far from the normal pyrrhotite of the ore that there is no linnaeite, worth mentioning. In order to detect pentlandite in the ore the author treated numerous samples rich in pyrrhotite with chromic acid (CrO_3 + HCl) according to the method of Short (1940), but the result was almost always negative. Only in very rare cases has it been possible to detect extremely tiny pyrrhotite grains, which, appearing almost as points, are rimmed by a thin iridescent atoll-like frames as in pentlandite. Insofar as this is pentlandite, its amount is in any event so insignificant that the nickel content obviously cannot — at least not wholly — be due to pentlandite (see Table X).

Magnetite occurs in parts of the ore rich in silicate either associated with silicates as dust-like pigment or occasional idiomorphic crystals and grain clusters. It may partly appear as inclusions in pyrite (Fig. c, Pl. XVII). In this case some magnetite crystals adjoining pyrite show alteration phenomena, the centre of the grain consisting of unaltered magnetite surrounded by a pyrrhotite zone, which again bounds on pyrite with sharp plane surfaces, following the traces of the original magnetite grain. Of some grains only a well preserved crystal form has been left as a relict. As magnetite is met with only in such parts of the orebody that contain an abundance of silicate minerals as relicts from the silicate rocks which had existed prior to the sulphide-mineralization, it seems very likely that also magnetite is mostly older than the sulphide-mineralization.

Chromite is intimately associated with magnetite, and it is met with as an extremely rare accessory mineral in the parts of the ore rich in silicates. It is partly dust-like in association with magnetite, or it occurs as small rounded and strongly corroded grains or groups of only a few grains. As the magnetite it may likewise represent relicts from the primary silicate rock, probably serpentine, which precede the sulphide-mineralization.

B. MINERAL PARAGENESIS OF THE CUBANITE ORE TYPE

Cubanite has been found only in the lower part of the ore plate. The areal distribution of this ore type has not, however, been exactly clarified in detail since the identification of cubanite is possible only with the aid of the microscope and because the knowledge of the lower parts of the ore plate is still incomplete.

In outward appearance this ore type does not differ from the normal ore type at all, which again makes the determination of its areal distribution more difficult. The chalcopyrite and pyrrhotite content is, however, on the average greater in the cubanitic type than in the normal type. Structurally it corresponds most nearly to the normal type and only occasionally is cubanite found associated with the brecciated type and still more rarely with the disseminated type. The cubanite content is very remarkable in the quartz-blebbed variety of the afore-described normal ore.

ORE MINERALS

C h a l c o p y r i t e occurs in the cubanite type in the same manner as in the normal type, differing from this only in so far as it contains more or less cubanite.

C u b a n i t e is the most characteristic mineral in the paragenesis of this ore type, occurring most frequently in chalcopyrite as narrow unmixing lamellae parallel to the (111)-cleavages (Fig. c, Pl. XV). The breadth of the lamellae varies between 0.15 and 0.05 mm and the length varies according to the grain size of chalcopyrite, for the lamellae often extend through the whole grain. Sometimes the cubanite content may be locally so high that the greatest part of the grain consists of cubanite, while chalcopyrite occurs only as narrow lamellae. Occasionally pure cubanite grains without chalcopyrite lamellae are met with, or cubanite occurs as thin veinleits in the cracks of pyrrhotite (Fig. d, Pl. XVII).

A cubanite rim about from 0.05 to 0.01 mm in thickness occurs at the contact of chalcopyrite and pyrrhotite, often surrounding the pyrrhotite grain (Fig. a, Pl. XVIII). The cubanite lamellae begin from this rim. It is in general homogeneous in composition, but here and there a lamellar texture may be observed, but it is so fine that it is not possible to define its character. Similar non-homogeneous lamellar texture occurs here and there in the cubanite veins met with in pyrrhotite.

In its characteristics the cubanite is normal. The polishing hardness is just a little greater than that of chalcopyrite, but distinctly lower than of pyrrhotite. The reflectivity is weaker than in chalcopyrite but stronger than in pyrrhotite, and it becomes distinctly weaker in an oil immersion. The colour is in unpolarized light pale rose-reddish and the reflection pleochroism is weak though distinct. The anisotropy in polarized light with crossed nicols is distinct, and depending on the optical position the colour varies from reddish brown to greenish blue-grey.

P y r r h o t i t e in cubanite ore differs in character from normal pyrrhotite in so far as it is not homogeneous, but there occur two optically quite different components which seem to have separated from each other by unmixing. This special feature is more or less distinctly evident in all the pyrrhotite samples taken from the regions where cubanite has been observed to occur, even though there is no cubanite in the particular sample examined.

In its optical properties C o m p o n e n t I (α-lamellae according to Scholtz, 1936) corresponds most closely to normal pyrrhotite, at the same time as it forms the main component of the grains. It is called pyrrhotite in the following description.

C o m p o n e n t I I (β-lamellae according to Scholtz, 1936) occurs in pyrrhotite as flame-like or narrow, wavy units in the form of »fishes», narrowing at their ends (Fig. d, Pl. XVII). The length of the »flames» varies from 0.1 to 0.03 mm and the breath, apparently according to the direction of the section, between 0.02 and 0.04 mm. The polishing hardness is less than in pyrrhotite, and owing to that fact the flame-like unmixing texture is noticeable as a distinct polishing relief in strongly polished sections.

The reflectivity is about the same as in pyrrhotite; the reflection pleochroism is weaker. The colour is about the same as in pyrrhotite. Owing to the strong reflection pleochroism of the pyrrhotite, the component II seems sometimes to be paler and sometimes darker, depending upon the optical position of the last-mentioned. Both components are also distinctly anisotropic and the unmixing texture becomes very distinctly visible in polarized light, especially in an oil immersion (Fig. b, Pl. XVIII). The unmixing texture becomes, however, more visible through the oxidizing etching according to Gaudin (1935) (Fig. b, Pl. XV).

The c o m p o n e n t I I occurs in pyrrhotite always as distinctly orientated parallel flames obviously following a definite crystallographic direction in the same grain. In separate grains the orientation is different (Fig. b, Pl. XV).

If a crumpling texture (»Zerknitterungsstruktur» according to Schneiderhöhn 1931) caused by pressure is noticeable, the flame-unmixing is diagonally directed in relation to the developed pressure lamellae (Fig. c, Pl. XIII).

The amount of component II varies in different grains, though this variation may also be ostensibly due to different directions of the sections. According to planimetric determinations in photographs, the proportion of component II varies from about 20 to 40 % of the whole grain surface.

Fine-flamed lamellar texture in pyrrhotite of the kind previously discussed has likewise been described, among others, by Schneiderhöhn (1931), Van der Veen (1925), Scholtz (1936) and Hawley (1943) without, however, their finding any satisfactory explanation for the phenomenon. Van der Veen assumes the phenomenon to be the result of unmixing, the character of which, however, is difficult to explain owing to its fine structure, because no pure samples of the different components can be obtained.

According to Ramdohr (1950), the structure would be the result of an internal alteration phenomenon of pyrrhotite. In its composition one of the components would correspond to the formula FeS (like troilite) while the other component, in the alteration process, would have absorbed all the excess of sulphur normally present in pyrrhotite.

To explain the reasons for the varying behaviour of pyrrhotite from different deposits in Sweden in the flotation process, Lindroth (1946) has observed in his X-ray study that the ores fall with regard to atomic structure into three groups:

I structure of pyrrhotite is of normal hexagonal type
II structure of pyrrhotite is anomalously monoclinic, the deviation of c_0-axis from the perpendicular direction against the a_0b_0-plane being very small (89.45°—89.67°)
III both the hexagonal and monoclinic phase occur together.

When pyrrhotite types II and III are heated in a scaled tube at +600°C, the anomaleous components change into the normal hexagonal type.

As types II and III occur in regions where the regional metamorphism has been strong, Lindroth assumes, basing his opinion on the scaled-tube-experiment, that the high pressure (»stressverkan») prevailing during the regional metamorphosis, has possibly caused the deformation of the unit cells of pyrrhotite.

In the author's opinion, the flame-like unmixing texture microscopically observed and the deformations in the unit cells of pyrrhotite detected by Lindroth may intimately belong together so that the group III of Lindroth would correspond to pyrrhotite of the kind where a flame-like unmixing texture is noticeable.

The development of the said texture may, however, be mainly due to the temperature factors, because the flamelike texture seems to be independent of the distinct structural alteration phenomena in pyrrhotite owing to pressure. At least in the Outokumpu ore the flame-like unmixed pyrrhotite is so intimately associated with the mineral paragenesis of the higher temperature, i. e. the cubanite ore paragenesis, that the author is inclined to consider the pyrrhotite of this type as a »geological thermometer» in the sense that its occurrence gives evidence of its belonging to the high temperature paragenesis.

Chalcopyrrhotite $CuFe_4S_5$ (Ramdohr 1950) is met with in cubanite ore as an extremely rare accessory at the contacts of pyrrhotite and chalcopyrite-cubanite grains (Fig. d, Pl. XIX) or as irregular mottles in chalcopyrite. The polishing hardness is approximately the same or somewhat greater than in chalcopyrite but distinctly less than in pyrrhotite.

The colour is in general pale brown, like leather or chocolate, being approximately the same as in cubanite in its darkest optical position. The anisotropy is especially weak and the mineral remains a dark chocolate-brown in polarized light with crossed nicols, being perhaps isotropic.

A strongly anisotropic mineral corresponding in its optical properties to cubanite occurs as thin lamellae associated with chalcopyrrhotite.

P y r i t e, s p h a l e r i t e, and l i n n a e i t e associated with the cubanite-paragenesis correspond in their mode of occurrence and properties to those of the normal ore paragenesis.

V a l l e r i i t e is found in greater amounts than in the normal ore type, and especially in parts of the ore body rich in cubanite its occurrence is very abundant. It occurs in association with chalcopyrite observed in its cracks as considerably bigger scales than in the normal paragenesis. As cubanite has in general a lamellar texture parallel to (111) chalcopyrite, valleriite cutting these lamellae (Fig. c, Pl. XVIII) is apparently younger than cubanite.

Silicate material occurs shooting into the same cleavage system with valleriite. It is younger than the latter, but it is difficult to determine its species in polished sections. From its even polish it is probably quartz and seems to have been derived from the silicate material surrounding the ore grains.

The occurrence of s t a n n i t e in the cubanite paragenesis is similar to that in the normal ore, v i z. chiefly associated with sphalerite. Only rarely is it met with in chalcopyrite as solitary grains and grain clusters or fine veinlets. The occurrence of stannite in conjunction with pyrrhotite is still rarer.

The mode of occurrence of m a g n e t i t e in the cubanite ore resembles that in normal ore, probably belonging to a paragenesis older than the sulphide mineralization.

SILICATE MINERALS

The occurrence of silicates in the cubanite ore is of the same kind as in normal ore. The silicate material probably represents in the main relicts of silicate rock, as they had been before the sulphide mineralization but crushed and ground up during this process. The rock has probably been schiefly quartzite and thus in its mineral composition relatively poor in species.

Q u a r t z appears also in the cubanite ore as the dominating silicaous mineral, being in its mode of occurrence similar to that in the normal ore.

T r e m o l i t e is met with as occasional prisms or fine fibrous fan-shaped or spherolitic bundles and partly as ragged relicts replaced by sulphides.

Besides tremolite, d i o p s i d e is rather common, occurring partly as grains replaced by sulphides and being corroded along their margins. They may also occur as sievelike grains. In addition, an alteration into a tremolite-talcmass has taken place along the cleavage network.

U v a r o v i t e, in the form of large idiomorphic crystals or crystal groups in ore, is met with extremely seldom. In the uvarovite-bearing parts the ore is coarse-grained, rich in pyrite and pyrrhotite and strongly brecciated.

S e r p e n t i n e occurs partly altered into talc or chlorite as rounded inclusions chiefly in the zones near the contacts of ore and serpentine. In the fine cracks in the ore serpentine is met with together with talc as an almost amorphous steatite-like mass.

B i o t i t e and s e r i c i t e are met with as occasional scales or scale-lenses, the former being in general strongly chloritized.

Small brecciated grains, reddish brown in colour, are occasionally met with. They are obviously chromespinel, p i c o t i t e. The margins of the grains and the cracks are opaque because of the dark oxide ore pigment, whereas the more unbroken central parts with reddish brown or blood-red shades are translucent though clouded by black ore pigment.

C o r d i e r i t e has been observed to occur in some thin sections made of the cubanite ore. When appearing in ore it is always strongly pigmented and pinitized in its margins. Owing to these and other alteration products it is clouded, making it difficult to define its optical properties quite exactly. In large grains pseudohexagonal triplets were detected in polarized light with crossed nicols.

For the present there is no sufficient statistical observation material to settle the question whether the occurrence of cordierite genetically belongs together with the cubanite-paragenesis in the Outokumpu ore; but at least in those few cases where cordierite has been found in thin sections, it has also been noted from polished sections that chalcopyrite contains cubanite.

Also the cordierite-antophyllite rock at Raivionmäki has proved to be cubanite-bearing.

THE PARALLEL OREBODY UNDER THE WESTERN PART OF LAKE JYRINLIETUKKA

A rather small orebody parallel to the Lietukka ore is situated above its southwestern part although separated from it by a quartzite-serpentine complex about 100 m in thickness (see map, Appendix III, Profile 7). The deposit is known only on the basis of surface diamond drilling and on account of its small size it has probably no economical importance, but it is interesting because of its extraordinary mineral paragenesis, which differs from the normal ore type of Outokumpu. In addition, the existence of such a formation indicates that there may be a possibility of discovering also economically important ore bodies in the Outokumpu complex or in other formations of the same nature.

According to observations on the diamond drilling cores, the sloping plate-like formation is situated as a conformable sulphide-mineralization below a rather thick serpentine body in a strongly metamorphosed skarn-quartzite complex. The strike and dip of the formation are the same as in the country rocks, the dip being about 30—35° southeast and the axial pitch approximately horizontal.

The contacts against the wallrocks are unsharp, the ore-mineral concentration diminishing gradually in the direction of the wallrock. In the deposit itself the mineral content varies zonally. Here and there compact sulphide concentrations about 1 m in thickness may be met with, while the intervening zones are more weakly mineralized.

MINERAL PARAGENESIS

ORE MINERALS

P y r r h o t i t e occurs in the ore type as the dominant sulphide mineral, differing from the pyrrhotite of the normal type in sofar as it displays a distinct cleavage (Fig. d, Pl. XVIII), apparently along (0001).

The same type of cleavage cracking in pyrrhotite can be observed in polished sections of the ore boulders found in the region of the southeast side of the Kumpu B outcrop. The boulders are somewhat weathered and the well advanced cleavage, as also the marcasitization observed in connection with the cleavage in the pyrrhotite, is obviously caused by the weathering. Probably the distinct cleavage of pyrrhotite occurring in the parallel orebody below Lake Jyrinlietukka is also the result of a weathering process caused by circulating ground water. The deposit is situated at a depth of about 40—60 m under the rock surface below Lake Jyrinlietukka. The influence of the ground waters along the fissures may well extend to such a depth.

An isotropic oxide ore mineral with weak reflectivity occurs intruded into the cleavage cracks and is probably magnetite. It occurs as similar vein-like stripes continuing from one grain to the other and also in the cracks of pentlandite associated with pyrrhotite, as well as in the cracks of the silicate grains surrounding the ore minerals.

P e n t l a n d i t e is regularly associated with pyrrhotite and occasionally occurs as independent idiomorphic grains or lumps. Owing to its local abundance certain parts of the deposit may be considered as nickel ore. The (111)-cleavage typical of pentlandite is always clearly visible. A distinct b r a v o i t i z a t i o n along the cleavage may be met with beginning from the cracks (Fig. a, Pl. XIX). In certain cases it extends through the whole grain, while pentlandite may be seen only as occasional relicts in the marginal zones of the almost pure bravoite grains.

C h a l c o p y r i t e occurs together with pyrrhotite or as independent grain groups in the same way as in the normal ore type.

