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THE PETOLAHTI DIABASE AND ASSOCIATED
NICKEL—COPPER—PYRRHOTITE ORE, FINLAND

BY
PENTTI ERVAMAA

WITH 23 FIGURES AND 2 TABLES IN TEXT AND 12 PLATES

ACADEMICAL DISSERTATION

HELSINKI 1962

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Helsinki 1962. Valtioneuvoston kirjapaino

PREFACE

This paper deals with the nickel-copper-pyrrhotite ore of Petolahti, which was discovered in 1957 by prospectors employed by the Geological Survey of Finland. The field work, in which the present author took part from the very beginning as a local geologist, was done in the years 1957—58. Subsequently, in 1959 and 1960, the author had the opportunity to carry out fairly thorough microscopic and other laboratory investigations of the material collected. For this as well as for the valuable support and critical suggestions given me in many ways during the course of the work, I extend thanks to my superior, Dr. Aarno Kahma.

At various stages during the course of the work, I received much valuable advice and guidance from my honored teacher, Prof. Martti Saksela, of the University of Helsinki, and this I wish to acknowledge with gratitude.

I am grateful also to the Foundation of the Outokumpu Company for assisting me financially as well as to a number of my colleagues on the staff of the Geological Survey for lending me a hand in my work. Mrs. Irja Huhta, M. A., Miss Kaija Karhunen and Messrs. A. Heikkinen, M. A., P. Ojanperä, M. A., and P. Väänänen, M. A., performed all the analyses appearing in the text, excepting the spectrographic analyses which were done by Mr. A. Löfgren, M. A. Prof. K. Neuvonen and Messrs. A. Vormaa and K. Hytönen carried out the powder X-ray determinations of several of the ore minerals.

In conclusion, it should be mentioned that the paper was translated into English by Mr. Paul Sjöblom, M. A.; and I am grateful to Dr. Vladi Marmo, executive director of the Geological Survey of Finland, for having kindly accepted my manuscript for publication in the series *Bulletin de la Commission géologique de Finlande*.

The Geological Survey of Finland, Otaniemi, November 1961.

Pentti Ervamaa

ABSTRACT

The diabase of Petolahti forms a lenticular, differentiated dike. The most basic differentiation product of the parent olivine-basaltic magma, the olivine diabase, contains variable amounts of disseminated pyrrhotite, pentlandite and chalcopyrite. The high-temperature exsolution products sometimes found in them in extraordinary abundance indicate that the sulfides referred to started to crystallize in an unusually high temperature as extensive solid solutions. The high solidification temperature is regarded as being connected with the hypabyssal character of the rock.

In the other ore types of the deposit, the sulfide veins and the disseminated wall rock of the diabase, the sulfides solidified at lower temperatures, which approached the high-hydrothermal phase.

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INTRODUCTION

In connection with prospecting operations carried out in the summer of 1957 by the Geological Survey of Finland, three large ore boulders were found in the western part of Petolahti (a commune in South Pohjanmaa, western Finland) consisting of serpentized olivine diabase. In addition, the boulders contained enough disseminated pyrrhotite, chalcopyrite and pentlandite to justify further explorations toward discovering the parent rock of the boulders.

During the autumn of 1957 magnetic, electromagnetic and gravimetric measurements were conducted in the near surroundings of the boulder finds with the result that several promising anomalies were met with. Since the bedrock in the area of the anomalies — as in the total area covered by the survey — was overlain by deposits of sand and till between four and six meters thick, an accurate estimation of the anomalies was possible only by means of diamond drilling. The drilling operations carried out in the years 1957—59 proved successful insofar as the parent rock of the boulders referred to was localized by the second drill hole. It was established, moreover, that the boulders had been transported from their parent rock a distance of only between 100 and 300 meters southward.

As the investigation proceeded, the ore body proved to be of relatively modest dimensions. Its length was estimated at 80—90, thickness at 4—9 and depth at 70—80 meters.

The ore body is associated with a shuttle-shaped, 5—80 meters thick diabase dike which, running N 65° W, cuts sharply across the foliation of the surrounding rocks belonging to the Bothnian supracrustal formation and is distinctly younger than they are. The diabase dike is more than 600 meters long, but an abundant ore content was noted only at its tapering, 5—11 meters thick ESE end, where the rock is considerably more basic than at the lens-like, ore-less core of the dike. Quite effective magmatic differentiation has thus taken place in the diabase. Since this in itself offers an interesting subject of study and since, in addition, it seems to be responsible for the formation of the ore, special attention has been focussed on the differentiation in the present paper.