P y r i t e is met with in comparatively small quantities and it occurs either as occasional equidimensional grains or aggregates.

V a l l e r i i t e occurs in the ore type in the same manner as in normal ore, i. e. as small scales or scale aggregates in the cracks of chalcopyrite. It is also found in cleavage or crushing cracks of pentlandite and it seems partly to replace pentlandite (Fig. b, Pl. XIX).

C h r o m i t e is in addition to pentlandite another mineral strange to the typical mineral paragenesis of normal ore. The amount of chromite varies locally within large limits and occasionally zones may be met with where chromite occurs as the dominant ore mineral.

Chromite occurs as roundish idiomorphic grains averaging from 1.0 to 0.1 mm in size, which are usually strongly corroded and sieve-like or brecciated (Fig. c, Pl. XIX). Intruded into the corroded holes and cracks pyrrhotite and chalcopyrite are met with. Silicate grains of varying size are abundantly present as inclusions.

SILICATE MINERALS

As mentioned earlier the ore mineralization occurs in a strongly metamorphozed skarn-quartzite complex, part of the sulphides being deposited in lime-magnesium-silicate rock and another part of the mineralized zone being quartzite schist rich in skarn minerals.

The occurrence of helicitic oxide ore pigment stripes in silicate minerals is an invariable feature of the mineralized zone.

Q u a r t z naturally is the predominant mineral in the quartzitic zones. A strong undulatory extinction and an abundance of pigment are characteristic.

T r e m o l i t e occurs as a prevailing lime-magnesium-mineral, being in its mode of appearance and characteristics similar to those of the normal paragenesis.

In some parts of the deposit there is also s e r p e n t i n e in which o l i v i n e relicts are preserved. Associated with olivine small yellowish red-brown i d d i n g s i t e-like grains are met with, partly serpentinized.

T a l c and occasional c a r b o n a t e occur as fine-scaled groundmass in the zones containing tremolite and serpentine.

C h l o r i t e occurs usually as a thin, weakly birefringent covering, which capsules the ore mineral grains, or as occasional scales and scale lumps on slicken-sides or in the zones containing tremolite-serpentine.

Almost colourless b i o t i t e, probably poor in iron, occurs in addition to chlorite. Biotite is always more or less chloritized.

U v a r o v i t e is found as occasional idiomorphic crystals in the parts of the deposit rich in chromite.

GENERAL CONSIDERATIONS

ORIGIN OF THE COUNTRY ROCKS

THE QUARTZITE-SERPENTINE COMPLEX

The quartzite-serpentine zone of Juojärvi—Polvijärvi joins as a conformable formation with the underlying and overlying mica-schist. The contacts between quartzite and micaschist, so far as they are exposed, are in general undisturbed and the mica-schist usually passes through a rather thin transition zone into pure mica-free quartzite. A graphite-bearing phyllitic black-schist often occurs as a mediating link in the contact zone. The occurrence of the black-schist intimately associated with quartzite leads to the inference that they are genetically intimately associated with each other, belonging to the same sedimentation phase. The fact that the black-schist, being finer in grain, seems to be less metamorphozed, is apparently due to the influence of the fine-grained organogenous graphite-dust obstructing the recrystallization. Black-schist also occurs in the contact of quartzite and serpentine, perhaps because black-schist horizons have, as mechanically weaker zones, favored the development of openings. These openings again have developed as the result of shear movements caused by folding; thus the intrusion of serpentine into these openings has been natural.

In his study on the tectonics of this region, Väyrynen (1939) has, on the basis of the general tectonic features, come to the conclusion that the Outokumpu complex constitutes one part of an overturned nappe, the »roots» of which were far to the northwest in the region of Keyretty-Kinahmi.

The chain of the argument, necessarily incomplete because of the small number of outcrops, is partly based only upon the application of tectonic regularities as known from general experience. Nevertheless, Väyrynen's idea seems in the light of observable facts to be plausible. At least it may be considered a good working hypothesis for later tectonic studies.

In the light of the conception just mentioned the ophiolitic serpentine-intrusions met with in the complex would have been separated from the magmas moving under the nappe either as olivine or pyroxene peridotites and displaced during the overthrust movements into the pressure minima of the nappe, at the same time serving as mobile horizons promoting the overturning movements.

DOLOMITE AND SKARN ROCKS

Dolomite

In his study on the serpentines of North Karelia, Haapala (1936, Pp. 75—80) concludes that the carbonate-rocks in the Outokumpu complex have developed from serpentine rocks as metasomatic replacement products, emphasizing his views in the following eight points:

1. The general mode of occurrence of dolomites in connection with serpentines suggests a close relationship of some kind between the carbonate rocks and the ultrabasics. As visible in the Outokumpu complex, in the outcrops, in the mine and in the drill-hole, the carbonate rocks zonally surround, as a rule, the serpentine bodies.

2. The gradual passage from the carbonate rock into serpentine indicates a host-guest relation between them, i. e. a replacement.

3. The microscopical examination of serpentine shows that a carbonatization of the silicate minerals has occurred, the alteration, consequently having occurred in the direction: ultrabasic rock → carbonate rock.

Apparently the parts of dolomite next to the contact can be taken as products of a metasomatic replacement of serpentines. As to the portions farther from the contacts, the following facts are to be considered:

4. The carbonate material, though often mixed with impurities, has the same composition.

5. The presence of chromite in dolomite as a complete image of the chromite in serpentines can hardly be explained but by assuming a similar origin for both of them. Besides the resemblance in the outer habit, the properties indicate also a similar content of chromium in them.

6. Patches of serpentine have been found, though rarely, deep within the carbonate rock.

7. The mode of occurrence of the ore particles in clouds without any relation at all to the structural features of the present constituents indicates a residual structure of a replaced host rock.

8. The general content of chromium both in the dolomites and in the skarn rocks is easily explained on the assumption that these rock are replacement products of the ultrabasics.

According to the present author's conception the carbonate metasomatism does not seem to be sufficiently demonstrated by the theses mentioned, and on the basis of the observations described earlier conclusions may be drawn which lead to quite a different result:

1. The general mode of occurrence of dolomites in the marginal zones of the serpentine lenses may be explained, according to our conception, in the following manner: in the intrusion phase of the serpentines (peridodites) during the overthrust movements the dolomite layers belonging to the schist formation have served as horizons, which have facilitated the movements; and it is especially into these horizons that the serpentine ophiolites have principally intruded.

2. The host-guest relation in the contact zones of dolomites and serpentines surely cannot be definitely explained according to Haapala's conception. In the case described earlier this host-guest relation is distinctly of such a nature that the dolomite acts as a host, i. e. the serpentine has intruded into it; the gradual transition from serpentine into dolomite is distinctly of such a kind as to indicate that the dolomite, intimately associated with the schist, has been more rigid and less liable to deformation. As a result, a dolomite-breccia with serpentine as matrix, i. e. the so-called ophidolomite, has developed, where the amount of serpentine is comparatively small. Farther from the schist the dolomite has been unprotected and, therefore, the mixing caused by the deformation has been more intimate; and a serpentine-dolomite mix-rock has evolved, making the host-guest relation difficult to explain.

3. On the basis of microscopical examination the carbonatization of the silicate minerals cannot be determined with certainty. In general the contact relations of the minerals are particularly indistinct. The case (Fig. d, Pl. IV) of the serpentine-dolomite relation described previously shows as distinctly as possible that the dolomite is older than the serpentine, which partly replaces it. As to the mineral sequence the case at hand is as definite as possible, the direction of the mineral sequence being: carbonate rock → serpentine.

4. That the carbonate material always has the same dolomitic composition supports, in our opinion, at least as well the hypothesis of its originally belonging to the primary sedimentary series. In the schist formations of the region Juuanvaara—Petrovaara to the north of the Outokumpu complex, perhaps belonging to the same stratigraphic horizon, dolomitic carbonate rocks associated with quartzites are met with abundantly. They are, at least for the present, considered to belong to the schist formation and to be sedimentary in their primary origin. (Frosterus 1902, Väyrynen 1933).

5. The similarity in the appearance of chromite in serpentine and dolomite does not necessarily signify any relict structure. Owing to its great

crystallization energy the chromite has almost always, independent of the age relations, approximately the same kind of habitus.

In addition, chromite is a comparatively rare component in the dolomite of the Outokumpu complex. The only dolomite deposits known at present which contain chromite have been met with in the prospecting channel at Raivionmäki and in some diamond drill-holes. But in the other dolomite zones chromite is extremely rarely found. The content of chromite is not characteristic of them, as it ought to be if they were secondary alteration products of serpentines.

6. The occurrence of serpentine lumps in dolomite may equally well indicate a mechanical mixing, which has taken place in the contact zone and led to formations in which inclusions of dolomite in serpentine are common (Fig. d, Pl. V). The mixing may have taken place either in a ground or plastic state, when sharp-edged fragments or distorted and elongated vein-like formations have evolved, which, however, have no connection outwards with the massive dolomite.

7. The sulphide ore grains in serpentine and dolomite are apparent results of a secondary mineralization younger than their hosts. Thus their possible mode of occurrence resembling a relict structure cannot give evidence for the carbonate metasomatosis.

8. The content of chromium in dolomite and skarn rocks need not necessarily signify a primary chromium content in the rock. The chromite veins in diopside skarn described earlier distinctly show that migration of chromium is also possible. If the conception is approved that the skarn rocks have metasomatically developed from serpentine through an intervening stage of carbonate, the aforementioned occurrence of veins in skarn rock is difficult to explain; for in this case, because the vein material, being obviously derived from serpentine or premetamorphic peridotite, ought to be older than the tertiary skarn rock, which has evolved from serpentine through an intervening stage of carbonate rock.

Although in origin most chromite deposits are generally considered as products of early magmatic crystallization-differentiates, there are many studies according to which part of the chromium may remain during the differentiation in the late magmatic phase, Bateman (1951).

Sampson (1929) maintains that a considerable part of the chromium may remain in the residual solutions during the magmatic differentiation and Ross (1929) points to the hydrothermal origin of some chrome-bearing silicates, such as chrome diopside, chrome-tremolite, and fuchsite. In his study on the Otravaara deposit, Saksela (1925) comes to the conclusion that the mica-containing chromium is of hydrothermal origin. According to Eskola (1933) all chromium minerals, incl. chromite, which occur at Outokumpu, are hydrothermal in their origin, and have developed later than serpentine, from which chromium obviously has been derived. In his

Boliden-study Ödman (1941) reaches the same conclusion with regard to mariposite, pointing out that chromium may follow the pneumotectic hydrothermal ore solutions. In his study on some chromite deposits in Egypt, Amin (1948) presents a hypothesis as to the hydrothermal origin of the vein-like chromite deposits occurring in serpentine and metamorphozed schists. According to Kovenko (1949) some of the chromite deposits in Turkey are certainly of late magmatic origin, the chromite occurring in them either as injection veins or »chimneys», which have developed from magmas rich in chromite and mineralizers under the influence of the injections. In this case the vein formations are obviously to be compared with the chromite veins found in the diopside skarn at Outokumpu. Even in the case of Outokumpu the late magmatic origin of chromite would seem most probable. The premetamorphic peridotite would have been the source of chromium, from which chromium has become mobile during the latest phase of the differentiation of peridotite. The mobilization of chrome-bearing solutions has taken place in the hydrothermal state in which the serpentinization of peridotite and the formation of talc magnesite rocks have taken place. The chromium content in skarn rocks can also be explained as the result of the influence of hydrothermal solutions containing chromium. The chromium concentration in the solutions in question has also varied rhythmically, owing to which remarkable local variations may be observed in the chromium content of the skarn minerals; this rhythmical variation can be detected even in single diopside crystals, as described earlier (Fig. a, Pl. VI).

A mere carbonate metasomatism does not suffice for the development of dolomites from serpentine if the source of calcium needed in the reaction cannot be satisfactorily explained at the same time, since talc-magnesite rocks normally develop as the result of carbonate metasomatism. This is e. g. the case in the region of Horsmanaho in the northeastern part of the Outokumpu complex.

According to Haapala »the solutions causing carbonatization probably absorbed the material required, viz. lime and carbon dioxide from the rocks with which they come in contact.»

Calcium sources sufficiently great to produce the dolomitization, assumed to have taken place on an especially large scale, have not been met with in the neighbouring formations; if the solutions causing dolomitization had come from sources farther away, dolomites ought to occur also in connection with other neighbouring serpentine-ophiolites, apparently of the same age. This is, however, not the case, but the serpentine-ophiolites of the region west of the Outokumpu complex are mainly altered into anthophyllite-asbestos rocks; the northeastern part of the complex and the serpentine zones east of it at Polvijärvi are altered into talc-magnesite rocks.

In addition, the fate of the silicic acid which is formed in the same reaction ought to be explained. The small tremolite content of the dolomite rocks, which might be considered as the reaction product of the liberated silicic acid and the excess carbonate does not suffice to explain the fate of the silica. The tremolite and diopside content in dolomite is too small to bind all the silicic acid set free.

Therefore the most logical conclusion would be to consider dolomite in its primary origin as a sedimentary rock belonging to the same sedimentation series together with the quartzites and black-schist. This is the case at least when massive dolomites or ophidolomites occurring in the contact zones of serpentine lenses and quartzites are involved.

Skarn Rocks

The regular situation of the skarn formations in the contact zones between quartzite and serpentine-carbonate rocks and the usual transition zone suggest that the skarn formations evolved as the result of their interaction. The dominance of tremolite in the skarn zones near serpentine and dolomite, as well as the dominance of diopside in the parts associated with quartzite, give direct evidence of the chemical composition and ratio of the components which have taken part in the reaction. The skarn rocks rich in diopside occurring as intermediate layers or lenses in quartzite may probably have evolved as reaction products from layers rich in carbonate in quartzite. The common chromium-content of the skarns, again, is due to the reaction of the calc-silicate rocks and chrome-bearing hydrothermal solutions which originated from serpentine or premetamorphic peridotite. Because the occurrence of the skarn formations is quite general in the whole stratigraphic horizon in which the serpentine ophiolites occur and to which the Outokumpu complex belongs, it is obvious that the skarn formations are reaction skarns caused by the regional metamorphism.

ANTHOPHYLLITE-CORDIERITE ROCK

The situation of antophyllite-cordierite rock in quartzite as a comparatively sharp »intervening layer» bordering on it structurally and in its mode of appearance resembles the skarn layers. This bolsters the assumption that they have had a rather similar sedimentary primary origin.

The difference in mineral paragenesis implies, however, that during its primary stage the antophyllite-cordierite rock must have been in its chemical composition a sediment rich in alumina. Its present mineral paragenesis results from the influence of the regional metamorphism.

The abundant sulphide mineral tenor of the anthophyllite-cordierite rock implies that the metasomatic alterations, typical of high temperature parageneses, have taken place in a comparatively high temperature, possibly under the influence of the factors connected with the ore genesis.

PEGMATITE DIKES

The situation of the pegmatite dikes preferably in the transversal fracture system, traversing the general axial pitch of the formation approximately perpendicularly and distinctly penetrating the ore, as well as their undisturbed structure imply that they belong to the youngest members of the complex. Ruptures and brecciated structures are only occasionally met with in the pegmatite dikes. From these Trüstedt (1921) concluded that the pegmatites were older than the ore. In such cases it is, however, only a question of brecciation in ore caused by late local movements. The difference in time between the *mise-en-place* of the ore and the intrusion of the pegmatite dikes has probably been relatively short, as part of the sulphides has still been mobile after the intrusion of the pegmatite veins. This fact is indicated by the fine sulphide veins found in them and the disseminated sulphides at the margins of the pegmatite dikes.

The contact relations and the structure of the dikes, however, distinctly indicate that already during the intrusion phase of pegmatite the ore deposit had become displaced, its temperature having fallen considerably below the crystallization temperature of the pegmatites. No significant tectonic disturbances took place in the formation after their intrusion. Thus the intrusion phase of the pegmatite dikes puts a distinctly lower limit to the genesis of the ore deposit.

Although the connection of the pegmatites with the granite of Maarianvaara cannot be proved in the absence of outcrops, they are, however, in their mineral composition and structure similar to the pegmatite dikes in the immediate neighbourhood of the Maarianvaara granite and in the granite itself and have therefore been generally considered to have been derived from this granite. Trüstedt (1921), Mäkinen (1919), Eskola (1933), Väyrynen (1939).

ORIGIN OF THE ORE

EVIDENCE OF THE CONTACTS AND TECTONIC PHENOMENA

When examining the contact relations between the ore and the wall-rocks in the light of the facts described, it is remarkable, in the first place, that the contacts, with certain exceptions, are generally conformable to the tectonic features of the wall-rocks. When a disseminated ore type is involved, the contact usually follows one and the same schistosity horizon, being comparatively sharp and rectilinear, though in such a way that the quartzitic wallrock is weakly impregnated with sulphides.

At the contacts of the normal ore type and the wallrocks, features cutting the tectonics of the wallrock can sometimes be observed, though in most parts of the deposit the contacts are conformable.

Moreover, it is remarkable that the contact surface against the underhand wallrock is in general comparatively straight and the underlying rocks are only slightly deformed in their structure. The contact surface of the hanging wall, on the other hand, is much more irregular than the former. When quartzite occurs above the hanging wall as wallrock, as is usually the case, remarkable local folding is likely to be found in it; the relief of the contact surface is still more irregular if the quartzite bordering on it is very thin or if the ore at its hanging wall directly adjoins serpentine.

The irregularity of the relief of the contact surface is obviously due to the compression by means of folding of the rocks lying above the hanging wall at the same time as a slight dilation has taken place in the underlying rocks, as appears from the occurrence of all the apophyses shooting from the ore into the wallrock on the footwall side, giving rise to dilation cracks into which the apophyses have intruded.

The occurrence of a zone of tectonic disturbance near the contact of serpentine and quartzite is obviously to be explained as follows: in the tectonic movements the zone in question has been rather exposed to the crushing and grinding process because of the different physical characters of the rocks bordering on each other.

Newhouse (1942) explains that by the influence of the tectonic movements, such as folding, etc., crushing zones develop at contact zones where two rocks different in their physical characters are in contact with each other. The crushing zones, again, are easily penetrated by solutions and thus favour the development of ores.

As to the contact zones of quartzite and serpentine, it is quite obvious that the crushing takes place in the quartzite, which, compared with the homogenous and tough serpentine, is remarkably more brittle.

Since in the schists the possibility of laminar shear makes the folding easier without any considerable brecciation, neither breccias nor ores are met with in considerable amounts in the country rock farther away from the serpentine. The possibilities of laminar shear have obviously been increased by the black-schist horizons intimately associated with quartzite. Plenty of deformation phenomena may be noticed in them in the form of minor folds and slickensides rich in graphite and chlorite.

Owing to these phenomena the development of crush zones through the influence of tectonic movements is bounded to the contact zones, favourable for crushing, in the immediate neighbourhood of serpentine.

The contact relations of the breccia and the normal ore type, as well as their structures, are distinctly of such a kind that they must be epigenetic in their origin with regard to their wallrocks. In respect to the disseminated ore type the fact would not seem so evident unless in appearance and mineral paragenesis it were not so intimately associated with the former that no doubt of its epigenetic nature remains.

The development of the brecciated ore type obviously shows the connection of the development of the ore deposit with the tectonic movements. The fragments of the brecciated ore type are generally of the disseminated type and often strongly contorted, while the normal disseminated ore is comparatively undisturbed in its structure. This shows that the development of the ore began with the genesis of the disseminated ore, while the geological environment was still in a comparatively undisturbed state.

During the development of the brecciated ore type the tectonic movements were obviously most violent, while the concentrated ore material intruded into the crushing zone developed in the contact zone of serpentine and quartzite. It was followed by a tectonically more quiet phase, during which the normal ore type developed. During this period the ore material filled the spaces opened by the tectonic movements in the pressure minima. Judging from the undisturbed structure of the normal ore type, no considerable tectonic disturbances any longer took place excepting the transversal fracturing, almost perpendicular against the axis, and the main tectonic fault movements, which have probably had some connection with the intrusion phase of the Maarianvaara granite.

On the basis of the facts and views mentioned it seems clear that the Outokumpu ore is decidedly epigenetic by nature and that the crushing zone in the quartzite near the contact of serpentine has been a necessary tectonic condition for the development of the ore. This crushing zone has been formed in the quartzite-serpentine complex through the action of the folding movements caused by the tectonic forces. The ore material intruded into this crushing zone under orogenic pressure.

FORMATION OF THE DISSEMINATED ORE TYPE BY REPLACEMENT

Both the main ore types of the deposit, the disseminated pyrite ore type and the normal ore type, differ from each other in their structure to such an extent that their development must have taken place under considerably different conditions.

In the disseminated ore type the relict structure of the quartzite is so plainly visible and the contact relations with the quartzite are of such a kind that a metasomatic replacement process must be assumed. The solutions causing the replacement process must have been driven along capillary openings or fissures and along the intergranular film of the quartzite (Wegman 1935).

As has been pointed out, disseminated sulphide occurs preferably in the schist horizons rich in skarn minerals, and in them relicts from skarn minerals partly replaced by sulphides are visible. Ragged and corroded quartzite grains may also be present, obviously being remains from bigger grains partly replaced by sulphides. But sulphides seem partly to occur also as fillings of the microtectonic fissures and capillary openings.

Where strongly metamorphozed, glass-like and compact quartz zones occur in the quartzite, they seem to have remained sterile in the sulphide mineralization, owing to which fact striped disseminated ore types have developed.

According to general opinion, the hydrothermal solutions may be either ionic or molecular dispersoids or genuine water solutions, or alternatively colloidal water solutions or combinations of several kinds. Common to all of them is that the heat was under the critical temperature of water. The dissolved materials may have originated either from volatiles of magmas or partly also derived from the wallrocks penetrated by the latter (Schneiderhöhn, 1941, P. 299).

In the case of Outokumpu the metasomatic phase, in the form of the genesis of the disseminated ore, seems at least partly to have preceded the development process of the normal ore, which is by its nature intrusive. Thus the development of hydrothermal solutions may be explained as a penetration of a liquid phase containing volatile matters and preceding the intrusive phase along the same opening channelways as the actual concentrated ore solutions, which followed it. According to Behrend (1936), gases derived from magmas, owing to the low heat conductibility of the rocks, advance more quickly than heat. Therefore in certain places minerals of lower temperature may have developed first, whereas minerals belonging to higher temperature regions could not originate before the wallrocks had warmed up by the influence of the solutions. In the case of Outokumpu the sequence pyrite pyrrhotite points to this.

Owing to the action of the cold wallrocks the temperature of the gases may even have fallen when hydrothermal solutions developed by the action of the water originated from the wallrocks or developed by condensation of water vapour. These solutions caused the metasomatic processes which led to the development of the disseminated ore type.

MISE-EN-PLACE OF THE NORMAL ORE BY DISPLACEMENT

As previously described, the contacts of the normal ore type against the wallrocks or the disseminated ore type are always sharp, though in general they are in conformity with the structural features of the wallrocks. Sometimes, however, there are fragments of wallrocks in the ore, brecciated contact zones, and apophyses shooting into the wallrock or into the disseminated ore met with at the contacts.

The contact relations and especially the structure of the brecciated ore suggest an intrusive formation of the normal ore. As concluded earlier, *mise-en-place* of the ore material must have taken place in a local pressure minimum caused by folding.

High pressure, probably resulting from orogenic movements, was the active force which mobilized the ore material. The orogenic movements caused the bending of the quartzite-serpentine complex and thus the formation of the secondary anticline, on the southeastern side of which the Outokumpu complex is situated.

The orogenic pressure must have been great enough to displace the material into its present position, partly pushing the walls of the channelways apart.

Gavelin (1939) and Ödman (1941) have used the term »displacement» in describing the said intrusive process, the significance of which term, used earlier in this study, is explained by Ödman (1941, p. 178) as follows: »The term 'displacement' implies that the ores were brought into place by the intrusion of the ore solution into a more or less schisted rock complex in which the solution pressed the walls of suitable channelways apart thanks to its intrusive force.» Väyrynen (1939) has also used the same term in his description of the development of the Outokumpu ore.

Through the action of more diluted hydrothermal solutions a more or less intensive metasomatic replacement process often follows this displacement process, according to Ödman.

As previously mentioned, it is obvious that at Outokumpu metasomatic replacement took place in the form of the development of disseminated ore already before the displacement phase of the normal ore. But it is equally apparent that secondary metasomatic alterations took place in the developed disseminated ore through the action of solutions from which the normal ore originated.

The alteration of pyrite by replacement either partly or wholly into pyrrhotite or chalcopyrite as described earlier obviously belongs to this later secondary metasomatic phase.

It is apparent that a comparatively pure disseminated pyrite ore type evolved as the result of primary sulphide mineralization preceding the intrusion of the normal ore type. The disseminated ore type derived its present secondary mineral composition as the result of the metasomatic replacement process caused by the action of more diluted hydrothermal solutions, which followed the intrusion phase of the normal ore type in its final stage.

NATURE OF THE ORE SOLUTIONS

According to the conclusions presented above, the normal ore type would have evolved by the displacement of concentrated ore solutions into the quartzite-serpentine complex deformed by orogenic forces.

The nature and appearance of the ore suggest an intrusive development and the ore solutions must have been pneumotectic by nature in the sense in which Graton and Mc Laughlin (1918), as well as Ödman (1941), explain it: »The pneumotectic solution is thus still closely related to the magmatic-orthotectic stage but constitutes an early residual solution which was separated from the magma immediately after its main crystallization.» (Ödman 1941, P. 159).

Unlike the hydrothermal solutions which caused the development of the disseminated ore type as the result of a metasomatic replacement process, the pneumotectic solutions must have been considerably concentrated and »dry» and more viscose, i. e. nearer the magmatic state. The development of minerals of higher temperatures, such as pyrrhotite, cubanite, and valleriite, shows that the temperature of the ore solutions have been remarkably high. The chalcopyrite-cubanite paragenesis implies, according to the studies by Borchert (1934), Schwartz (1923, 1927, 1937) and others, a temperature of about 400—500°C. The lamellar texture in chalcopyrite as well as the star-like sphalerite skeletons separated by unmixing suggest also high temperatures during the development of the ore.

Also according to Väyrynen (1935), the Outokumpu ore originated under pneumatolytic conditions in a relatively high temperature, above the critical temperature of water but, on the other hand, under the temperature required for the Wollastonite reaction: $CaCO_3 + SiO_2 = CaSiO_3 + CO_2$ (i. e. below +800°C).

A high S-, Fe-, Cu- and Zn-content has been characteristic of the chemical nature of the solutions, whereas Co, Ni, and Sn occur as smaller components. During the development of the primary disseminated ore, the H_2S-Fe-content has obviously been the dominating factor in the hydrothermal solution. But during the chief stage of the ore genesis, during the development of the normal ore, the solution had been purely pneumotectic in its nature.

The fact that a fine fibrous white tremolite-skarn formation is often met with at the contact of ore and serpentine implies that the ore solutions also contained silicic acid in appreciable amounts. The zonal formation of talc in the marginal zones of serpentine fragments in the ore suggests the same.

SOURCE OF THE ORE SOLUTIONS

As for the source of the ore solutions, the geochemical composition of the ore suggests some ideas in the search for the source of the ore. Especially the nickel-cobalt ratio of the ore is remarkable in this respect.

According to J. H. L. Vogt's study (1898), the nickel-cobalt ratio is on an average 100 : 8 in early magmatic sulphide differentiates in which the nickel content is found chiefly in pentlandite. Rather, the late magmatic sulphide differentiates contain cobalt in comparatively greater amounts, as cobalt is concentrated in residual magma during the crystallization differentiation. In these late magmatic sulphide differentiates, the nickel and cobalt content enters into different sulphides and arsenides, as e. g. into minerals of the linnaeite groups (Rankama and Sahama, 1950).

The nickel-cobalt ratio varies in the Outokumpu ore between 2 : 1 and 1 : 3 and is on an average, according to hundreds of drift analyses, approximately 1 : 2.

According to Goldschmidt (1935) the different magmatic rocks contain nickel and cobalt on an average in the following amounts:

	NiO	CoO	NiO : CoO
Nepheline syenite	0.0003 %	0.001 %	100 : 300
Granite	0.0003 »	0.001 »	100 : 300
Diorite	0.005 »	0.004 »	100 : 80
Gabbro	0.02 »	0.01 »	100 : 50
Peridotite	0.40 »	0.03 »	100 : 8

The nickel-cobalt ratio in the Outokumpu ore thus approximately corresponds to the ratio which, according to the above table, prevails about midway between diorite and granite.

On the basis of the geochemical regularities and the nickel-cobalt ratio prevailing in the ore, it seems likely that the solutions from which the ore has evolved have been late magmatic in their origin, pneumotectic in their character and derived from some magma approximately of a granodioritic composition.

Eskola (1944) has referred to the pneumotectic nature of the Outokumpu ore, but owing to the character of the work as a textbook his opinions are not elucidated in detail. Väyrynen (1939) on his part has expressed the opinion that the ore has originated from some magma more acid than the peridotitic. He assumes, however, that the ore has been displaced as a »true ore magma».

The latter opinion concerning the existence of ore magmas, expressed earlier e. g. by Vogt (1898) and Spurr (1923), has not, however, gained general approval in ore geology. Especially Behrend (1935, 1936) has eagerly disputed it as untenable, i. e. considering the occurrence of sulphide magmas to be improbable on physico-chemical grounds.

Among intrusives approximating diorite or granite in composition, the Maarianvaara granite and its satellites alone are known in the neighbourhood of the Outokumpu complex. Trüstedt (1919, 1921) has assumed this granite to have »transmitted» the ore. Since, however, the granite of Maarianvaara or at least the pegmatite dikes derived from it, are distinctly younger than the ore, the standpoint of Trüstedt does not seem justified, as Mäkinen has already pointed out (1919). In addition, the Maarianvaara granite, being probably palingenic, has hardly had any qualifications to serve as the source of the ore solutions.

According to Mäkinen (1919) the ore would have differentiated from serpentine, with which it seems to be intimately associated. From a geochemical standpoint this view is, however, untenable, as on the basis of the general norm pentlandite-pyrrhotite ore should have evolved if it were derived from an ultrabasic magma, and the Outokumpu ore is not of that kind.

As other acid intrusives besides the Maarianvaara granite are not met with in the neighbourhood, the only possibility is to assume that the intrusive which the ore solutions derive from is situated somewhere below the schist formation; and thus there is no necessity of having an outcrop on the present erosion surface.

ANALOGIES TO THE OUTOKUMPU DEPOSIT IN OTHER REGIONS

The author has not had sufficient opportunity to explore the geological literature to discover possible analogies to the Outokumpu deposit.

While studying general manuals on ore geology, the author has come to the conclusion that wholly analogous deposits are in any event comparatively rare.

Nevertheless, on the basis of the available literature and personal observations, it has been possible to ascertain the existence of some quite analogous deposits.

A rather small, complicated serpentine-quartzite complex occurs in eastern Finland 30 km northwest of Outokumpu at Luikonlahti, in the parish of Kaavi, closely associated with the Maarianvaara granite. In connection with the complex at least two ore bodies resembling the Outokumpu ore in their mode of occurrence and mineral paragenesis have been noted.

No special study on the geology of the Luikonlahti deposit has been published so far but the author has had occasion to perceive its similarity to the Outokumpu deposit on the basis of field observations made on the spot and microscopical examinations of some polished sections.

The deposits are situated in diopside skarn associated with a serpentine-quartzite complex or in quartzite rich in skarn minerals. The ore seems at least partly to replace the skarn. The ore mineral paragenesis is approximately the same as at Outokumpu. Pyrrhotite occurs as the major component, in addition to which there is some chalcopyrite and sphalerite. The complete absence of pyrite in the complex is remarkable; in any case the author has not found any. At least linnaeite and stannite are met with as accessory minerals. The ore deposit is cut by several pegmatite and granite dikes, most of which are almost horizontal, a circumstance that diminishes the in themselves poor economical possibilities for exploiting of the ore.