The ore mineral paragenesis pyrrhotite + chalcopyrite + pentlandite and the ratio of the various metals contained in the Petolahti ore are typical of early magmatic sulfide deposits. Microscopic study of the ore minerals brought out, however, numerous interesting special features, such as the following exsolution textures fairly commonly met with in the Petolahti ore: in the pyrrhotite, two kinds of chalcopyrite lamellae as well as ordinary pentlandite flames; in the chalcopyrite various pyrrhotite, cubanite and pentlandite exsolution bodies; and in the pentlandite, chalcopyrite exsolution lamellae and pyrrhotite blebs.

Many of the exolutions mentioned are foreign to the nickel-copper ores associated with the subsilicic plutonic rocks. On the other hand, Pauly (1958) recently described numerous similar exsolution textures in his study of Igdlukúnguaq ore which is connected with a basaltic dike. On the basis of the observations made of the Igdlukúnguaq and the Petolahti occurrences, a number of the exsolution textures referred to are characteristic of early magmatic nickel-copper ores associated with near-surface subsilicic intrusions which have crystallized principally under conditions of magmatic diabase facies.

It should be pointed out, furthermore, that several nickel-copper ores associated with rather small hypabyssal intrusions are known to exist in different parts of Europe, including Sohland a. d. Spree in East Germany and a number of the deposits of the Dillmulde area in southwestern Germany. Although, on the basis of both descriptions in the literature and my own observations, they deviate from the Petolahti deposit in numerous respects, they nevertheless, like the Igdlukúnguaq ore, afford quite a few interesting points of comparison. In addition to the ones referred to in the foregoing, a brief comparative description of a Finnish deposit is also included in the concluding part of the present paper.

MAIN GEOLOGICAL FEATURES OF THE AREA

As the Petolahti diabase and its near surroundings are totally covered by thick deposits of sand and till, the picture of the bedrock of the area remains perforce comparatively deficient. On the basis of diamond drillings and geophysical measurements as well as of observations made of the nearest outcrops, situated a few miles away, it may be stated that the principal rock in the area is a mica gneiss of relatively even quality. It is the prevailing variety of rock in the entire Bothnian supracrustal formation to which the bedrock of the Petolahti area also belongs (Fig. 1, p. 10).

The chief minerals of the mica gneiss are here, as elsewhere, plagioclase An_{15-30} , quartz and biotite as well as, in spots, garnet. The most common minor constituents are graphite, pyrite, pyrrhotite and oxide minerals, with apatite and sphene occurring as accessories. Potash feldspar very rarely occurs in the rock. The mineral composition of one sample is represented on p. 30.

As in many other places, too, the mica gneiss in the Petolahti area is often converted into migmatitic veined gneiss. In such cases the rock contains an abundance of concordant veins of granitic and pegmatitic material. Some of the pegmatitic veins may be several meters thick. A conspicuous metasomatic alteration has taken place in the mica gneiss component of the migmatites. Microcline, sericite and sillimanite (Saksela, 1935) occur as metasomes. According to Saksela (op. cit.), the regional occurrence of veined gneisses is quite often associated with granitic intrusions belonging to the synorogenic series, which are likewise met with abundantly in the Petolahti area.

The strike of the foliation of the mica gneiss in the immediate surroundings of Petolahti varies between N 0—35 W, the dip being 10—40° E or NE. The fold axes run, according to Saksela (1935), east and west in an extensive area in the surroundings and dip 40—70° to the east.