In Norway in the regions of Röros-Sulitelma there occur a number of sulphide-ores of the so-called Röros-type, which in regard to their tectonic and mineral paragenesis are analogous to the Outokumpu ore. According to the study of Carstens (1936) on sulphide ores in Norway, at least the deposits of Storvarts, Hestekletten, and Mugg in the Röros district as well as the Lökken, Merakker, and Sulitelma deposits can be compared with the Outokumpu deposit in regard to their mode of occurrence.

The ores occur in either mica or chlorite schists closely associated with gabbro or amphibolite massifs. Although the rock paragenesis differs from that of Outokumpu, the ores are very similar to those in the Outokumpu complex in regard to their ore mineral paragenesis and tectonic occurrence as plate-like formations following the tectonics of their wallrock. The wallrocks have attained their petrographic appearance before the genesis of the ores, which obviously took place during the mountain folding. Thus the deposits are epigenetic in origin and belong to the same formation phase with the mountain folding.

In North America in the Appalachian regions many deposits of the so-called Tucktown-type are met with which may be considered analogous to the Outokumpu deposit. On the basis of the descriptions by Ross (1935) and Thompson (1914) the ores occur in the schists replacing the silicates and, in part, the carbonates, where these occur. The ore material has intruded into the schists under pressure. The essential ore minerals are: pyrrhotite, pyrite, chalcopyrite, and sphalerite. As accessories some galena and cubanite have occasionally been noted. Here, too, the ore source, i. e. the intrusive from which the ore solutions evolved, is not exposed.

According to a study by Weed (1911) the Orange Country and Copperfield or Ely-Mine deposits in Vermont, USA, belong to the same group as the Tucktown type. The ores here, too, are intruded into the schistose rocks, the silicates being replaced by sulphides. Pyrrhotite and chalcopyrite occur as essential ore minerals.

In Japan the deposits of Hitachi may be compared with Outokumpu in regard to their mode of appearance and ore mineral paragenesis. According to the studies of Watanabe and Landwehr (1924) the ores in Hitachi occur as plate-like, epigenetic formations in metamorphozed schists, while the ore tectonic and the suphide mineral paragenesis are principally the same as in the Outokumpu deposit.

SUMMARY

The ore deposit of Outokumpu is situated in Finland, in the region known as North Karelia, about 70 km east-southeast of the town of Kuopio.

The deposit was discovered as the result of prospecting work conducted by Dr. Otto Trüstedt in 1910. A glacial boulder found at Kivisalmi, in the parish of Rääkkylä, two years earlier gave the impetus for the investigations.

Mining operations began in 1913. Large-scale production was finally achieved in 1928 when the railway line was completed. The annual output of the mine is about 600 000 tons of raw ore.

The ore deposit of Outokumpu is part of a long beltlike complex made up of quartzite- and serpentine rocks, which extends in the direction northeast-southwest from the parish of Polvijärvi to Lake Juojärvi.

This so-called Outokumpu complex is situated in the western part of the depression area of Joensuu belonging to the Karelian schist formation. The gneissose-granite-cupola of Sotkuma—Vaivio, belonging to the basement of the schist formation, is situated to the east of the Outokumpu complex. The general dip of the plate-like Outokumpu complex is approximately 50—30° southeast and the general strike about north 45° east. At the northeastern end the axial pitch is about 25—30° south-southwest, after which it slopes gently, being approximately horizontal in the middle parts of the formation and 5—10° east-northeast at the southwestern end of it.

Below the footwall and above the hanging wall normal mica-schist comprises the wallrock of the complex. On the western side of the schist formation is situated the oval-shaped late Karelian Maarianvaara granite massif. Feldspar-quartz-pegmatite dikes derived from it penetrate the surrounding schists and also the Outokumpu complex.

At least two large faults cut the Outokumpu complex. Their general strike is almost perpendicular to the general strike of the complex. One

of these faults is found in the mine. The slip of this so-called Kaasila fault is approximately vertical and the displacement about 100 m. As for the other, the so-called Naumanen fault, there is no exact proof; but the geological features inferred from diamond-drilling and geophysical indications, make its existence most probable.

In each fault the part to the northeast is the downthrow side.

The Outokumpu complex chiefly consists of sheet-like quartzite zones between which thin ophiolitic serpentine lenses, narrowing at their ends, have squeezed.

Thin phyllitic black-schist zones, plate-like in form, occur intimately associated with quartzites.

Calcium-magnesium-silicate rocks, skarns and dolomitic carbonate formations generally occur in conjunction with serpentines, especially in the contact zones of the latter and quartzite.

The occurrence of green chrome-bearing skarn minerals is typical of skarn rocks.

According to the present study both the quartzite and conjoining black-schist formations genetically belong to the same formation series as the mica-schist, which forms the wall-rock.

As to the origin of the serpentine rock, the author agrees with Haapala (1936), who regards the serpentine rocks as having evolved as the product of autometasomatism from the primary dunitic olivine rock or pyroxene-peridotite through the influence of magmatic water and silicic acid contained in them.

The displacement of the serpentines (i. e. peridotites) obviously took place during the folding of the schist formation, when the horizons of quartzite and black-schist were most liable to the formation of necessary opening in pressure minima, obviously on account of the structural and mechanical character of the said rocks.

The dolomitic carbonate rocks met with in the contact zones of serpentine and quartzite represent, in the author's opinion, strongly metamorphozed zones rich in carbonate which, together with quartzite and black-schist plates, have originally belonged to the same sedimentation series.

Owing to the mobility of carbonate material these zones served as horizons furthering the shearing action during the folding movements. At the same time they were more exposed to the displacement of serpentine ophiolites.

On the other hand, the formations rich in carbonate met with in pure association with serpentines and, especially, in the central parts of the serpentine lenses, may perhaps have been derived as a product of carbonate metasomatism from serpentine, which is Haapala's point of view.

The regular occurrence of skarn rocks in the contact zones of quartzite and serpentine or as intervening layers in quartzite implies that they have developed as reaction products of the regional metamorphism between primary carbonate rocks and silicate rocks.

The general chrome content of skarn rocks is due to the reaction influence of the chrome-bearing hydrothermal solutions, which obviously originate from serpentine.

The Outokumpu ore is situated in the tectonic disturbance zone of quartzite and near the contact of serpentine, so that the country rock both in the footwall and hanging wall consists of quartzite, usually varying in thickness. Sometimes serpentine occurs as the country rock of the ore.

The ore appears in two sequent plates »*en echelon*», of which the so-called Kumpu-plate is divided by the Kaasila fault into two separate ore-bodies. In its tectonic features the ore is in conformity with its wallrocks.

The total length of the ore plates is about 3 800 m, the approximate breadth about 300—350 m and thickness 7—9 m. In the light of present knowledge the original ore resources have been about 25 million tons. The remaining ore resources are estimated at about 16 million tons. The average metal content of the ore is 3.71 % Cu, 28.19 % Fe, 24.75 % S, 1.07 % Zn and 41.97 % silicates (chiefly as quartz).

On the basis of its structural features and contact relations the ore is distinctly epigenetic and is situated in the crushing zone, caused by tectonical movements. This crushing zone is situated in the contact zone of quartzite and serpentine.

A relatively pure disseminated pyrite ore type has evolved as the result of primary sulphide mineralization in the weakly disturbed quartzite. The mineralization was caused by a hydrothermal solution, produced from a cooled gas phase and attendant water vapors, which both have preceded the intrusion of normal ore.

On account of the tectonical movements the primary disseminated ore was crushed when the concentrated sulphide solution, caused by an orogenic pressure, intruded into the pressure minimum. In the central parts of the disturbance zone a massive normal ore type has evolved in the open folds parallel to the schistosity.

Recrystallization and metasomatic replacement processes took place in the ore during the final stage of the intrusion of ore solutions, caused by the influence of weaker hydrothermal residual solutions. In those processes the ore obtained its present structure and mineral composition.

The structure and mode of occurrence of the ore distinctly point to an intrusive origin; and the ore solutions have been so-called pneumotectic in nature, i. e. they first separated from some magma after its main crystallization and were relatively hot.

According to the »geological thermometers» occurring in the mineral paragenesis, the temperature during the formation stage of the normal ore type was about 400—500°C.

The chemical composition of the ore, especially the Co-Ni-relation, is of such a kind that, according to the geochemical regularities, the ore solutions must have separated from some relatively acid magma with a composition nearly granodioritic.

Intrusives of corresponding composition are not met with in the adjacent formations. The one conceivable exception, perhaps, is the Maarianvaara granite; but, because it is rather certain that this granite is younger than the ore, its having served as the source of the ore is not plausible.

On the other hand, it is conceivable that below the schist formation an intrusive of suitable composition organically joined to the Outokumpu complex could have existed underneath the present erosion surface at some stage in the folding movements and thus, perhaps, acted as the source of the ore solutions.

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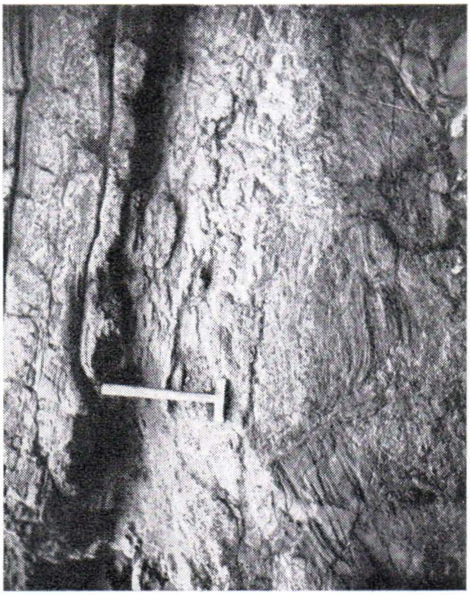
PLATES

EXPLANATIONS TO THE PLATES	I—VI	AFTER	PLATE III
	VII—XII	»	PLATE IX
	XIII—XVIII	»	PLATE XV

ABBREVIATIONS FOR MINERALS USED IN MICROPHOTOGRAPHS

1.	Bravoite	Br	10.	Magnetite	Mg
2.	Chalcopyrite	Cp	11.	Pentlandite	Ptl
3.	Chalcopyrrhotite	Cpy	12.	Pyrite	P
4.	Chromite	Crt	13.	Pyrrhotite	Py
5.	Cubanite	Cub	14.	Sphalerite	Sph
6.	Galena	Ga	15.	Stannite	St
7.	Gold	Au	16.	Valleriite	Va
8.	Linnaeite I	Li I	17.	Carbonate	Crb
9.	Linnaeite II	Li II	18.	Silicate	Si



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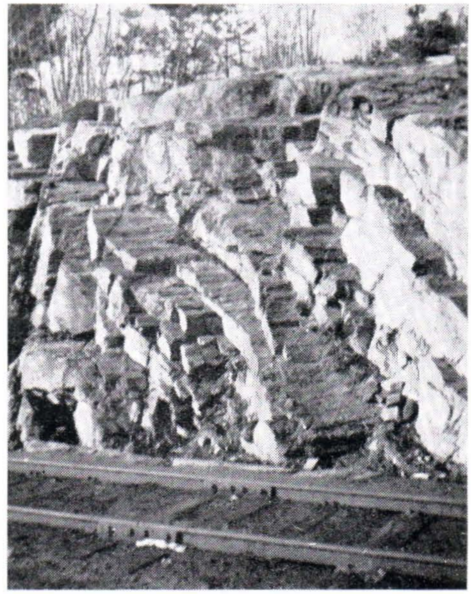

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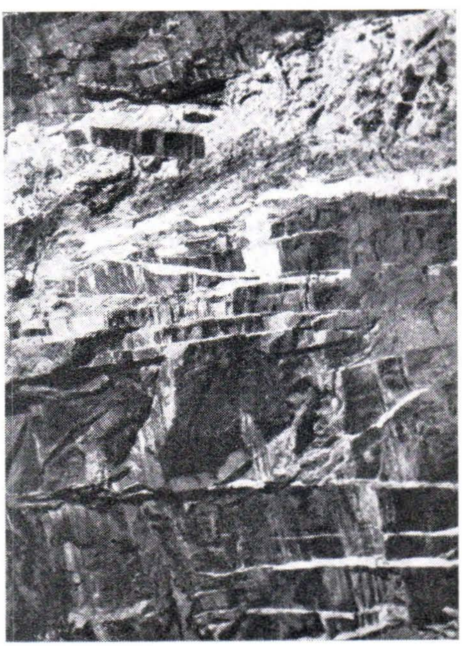

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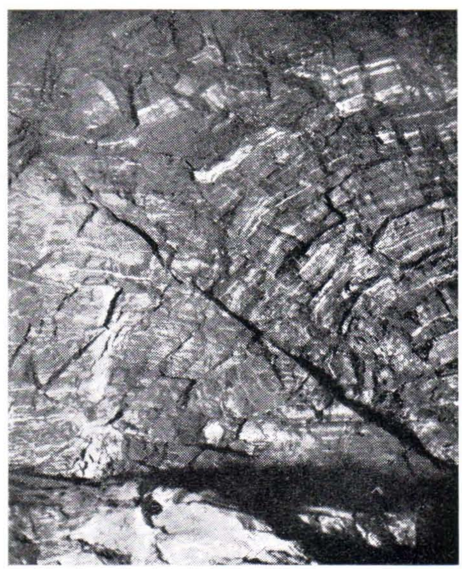

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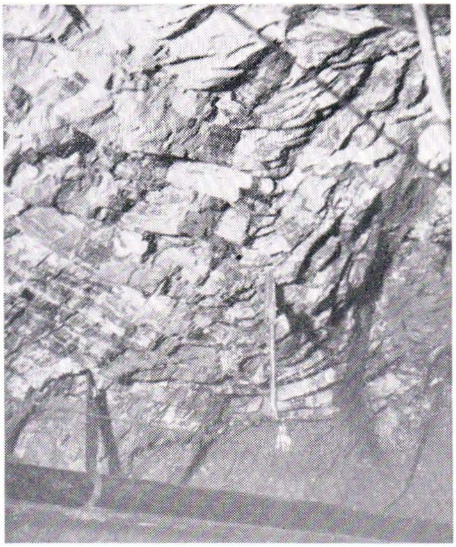

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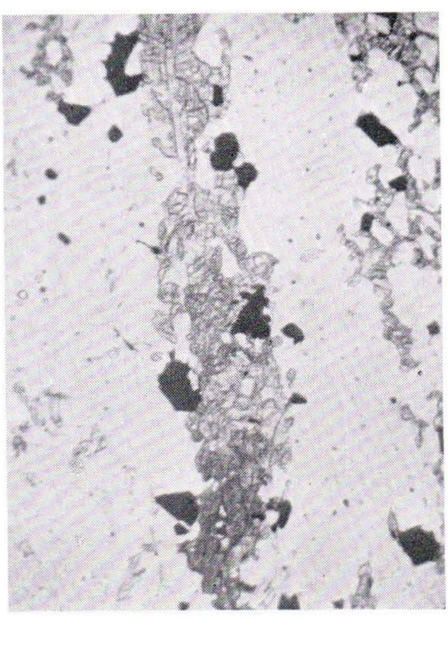

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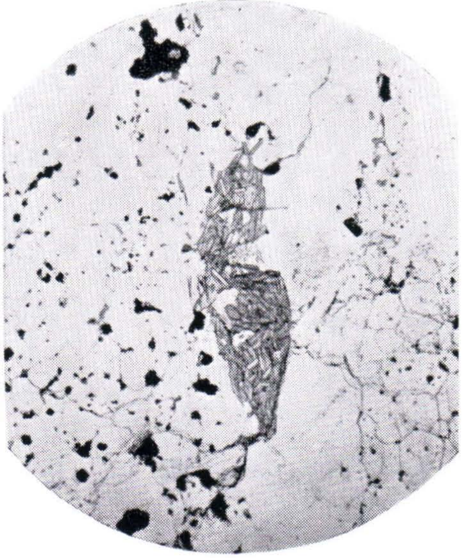

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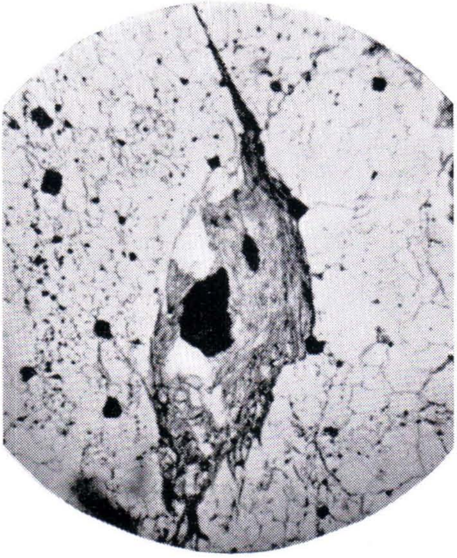

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EXPLANATIONS

PLATE I

Fig. a. Contact between ore and quartzite. Below hangingwall disseminated ore type and below it brecciated type. Outcrop at Kumpu B.

Fig. b. Transversal cleavage in quartzite. Railway cut at Outokumpu station.

Fig. c. Transversal cleavage in quartzite, serpentine-talc material and fragments of quartzite are as filling of opened cracks. Sh I +250 level, Kaasila Dr. 1 E.

Fig. d. Tectonized, banded quartzite. Mökkivaara +250 level, Dr. 2.

PLATE II

Fig. a. Quartzite bent by the influence of fault movement, (in fig. the fault is situated to the right) Mökkivaara +250 level, Dr. 2.

Fig. b. Bedding in quartzite fragment. Mökkivaara +250 level, Rs 12 a sublevel 3. Thin section, ×25.

Fig. c. Diopside-grains parallel to the schistosity in quartzite. Sh I +250 level, Kaasila, Dr. 1 E. Thin section, ×25.

Fig. d. Quartzite containing zones rich in tremolite parallel to the schistosity. Sh I +285 level, Dr. 1 W.

PLATE III

Fig. a. Carbonate grain (in centre) replaced by diopside and tremolite. Sh I +285 level, Dr. 3. Thin section, ×25.

Fig. b. Fuchsite lense in quartzite. Mökkivaara +250 level, Dr. 1. Thin section, ×25.

Fig. c. Picotite in central part of a fuchsite lense in quartzite. Polvijärvi, Haaralanniemi. Thin section, ×30.

Fig. d. Graphite-bearing phyllitic black-schist. Drill hole K 323, depth 11.99 m. Thin section, ×25.

EXPLANATIONS

PLATE IV

Fig. a. Pentlandite (white) associated with pyrrhotite (pale grey) in dolomite (black). Pentlandite partly bravoitized. Drill hole 40 a, depth 48.95 m. Polished section, × 575.

Fig. b. Chromite in dolomite. Prospecting channel at Raivionmäki. Thin section, × 13.

Fig. c. Dolomite »blebs» in serpentine. Sh I + 285 level, Dr. 5. Polished specimen.

Fig. d. Contact between serpentine and dolomite grain. Remains of dolomite occurring in serpentine. Sh I + 285 level, Dr. 5. Thin section, × 55.

PLATE V

Fig. a. »Ophidolomite» Sh 1 + 165 level, Kaasila Dr. 1 E. ½ × natural size.

Fig. b. Serpentine lath in ophidolomite. Amphibole crystals in contact zone between serpentine and dolomite. Mökkivaara shaft. Thin section, × 25.

Fig. c. Ophidolomite structure in frozen mill tailing.

Fig. d. Dolomite fragments in serpentine. Mökkivaara + 285 level, Dr. 5.

PLATE VI

Fig. a. Zonal diopside, dark zones are chrome-green and pale zones greenish-grey in colour. Mökkivaara + 285 level, Dr. 5. Polished specimen.

Fig. b. Pigment-free diopside rim surrounding sulphide grains, in central grossularite garnet. Sh I + 285 level, Dr. 1. Thin section, × 25.

Fig. c. Chromite grains surrounded by uvarovite rim in diopside skarn rich in sulphide. Sh I + 285 level, Dr. 1. Thin section, × 25.

Fig. d. Uvarovite crystal (to the left) surrounded by diopside-carbonate contact rim against dolomite (to the right). Mökkivaara drain cut. Thin section, × 13.

PLATE IV

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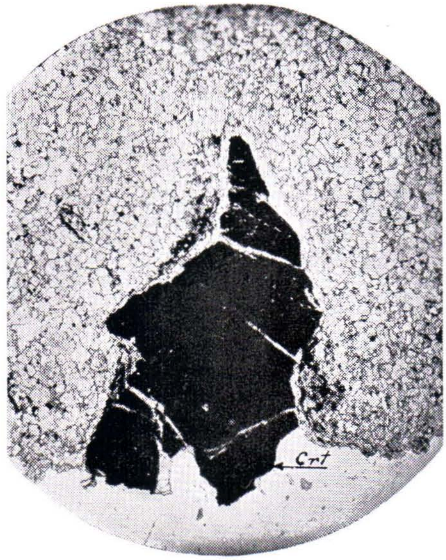

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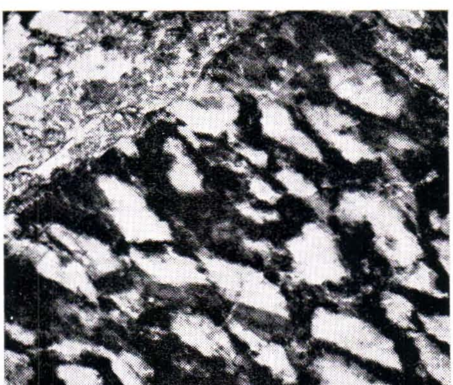

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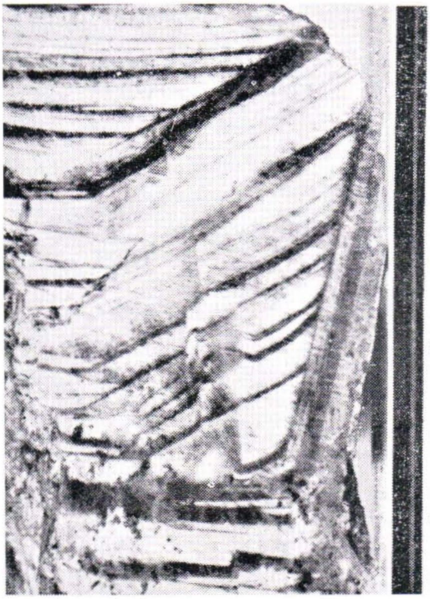

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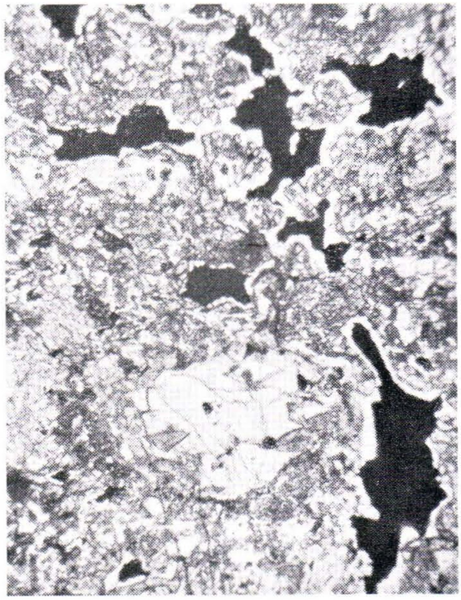

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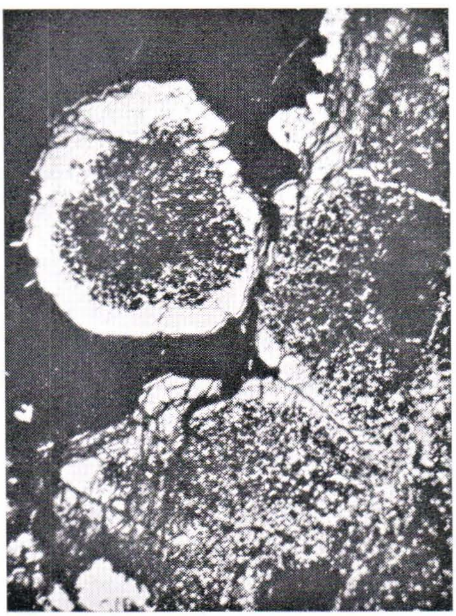

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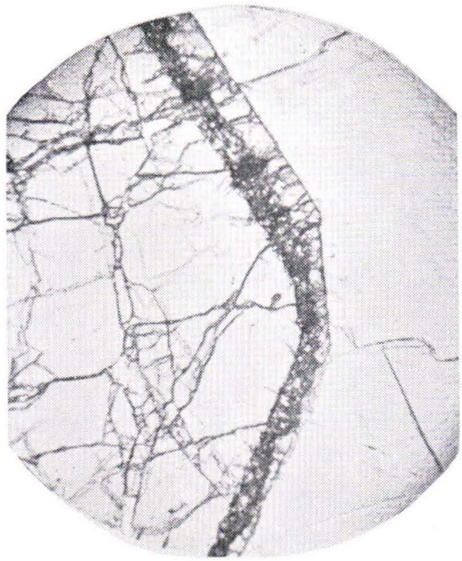

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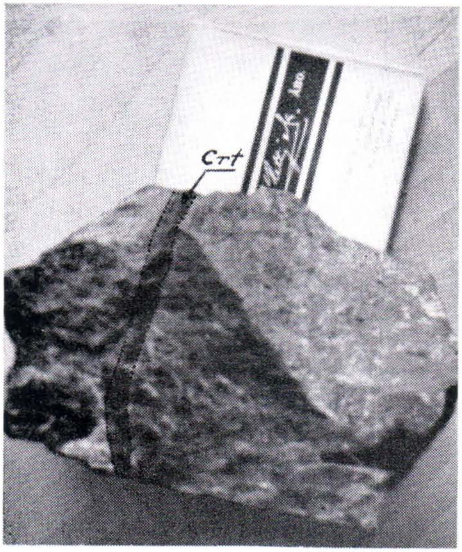

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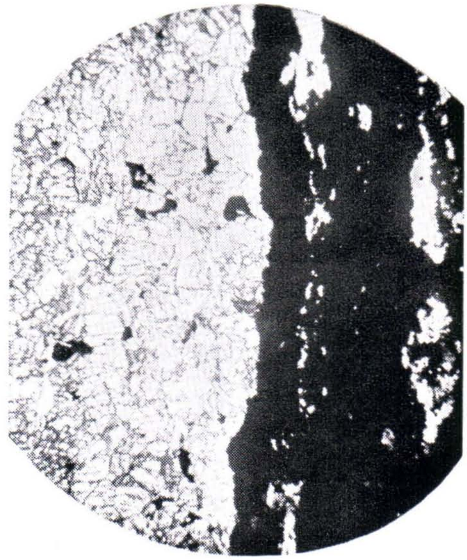

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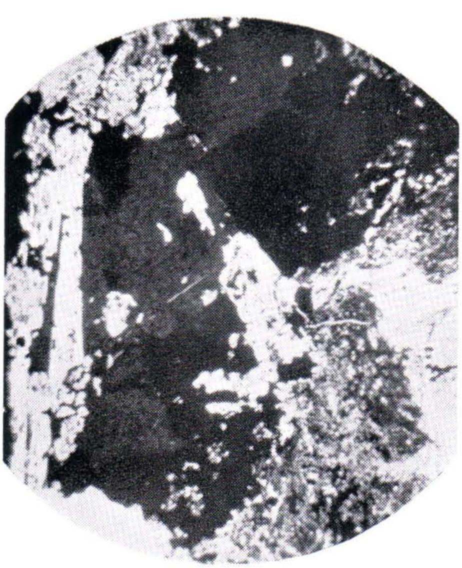

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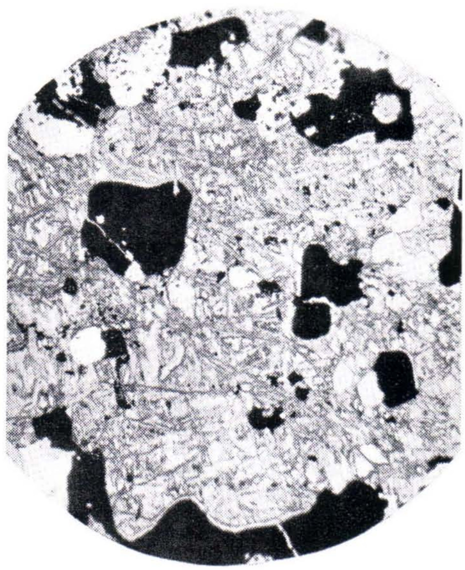

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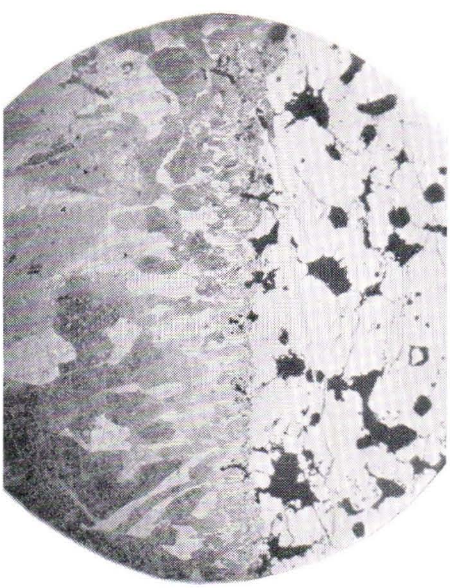

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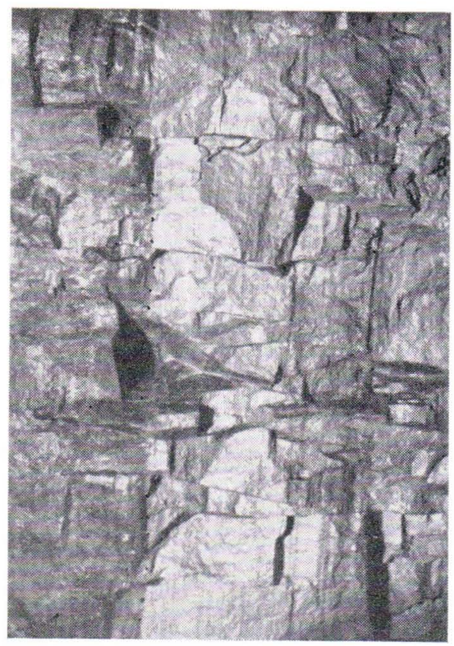

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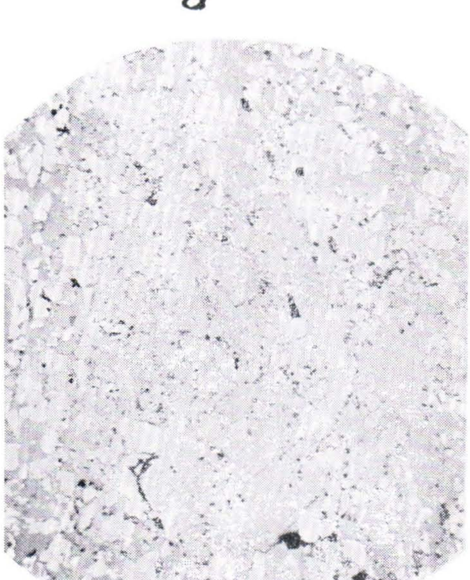

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EXPLANATIONS

PLATE VII

Fig. a. Chromite vein in diopside skarn. Sh I +250 level, Kaasila Rs. 1. sublevel 6. ½ × natural size.

Fig. b. Contact between chromite vein and diopside skarn. Sh I + 250 level, Kaasila Rs. 1, sublevel 6. Thin section, ×13.