The otherwise very monotonous bedrock of the area receives extra color from pyroxene and hornblende gneiss, which are met with as thin — at most a few meters thick — intercalations of mica gneiss. Graphite-rich, pyrite- and pyrrhotite-bearing black schist layers are also common. Drillings

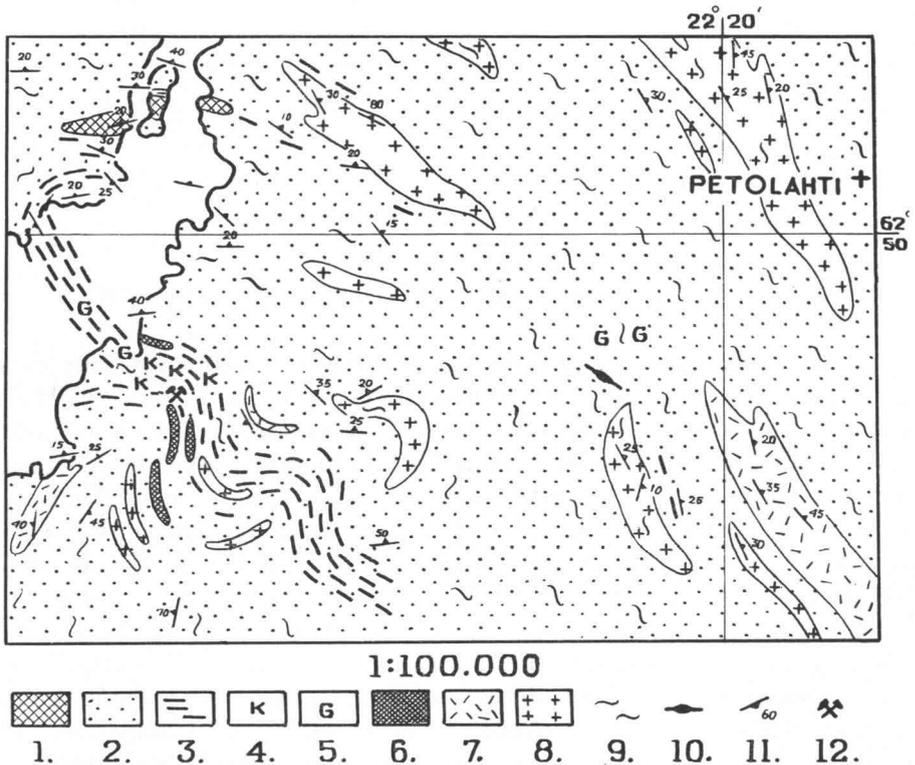


Fig. 1. Geological map of Petolahti area (Nykänen, 1960). 1. Amphibolite; 2. Mica gneiss; 3. Pyroxene gneiss, quartz-feldspar schist and amphibole-rich intercalations; 4. Skarn and limestone; 5. Graphite-bearing rock; 6. Ultrabasic rock; 7. Quartz diorite and granodiorite; 8. Microcline granite; 9. Granitic veins; 10. Diabase dike of Petolahti; 11. Strike and dip of foliation; 12. Lead mine of Korsnäs.

have led to their being observed, along with pyroxene gneiss and hornblende gneiss intercalations, also in the immediate proximity of the diabase dike to be described in the following.

A few miles southwest of Petolahti, in the surroundings of the lead mine of Korsnäs, the bedrock is considerably more variable. Pyroxene gneiss, quartz feldspar schist and amphibole-rich intercalations as well as skarn and limestone lenses in mica gneiss are common in the locality. Ultrabasic rocks are represented by a few synorogenic intrusions. Abundant hydrothermal mineralization of galena is met with in certain fault zones, abruptly cutting the structures of the surrounding rocks.

THE DIABASE DIKE

The diabase dike, with which the nickel-copper-pyrrhotite ore of Petolahti is associated, cuts sharply across the structure of the adjacent rocks in a N 65° W direction while dipping an average of 80° SSW. Except for slight shearing that has taken place in the proximity of the contacts, the diabase is conspicuously weakly disturbed, deviating also in this respect quite distinctly from the schistose rocks surrounding it.

On the basis of the results obtained by means of geophysical explorations and drillings, the length of the diabase is at least 600 meters and its thickness 5—70 m. In the core of its lenticular middle part, it consists of medium-grained quartz diabase, which grades over by degrees toward the margins and thinner terminal parts into a finer-grained and, at the same time, more mafic type of rock. The fine-grained border zone of the diabase generally measures a few dozen centimeters in thickness. The most fine-grained type is met with in a few aphanitic diabase apophyses cutting across the mica gneiss.

The diabase has caused marked contact metamorphism in its wall rock, the contact zone being in places more than ten meters thick. On the basis of this and the previously mentioned circumstances, the diabase may be judged to be distinctly younger than the surrounding supracrustal rocks. For lack of suitable objects of comparison, no precise age determination is, however, possible. The similarity of the mineral composition and, in part, mode of occurrence, too, to the olivine diabases of the Satakunta and Vaasa archipelago nevertheless give grounds for assuming that the Petolahti diabase can be compared in respect to age to these diabases. At least the former are considered to be of Jotnian age (Sederholm, 1897).

Nor has it been precisely determined at what depth the diabase has solidified, although its hypabyssal character appears to be quite evident. This is indicated, e. g., by the clear ophitic texture of the rock, the fine-grained border zones and the aphanitic apophyses. Just as is pointed out in greater detail later on, in the part dealing with the ore minerals, a number of the exsolution textures met with in the sulfides likewise chiefly suggest solidification occurred under conditions of magmatic diabase facies.

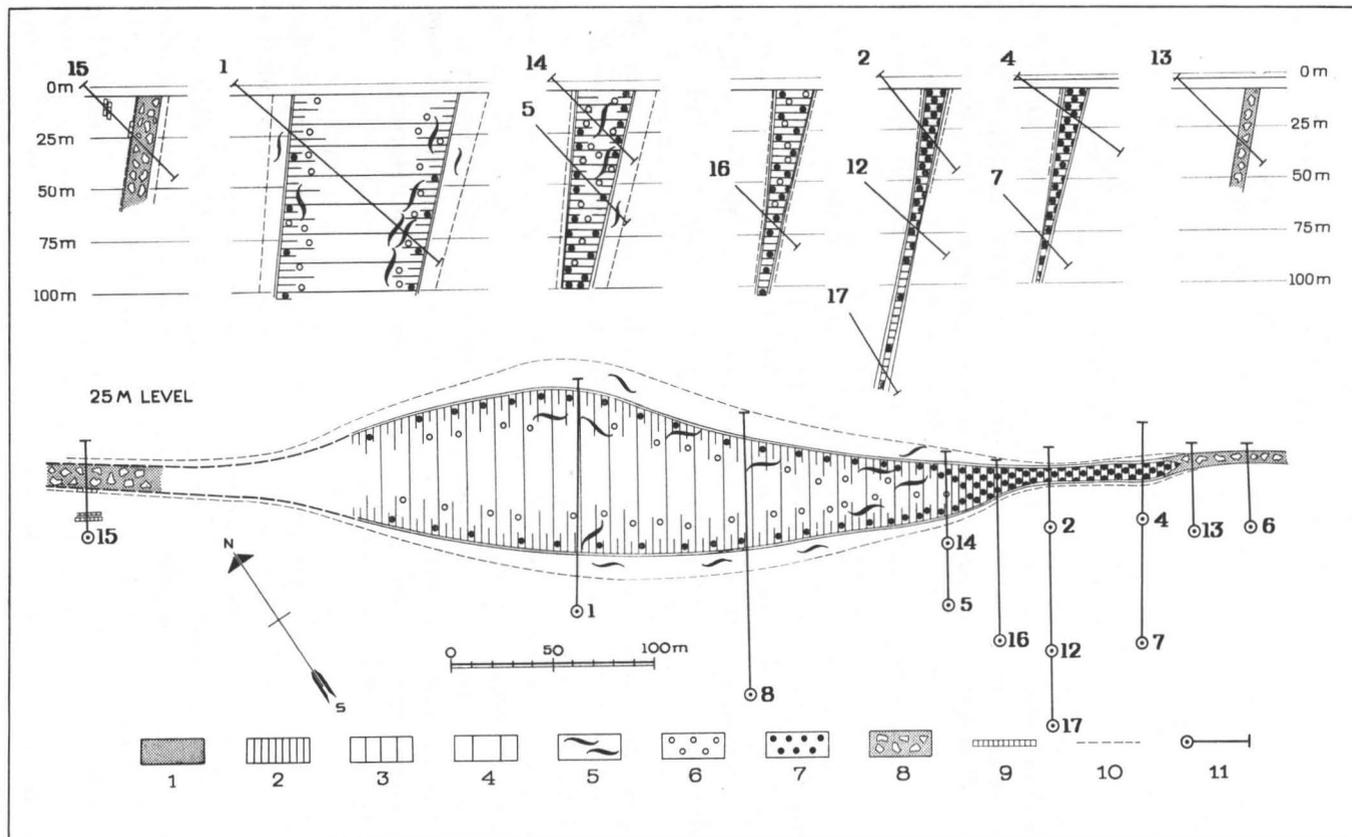


Fig. 2. Seven vertical cross sections and a horizontal cross section at the 25 m level of the Petolahti diabase. 1. Fine-grained border zone of diabase; 2. Olivine diabase; 3. Pyroxene diabase; 4. Quartz diabase; 5. Granophyric veins; 6. Calcite-quartz amygdules; 7. Disseminated sulfides; 8. Gneiss xenoliths; 9. Aphanitic diabase apophysis; 10. The outer boundary of the contact zone; 11. Drill hole.

DIABASE TYPES AND ROCKS ASSOCIATED WITH THE DIABASE

As mentioned in the foregoing, the diabase dike of Petolahti is quite inhomogenous not only in grain size but also in mineral composition. On the basis of these differences detectable even megascopically, the following main types can be distinguished:

- Quartz diabase