Fig. c. Tremolite replaced by sulphides. Mökkivaara +285 level, Dr. 1 W. Thin section, × 13.

Fig. d. Corroded diopside grain replaced by tremolite-talc mass along cleavage cracks. Sh I +250 level, Rs. 4 c, sublevel 8. Thin section, ×25.

PLATE VIII

Fig. a. Cordierite-anthophyllite rock. Raivionmäki, prospecting channel. Thin section, ×25.

Fig. b. Pinitized cordierite in ore. Mökkivaara +285 level, Drill hole K 388 depth 5.60 m. Thin section, ×25.

Fig. c. Contact between ore and pegmatite dike (to the left). Sh I +205 level, Kaasila Dr. 1. Thin section, ×13.

Fig. d. Rectilinear contact between ore and quartzite. Sh I +285 level Dr. 3.

PLATE IX

Fig. a. Brecciated contact between ore and quartzite. Mökkivaara +285 level, Dr. 1 W.

Fig. b. Serpentine fragments in ore, partly replaced by talc in its outer parts. Mökkivaara +285 level, Dr. 2 W. Thin section, ×25.

Fig. c. Disseminated ore type. Sh I +250 level, Rs. 1, sublevel 3. Polished section, ×4.

Fig. d. Sulphides intruded into brecciated quartzite, the primary stage of »blebbed type». + 285 level. Drill hole K 482 depth 9.20 m. Thin section, ×13.

EXPLANATIONS

PLATE X

Fig. a. Disseminated ore type. Chalcopyrite and pyrrhotite intruded into cracks. Above, to the left, normal type without sharp contacts. From polished ore specimen in O. Trüstedt's collection.

Fig. b. Disseminated ore type where secondary normal ore has intruded into opened crack, parallel to the schistosity. Sh I +250 level, Rs. 12 a, sublevel 2. ½ × natural size, drawn by author.

Legend to figs. a and b

1. quartzite
2. » poor in pyrite
3. » rich » »
4. pyrrhotite
5. chalcopyrite
6. quartz

PLATE XI

Fig. a. Quartzite »blebs» in ore. Sh I +285 level, underhand crosscut Rs. 6. Polished section, ×4.

Fig. b. Quartzite »blebs» in ore, below in centre a rounded diopside fragment. Sh I +285 level, underhand crosscut Rs. 6. Thin section, ×25.

Fig. c. Quartzite fragment in ore. Mökkivaara +285 level, car repairing drift.

Fig. d. Apophysis of the normal ore type in disseminated ore type. Contacts marked with crayon. Mökkivaara +285 level, Dr. 1 W.

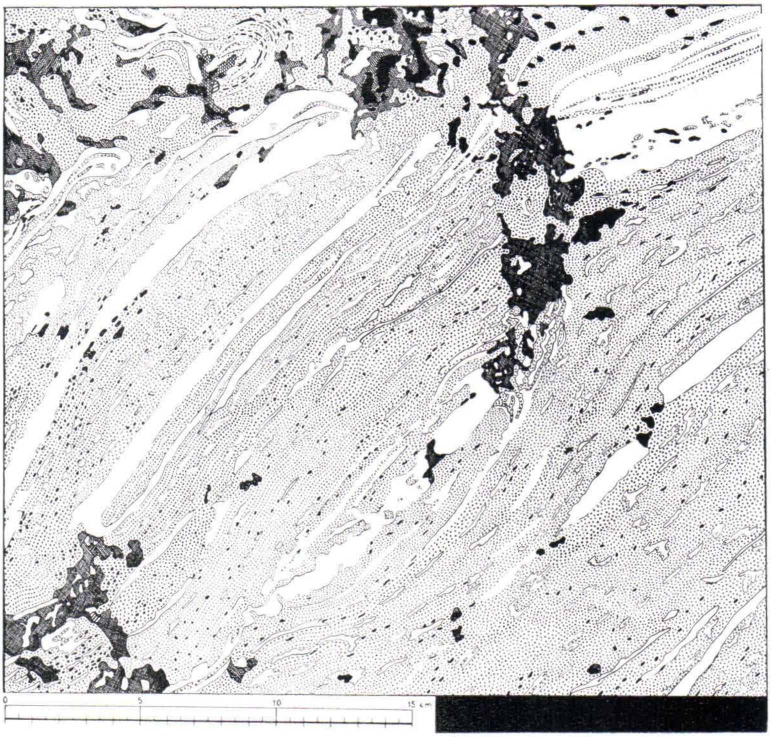
PLATE XII

Fig. a. Fragment of tremolite-skarn in ore. Tremolite is partly replaced by sulphides. Mökkivaara +250 level, Dr. 1. Polished section, ×5.

Fig. b. Relicts of silicate mineral in ore. Replacement (chalcopyrite-cubanite) beginning from centre of crystals. +285 level, drill hole K 441 depth 37.52 m. Polished section, ×390.

Fig. c. Corner of a pyrite crystal replaced along cleavage cracks by chalcopyrite. +285 level, drill hole K 437 depth 51.20 m. Polished section, ×65.

Fig. d. Chalcopyrite in pyrite. Replacement of pyrite beginning from centre parts of crystal. Sh I +250 level, Rs. 9 a sublevel 3. Polished section, ×5.



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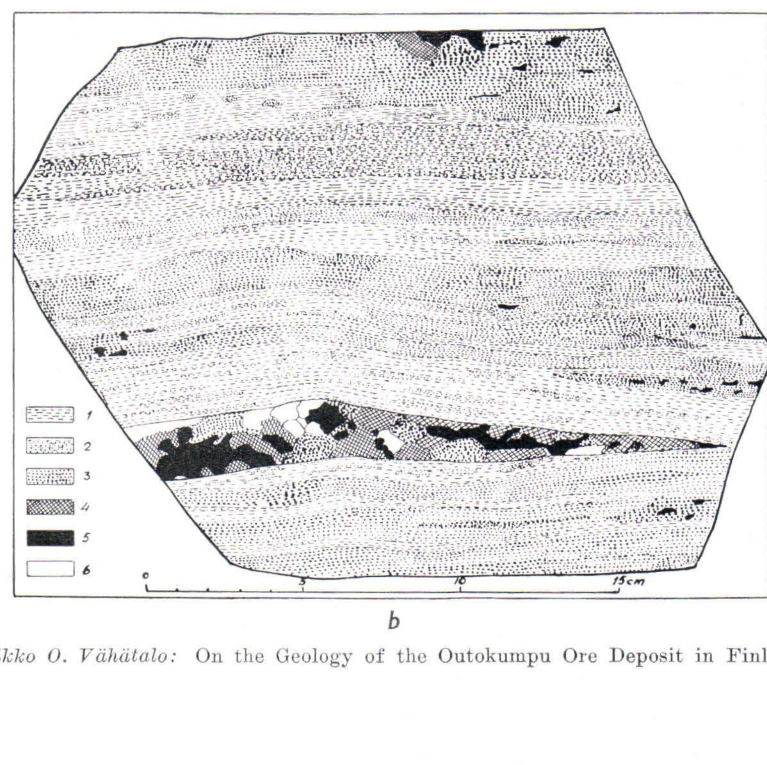

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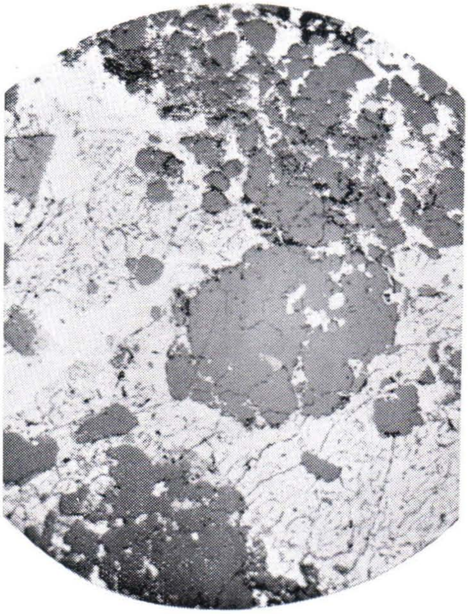

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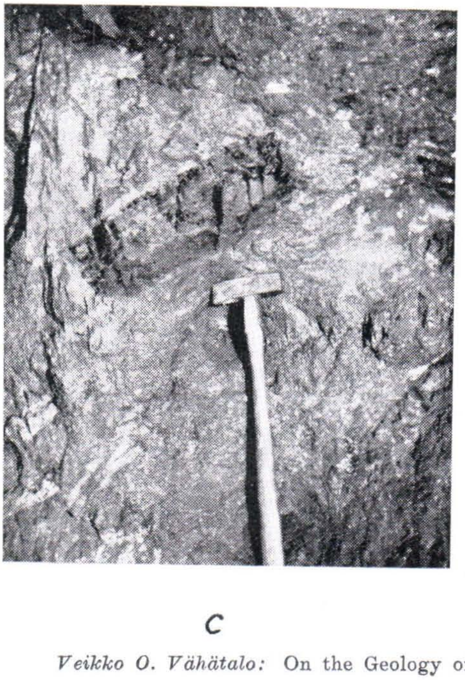

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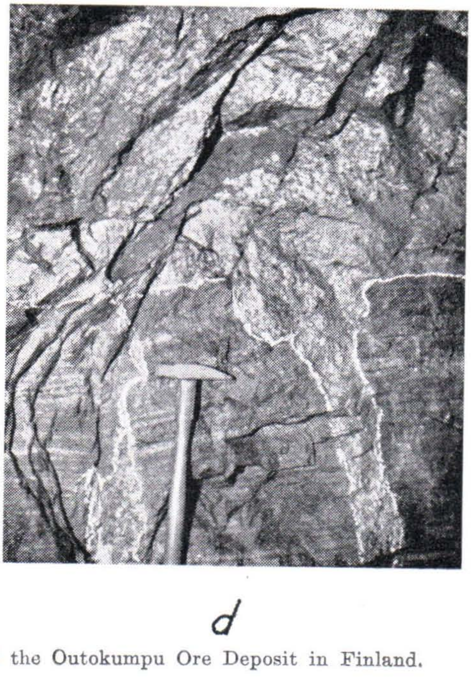

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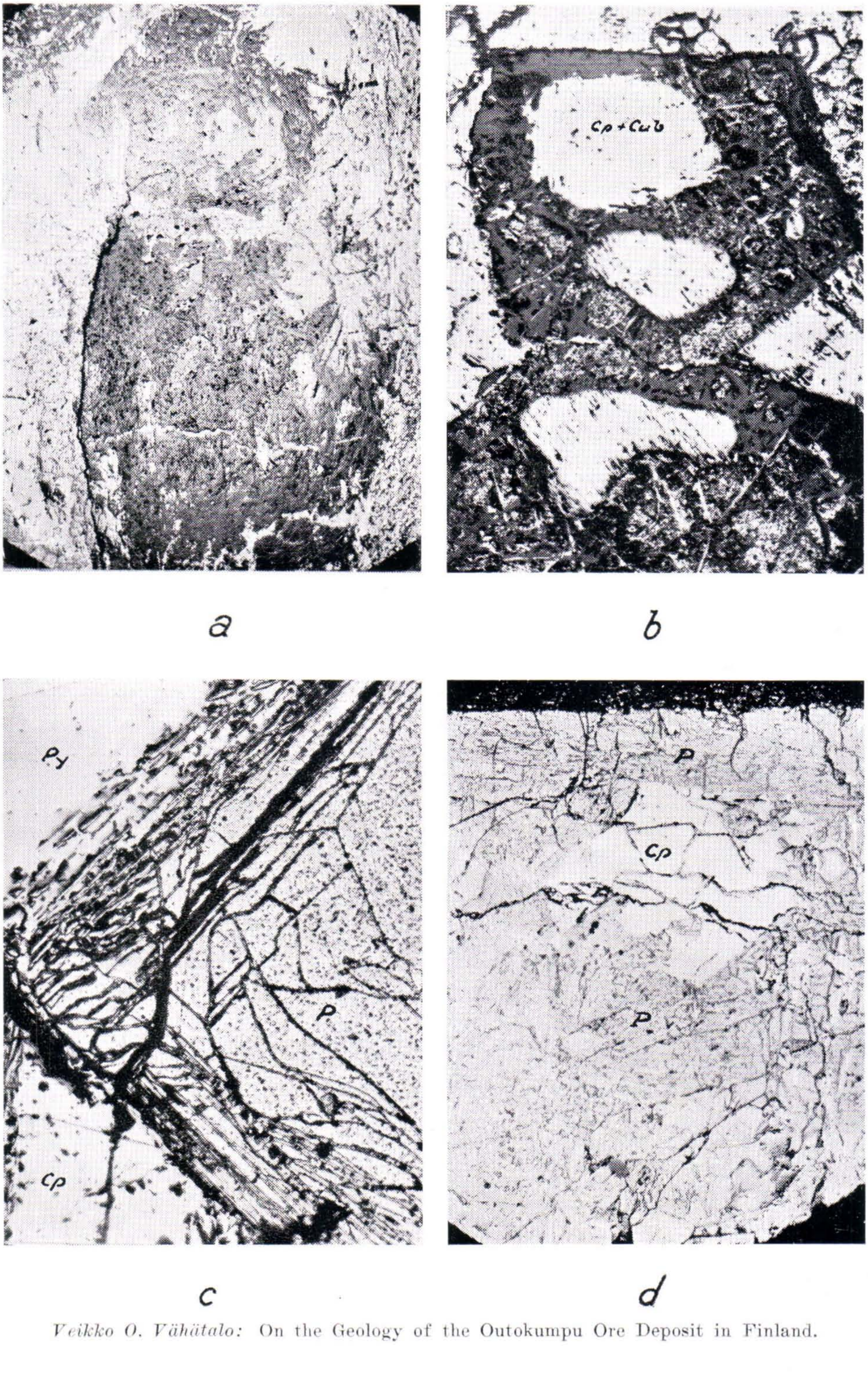

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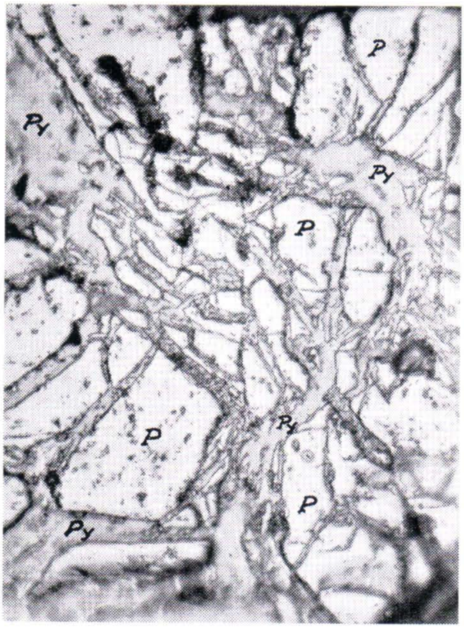

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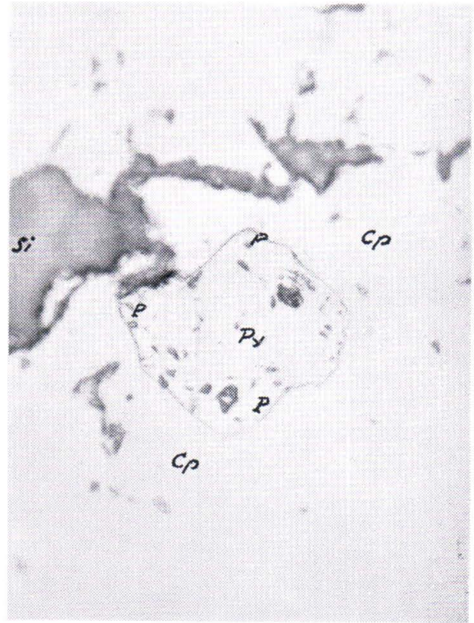