- Pyroxene diabase
- Sulfide-bearing olivine diabase
- Fine-grained border zones of the diabase
- Aphanitic diabase apophyses

Further, the following types of rock are closely associated with the diabase:

- Granophyric veins
- Contact-metamorphic wall rock of the diabase

The occurrence of these and the various types of diabase is shown in Fig. 2, p. 12.

QUARTZ DIABASE

According to observations made from drill samples, the core of the Petolahti dike consists of medium-grained quartz diabase, which is at the same time the main variety of rock. Its chief minerals are plagioclase and diopsidic augite. Minor constituents include a slight amount of quartz, potash feldspar, albite, calcite, biotite, ilmenite and magnetite, with apatite and sphene occurring as accessories. Secondary alteration products of the diopsidic augite are, consistently, green hornblende and, sometimes, also talc. The biotite has in part altered to chlorite. The chemical composition of the rock is presented in Table I, 4, p. 31, the mineral composition of two of the samples being presented in Fig. 3, 1 and 2, p. 14. On the basis of its chemical composition and regular quartz content, amounting to a few per cent, the diabase type in question will here be referred to as quartz diabase.

Plagioclase, the mineral clearly occurring in greatest abundance in the rock, is met with as 1–5 mm long, unoriented laths, which give the rock a distinctly ophitic texture (Fig. 5, p. 15). Under the microscope a strongly developed zonal structure is often to be seen in the plagioclase grains. According to maximal extinction angles of twinning lamellae in symmetrical sections, the anorthite content of the core of the grains is An_{60-65} , decreasing

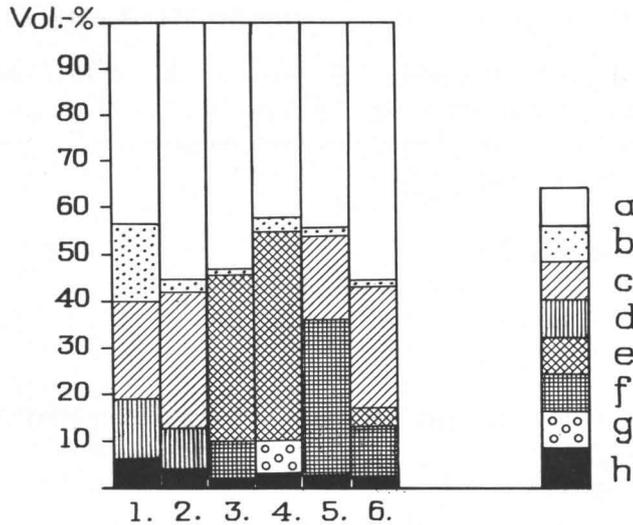


Fig. 3. Variation in the mineral composition of diabase in drill hole 1. — a. Plagioclase; b. Quartz + alkali feldspars; c. Diopsidic augite; d. Hornblende + biotite + chlorite; e. Talc + chlorite; f. Olivine + serpentine; g. Calcite; h. Ore minerals.

1. Quartz diabase, 31 m from the contact.
2. Quartz diabase, 14.5 m from the contact.
3. Altered pyroxene diabase, 4 m from the contact.
4. Conspicuously altered pyroxene diabase, containing calcite amygdales, 3.5 m from the contact.
5. Olivine diabase, 0.6 m from the contact.
6. Fine-grained border zone of the diabase, 0.1 m from the contact.

at the rim to An_{40} , and in the case of a few grains to as low as An_{30} . As shown in Fig. 5, the edges of the plagioclase grains are usually very irregular. In cores richer in anorthite, on the other hand, beautifully developed idiomorphic forms are often to be seen. Judging by this, it would seem that the plagioclase was the first of the chief minerals in the rock to begin crystallizing, but the marginal parts of the grains crystallized at just about the same time as the other principal mineral of the rock, the diopsidic augite.

The augite generally occurs as xenomorphic grains that are appreciably smaller than the plagioclase laths. Only a few grains are bounded by their own crystal faces. In thin section the augite is a pale brownish hue and not pleochroic. According to the optical properties: $N_x = 1.694$, $N_z = 1.720$, $N_z - N_x = 0.026$, $ZAc = 38-41^\circ$ and $2V_z = 46-52^\circ$ the pyroxene involved consists of diopsidic augite relatively poor in iron (Winchell & Winchell, 1951).



Fig. 4. A glacial boulder of Petolahti Ore (in middle), 100 m south of the outcrop. Note the typical surface weathering of diabase. In the background, the old Korsnäs—Petolahti—Vaasa road.

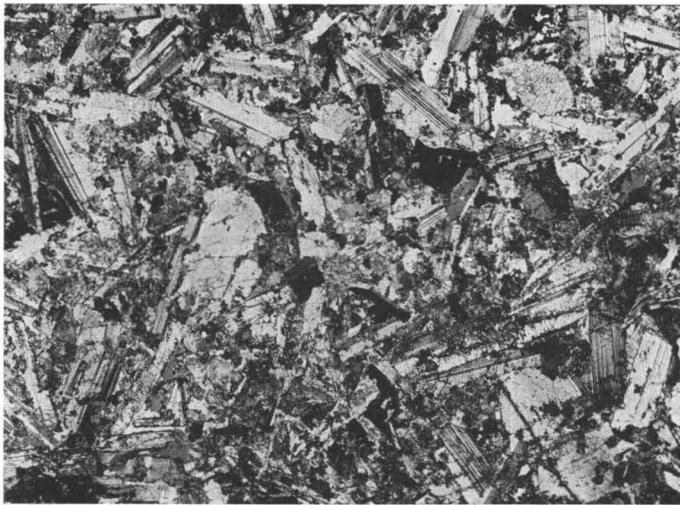


Fig. 5. Thin section, $\times 8$, nic. +. Photo E. Halme. Quartz diabase from the core of the dike, 31 m from the contact. In the interstices of the plagioclase laths, small grains of diopsidic augite and granophyric intergrowth of quartz and alkali feldspars. Drill hole 1.

Among the minor constituents in the rock, the most abundant, quartz, potash feldspar and albite, occur as a granophyric intergrowth, in conjunction with which there are met with in most cases slight amounts of calcite and biotite, too, in addition to some sporadic sulfide grains. The fine-grained material composed of the minerals mentioned, varying in amount from 4 to 16 Vol.-%, fills the interstices of the plagioclase and augite grains and was the very last of the constituents of the rock to solidify. As regards the mineral composition of the granophyric intergrowth, it should be mentioned, furthermore, that the ratio of the potash feldspar and albite contents in it is approximately 3:1, as has been ascertained, e.g., by means of the etching test of the potash feldspar carried out with a sodium cobaltinitrite solution.

As pointed out, the quartz diabase contains sulfides in only very scanty amounts. On the other hand, oxide minerals, ilmenite and titanomagnetite, amount to 4—8 Vol.-%. They occur as evenly disseminated roundish grains measuring 1—3 mm in diameter.

Here and there the quartz diabase contains fractures filled with carbonate. These fracture veins vary in thickness between fractions of a millimeter and a couple of centimeters. An analysis (P. Ojanperä) made from one such vein yielded the result:

TiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	1.82 %
MgO	0.71 »
CaO	52.64 »
CO ₂	42.06 »
Insoluble	2.20 »
	<hr/>
	99.43 %

According to the analysis, the carbonate is pure calcite. The insoluble part apparently consists of quartz and chlorite, which regularly occur to some extent in conjunction with calcite.