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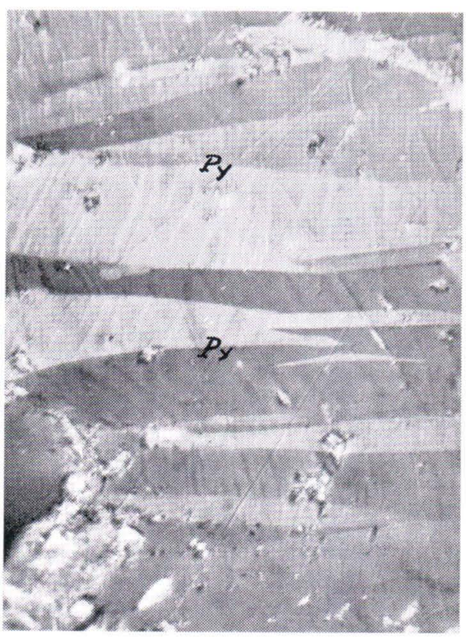

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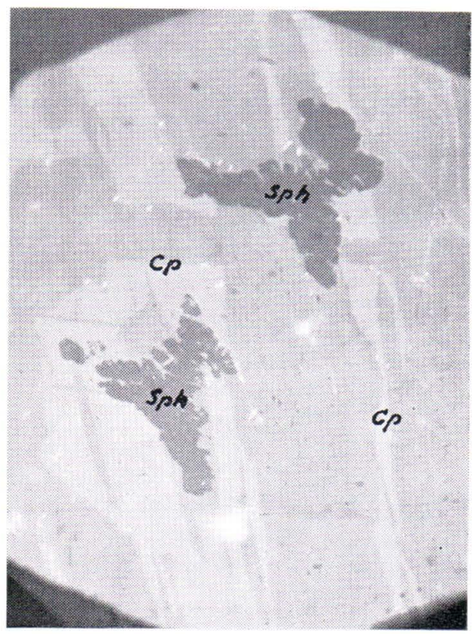

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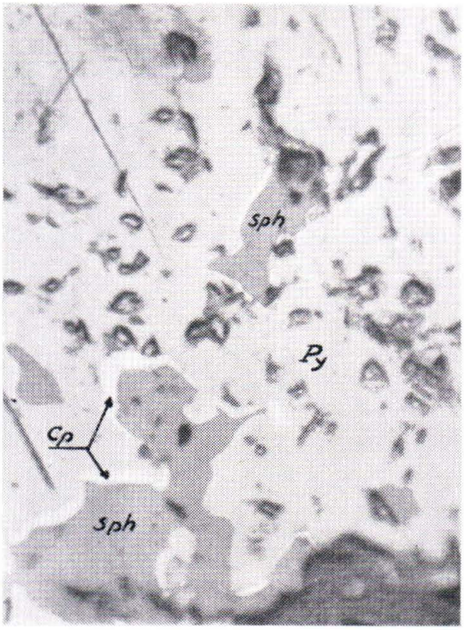

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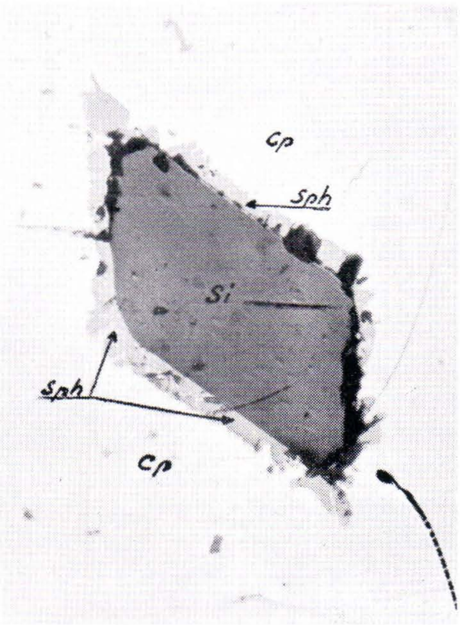

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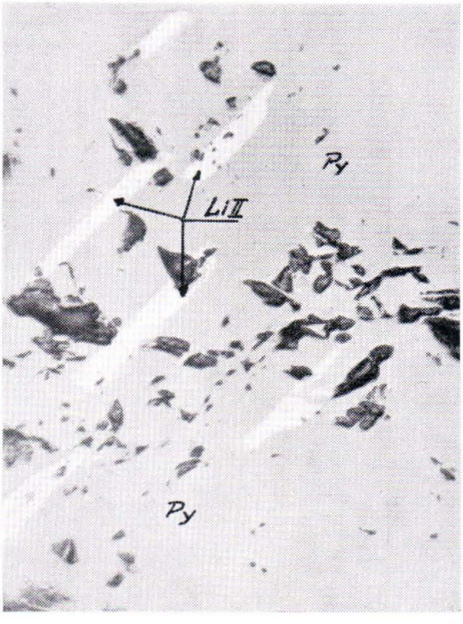

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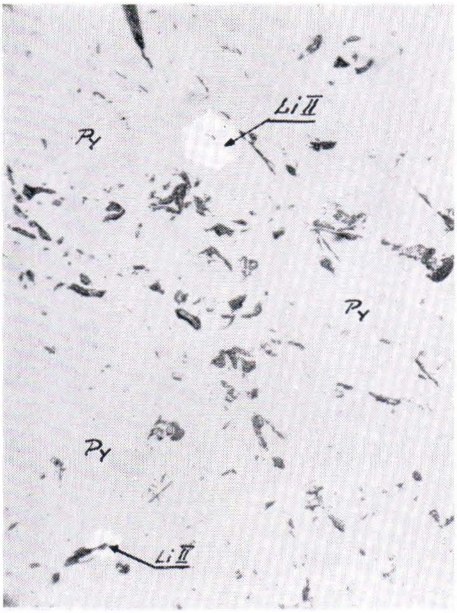

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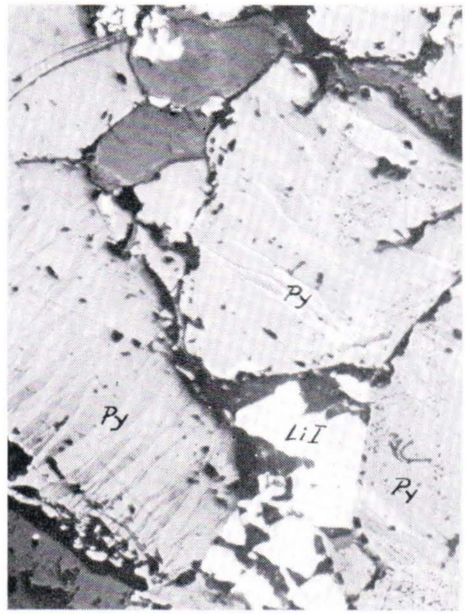

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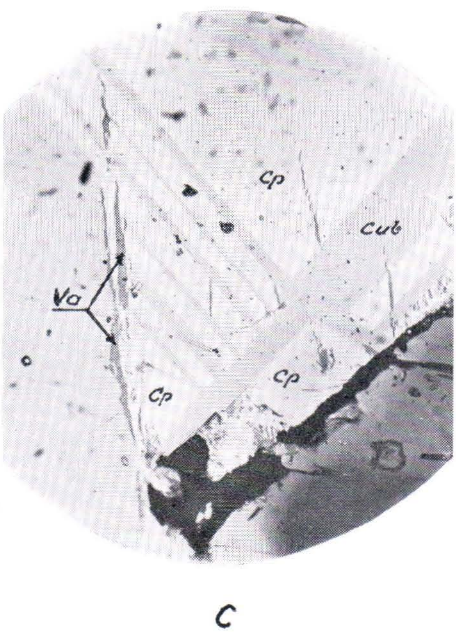

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EXPLANATIONS

PLATE XIII

Fig. a. Pyrite replaced by pyrrhotite along cracks. Sh I +250 level, Rs. 2 b, sublevel 5. Polished section, ×575.

Fig. b. Quadratic pyrrhotite grain in chalcopyrite. Pyrite relicts as »atolls» at borders of pyrrhotite. +250 level, drill hole K 529, depth 10.30 m. Polished section, ×300.

Fig. c. Pressure lamellae in pyrrhotite. Approximately perpendicular to these, an unmixing texture is noticeable in pyrrhotite. +285 level, drill hole K 543, depth 8.55 m. Polished section, × 300. Nicols crossed.

Fig. d. Skeletons of »star-like» sphalerite in chalcopyrite. Twinning lamellae is noticeable in chalcopyrite. +285 level, drill hole K 521, depth 36.40 m. Polished section, ×300. Nicols crossed.

PLATE XIV

Fig. a. A rim of chalcopyrite between pyrrhotite and sphalerite. Sh I +250 level, underhand crosscut Dr. 1. Polished section, ×300.

Fig. b. Amphibole crystal as crystallization centre for sphalerite in chalcopyrite. +285 level, drill hole K 422, depth 10.16 m. Polished section, ×150.

Fig. c. Linnaeite I (white) in pyrrhotite (grey). +285 level, drill hole K 446, depth 24.65 m. Polished section, ×300.

Fig. d. Linnaeite II (white) as laths in pyrrhotite (grey). +285 level, drill hole K 446, depth 24.65 m. Polished section, ×300.

PLATE XV

Fig. a. A hexagonal section of linnaeite II (white) in pyrrhotite (grey). +285 level, drill hole K 474, depth 0.56 m. Polished section, ×300.

Fig. b. Linnaeite I (white) in pyrrhotite with unmixing texture (dark grey with flame texture). +285 level, drill hole K 388, depth 18.00 m. Polished section, ×130, etched with (CrO_3 + HCl).

Fig. c. Valleriite (dark grey) in cubanite (grey) bearing chalcopyrite (pale grey). Black represents silicate. Sh I +250 level, Rs. 2 b, sublevel 5. Polished section, ×300.

Fig. d. Linnaeite vein (white) in pyrrhotite (grey). Sh I +250 level, Kaasila Rs. 1. Polished section, ×55.

EXPLANATIONS

PLATE XVI

Fig. a. Stannite (dark grey) in chalcopyrite (pale grey). Black grains represent silicate. +285 level, drill hole K 318, depth 20.85 m. Polished section, ×450.

Fig. b. Stannite rim (dark grey) surrounding a sphalerite skeleton (black) in chalcopyrite (pale grey). +285 level, drill hole K 586, depth 3.28 m. Polished section, ×600.

Fig. c. Stannite (grey) in sphalerite (dark grey). The pale grey parts are of pyrrhotite. +285 level, drill hole K 586, depth 3.28 m. Polished section, ×300.

Fig. d. Deformed galena grain in ore. Sh I +285, Dr. 9. Polished section, ×100.

PLATE XVII

Fig. a. Gold (white) associated with sphalerite (dark grey) in chalcopyrite (pale grey). +285 level, drill hole K 290, depth 7.00 m. Polished section, ×300.

Fig. b. Pentlandite (light grey) associated with pyrrhotite (dark grey). In pentlandite there occurs a small bravoitization along cleavage fissures (below to the left). +285 level, drill hole K 394, depth 29.74 m. Polished section, ×200.

Fig. c. Magnetite as inclusions in pyrite. +285 level, drill hole K 388, depth 15.45 m. Polished section, ×50.

Fig. d. Cubanite (pale grey) in cracks of unmixed pyrrhotite (dark grey) with flamelike lamellae. +285 level, drill hole K 388, depth 18.00 m. Polished section, ×400.

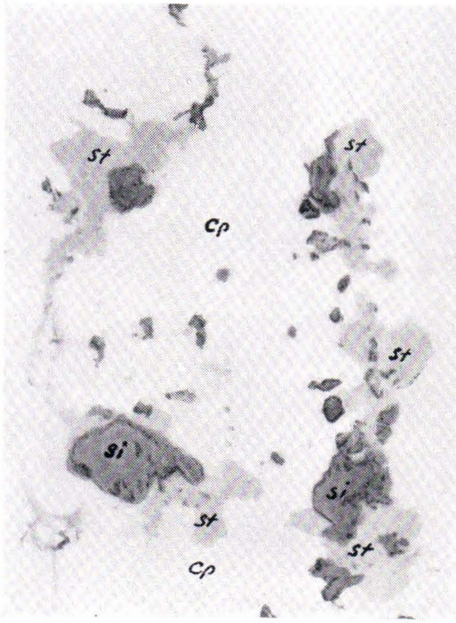
PLATE XVIII

Fig. a. Cubanite rim (grey) surrounding pyrrhotite (dark grey). Sh I +285 level, Rs. 4 Polished section, ×700. Oil-imm.

Fig. b. »Flame lamellae» texture in unmixed pyrrhotite. Sh I +285 level, Rs. 4. Polished section, ×700. Oil-imm.

Fig. c. Valleriite (dark grey below to the right) penetrating cubanite (grey), light grey is chalcopyrite. +285 level, drill hole K 281, depth 77.35 m. Polished section, ×300.

Fig. d. A weathering cleavage in pyrrhotite (grey below to the right), Pentlandite (light grey to the left). Jyrinlietukka, drill hole 53 a, depth 79.65 m. Polished section, ×130.



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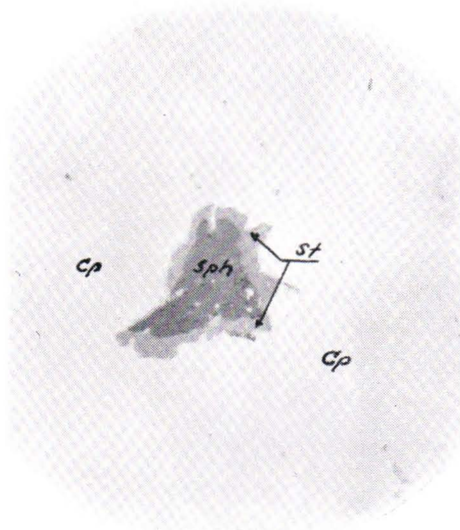

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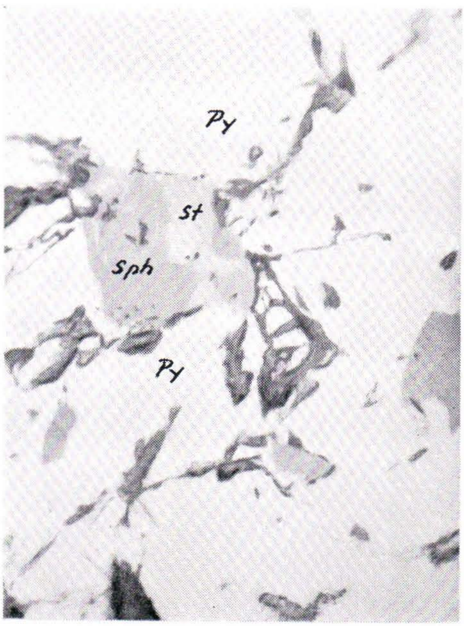

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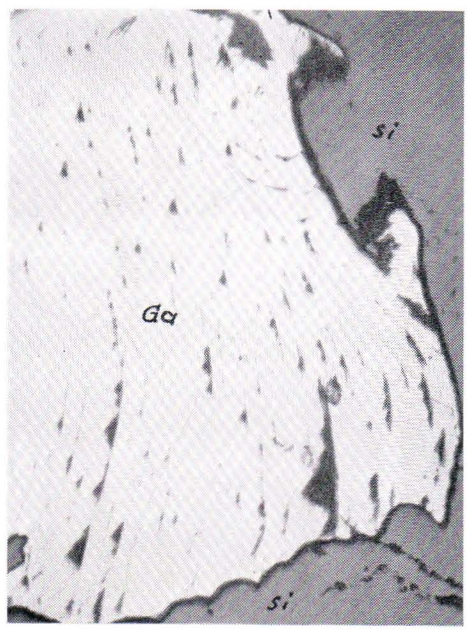

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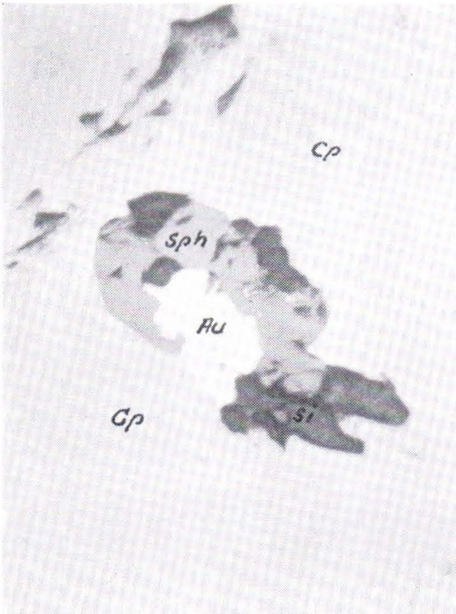

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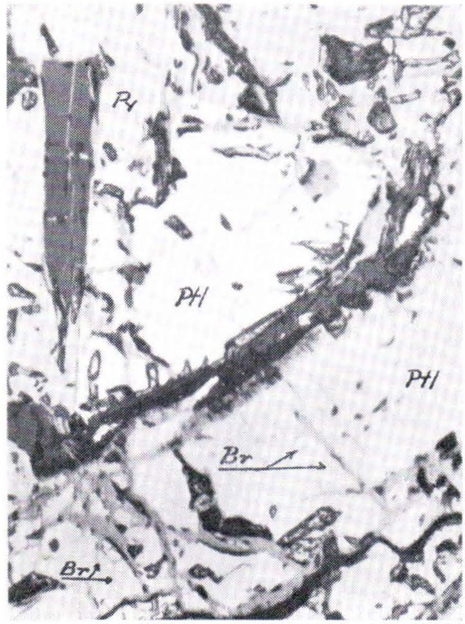

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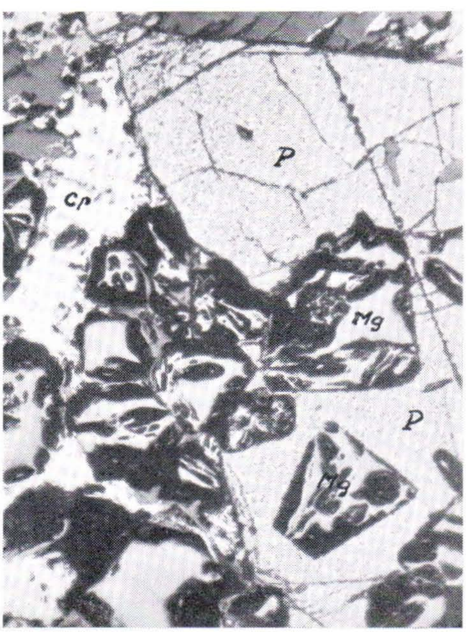

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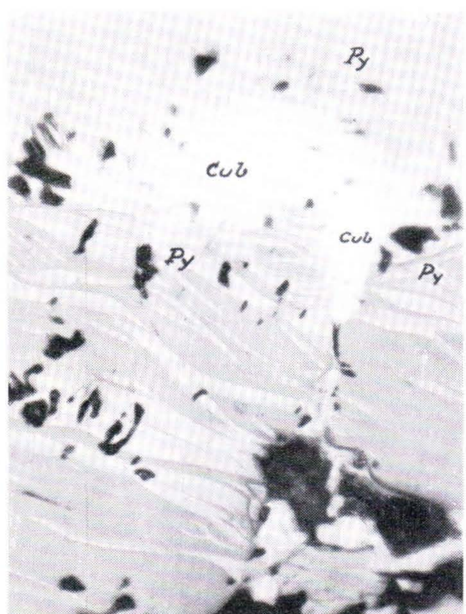

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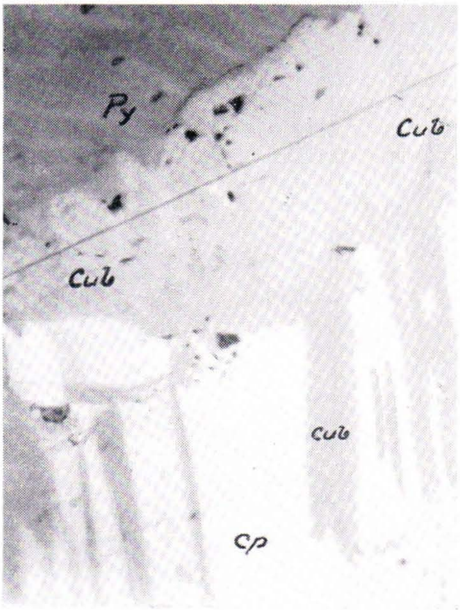
PLATE XVIII



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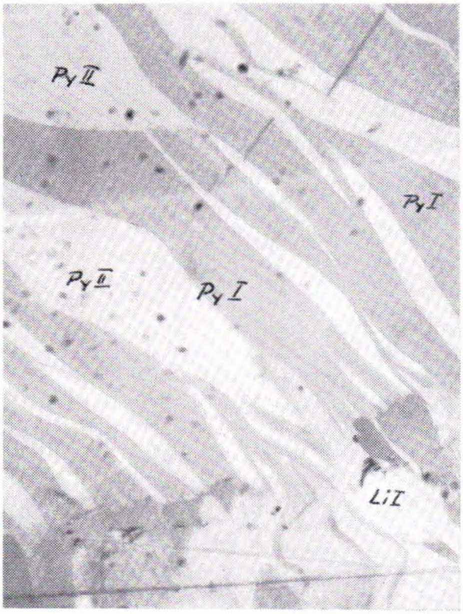

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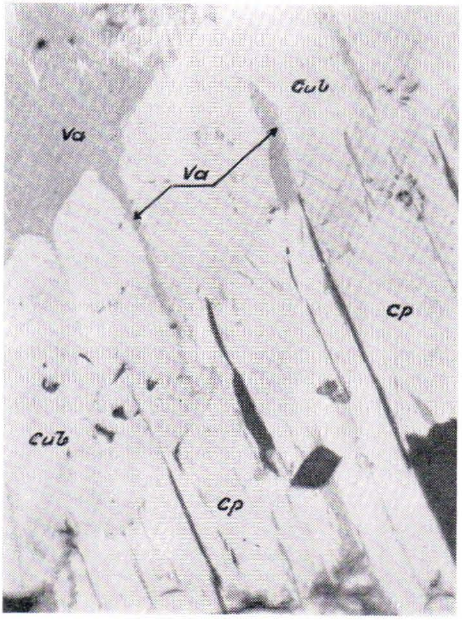

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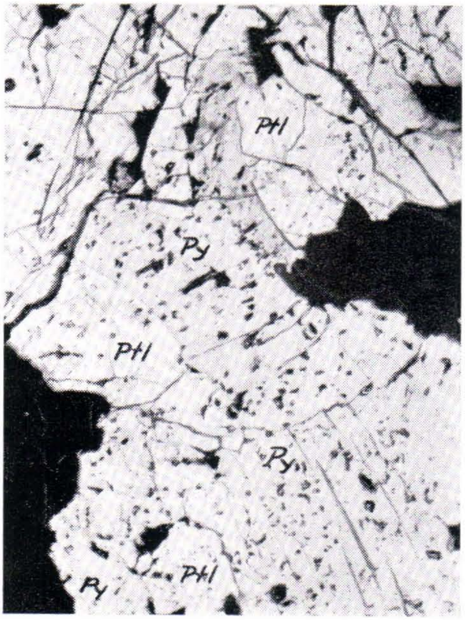

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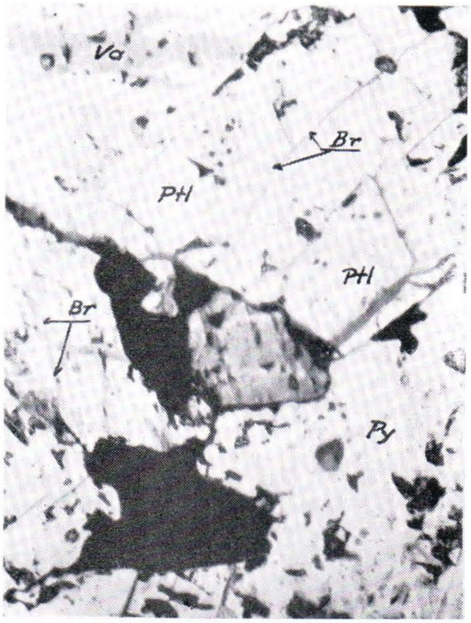

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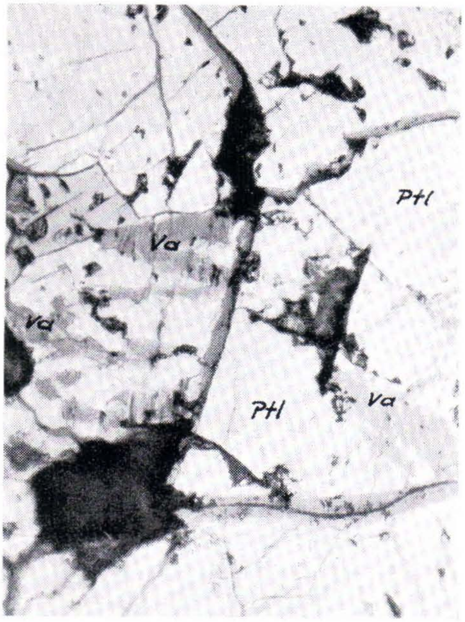

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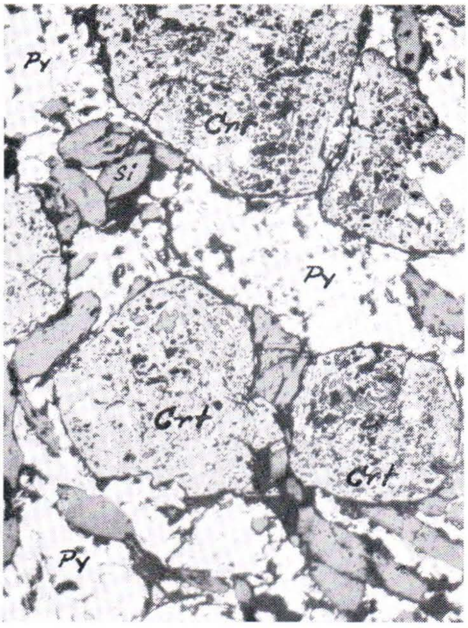

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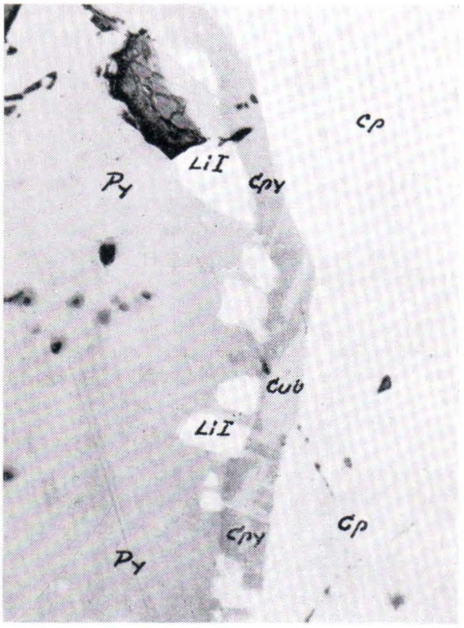

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EXPLANATIONS

PLATE XIX

Fig. a. Bravoite (dark grey) along cleavage fissures in pentlandite (light grey). Below to the right pyrrhotite (dark grey). Jyrinlietukka, drill hole 53 a, depth 79.65 m. Polished section, × 575.

Fig. b. Valleriite (dark grey) in pentlandite (light grey). Jyrinlietukka, drill hole 53 a, depth 79.65 m. Polished section, × 575.

Fig. c. Corroded chromite grains (grey) and pyrrhotite (light grey). Silicate crystals with amphibole habitus (dark grey). Jyrinlietukka, drill hole 53 a, depth 97.90 m.

Fig. d. Chalcopyrrhotite rim (dark grey) in contact between pyrrhotite (medium grey) and chalcopyrite. In pyrrhotite contact there occur some linnaeite grains (more light grey). Sh I +285 level, Rs. 5 helpraise 10. Polished section, × 450.

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*N:o 1.	Ramsay, Wilhelm und Nyholm, E. T. Cancrinitsyenit und einige verwandte Gesteine aus Kuolajärvi. S. 1—12. 4 Fig. 1895	—
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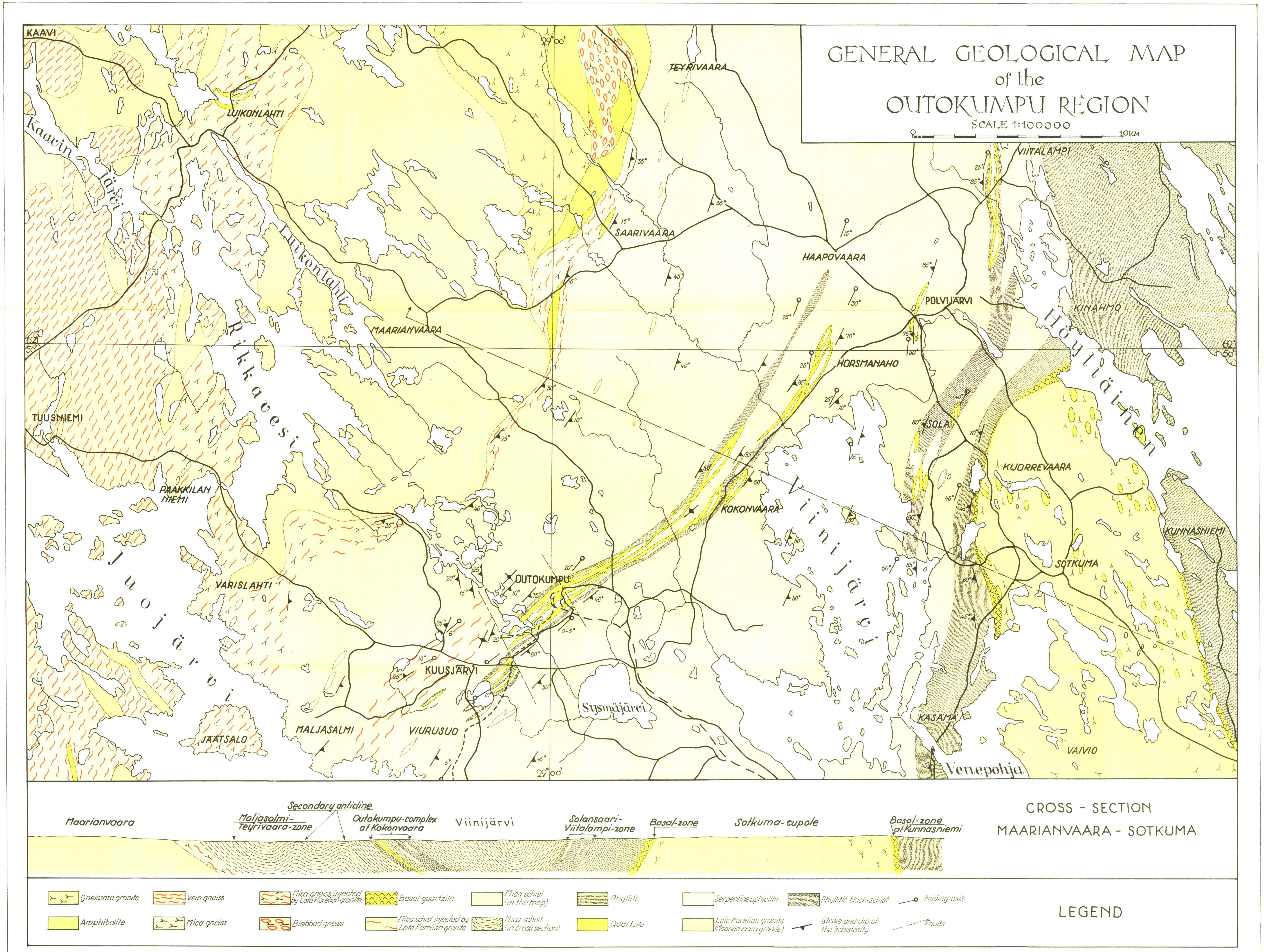

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