With the exception of the above-mentioned fractures, the quartz diabase exhibits no signs whatsoever of deformation. Furthermore, the autometamorphic alterations of the minerals are comparatively slight, and in this respect the rock distinctly deviates from the more mafic marginal and terminal portions of the diabase. To a certain extent, however, the diopsidic augite has changed, starting from the edges of the grains, to light green hornblende or chlorite. More seldom has the augite changed to coarse talc.

Like the augite, the other mafic mineral of the rock, biotite, has also partially undergone alteration to chlorite. With the exception of weak saussuritization, the plagioclase, on the other hand, has remained fairly unaltered, as has the primary texture of the rock, too.

PYROXENE DIABASE

Proceeding from the core of the diabase toward the borders of the dike, the rock becomes gradually finer of grain and its texture more poikilophitic. At the same time, there appear in the rock sparse serpentine aggregates, which, judging by the relicts, had originally consisted chiefly of rhombic pyroxene as well as partly of olivine. On the other hand, the granophyric alkali feldspar-quartz intergrowth decreases in quantity considerably, so that, judging by its mineral composition, the rock as a whole is distinctly more basic than at the core of the diabase lens. A clear change also takes place in the proportions of the ore minerals represented in the rock: toward the borders the oxide minerals decrease markedly, whereas the sulfides increase slightly. The changes in mineral composition involved are revealed most clearly by Fig. 3, (p. 14), in which the pyroxene diabase is represented by samples 3 and 4.

A clear change can be observed not only in the ratio of the minerals and in the texture of the rock but also in the composition of individual minerals. The plagioclase, which is still obviously the most abundant mineral, occurs as sharp-edged, 1—2 mm long laths surrounded or poikilolithically enclosed by xenomorphic augite grains measuring 1—6 mm in diameter. According to the maximal extinction angles of symmetrical sections, the anorthite content of the plagioclase in the cores of the grains is An_{60-65} and along the borders An_{45-55} , which means that on the whole it is somewhat richer in anorthite than at the core of the dike. A change in composition could be noted also in the diopsidic augite. With a smaller birefringence, extinction angle of $Z \wedge c = 36^\circ$ and axial angle of $2V_z = 43-48^\circ$, it is somewhat richer in magnesium than in the case of quartz diabase.

The pyroxene diabase under discussion, met with as an intermediate zone 4—8 m thick around the core, is further characterized by the conspicuous autohydration it has undergone. Owing to its influence, the primary minerals of the rock, with the exception of plagioclase, have almost totally changed to secondary hydrous minerals. The most abundant of the mafic minerals, the diopsidic augite, has — with the exception of slight remnants — changed to talc of a pale green hue. For the most part, the talc occurs as a fine-scaled aggregates but in many cases also as large crystals, in which the form of the original augite grain has been preserved intact. Along the edges of the talc grains there often occurs a thin border of chlorite, which in thin section is a very pale greenish hue and in the majority of cases wholly isotropic.

In most cases the rock also contains a minor percentage of coarse-grained serpentine. This is evidently a variety of antigorite called bastite

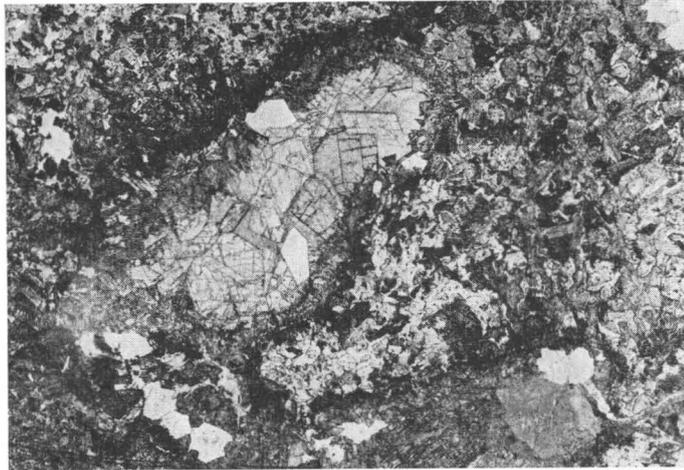


Fig. 6. Thin section, $\times 6$, nic. +. Photo E. Halme. Oval calcite-quartz amygdales in strongly altered pyroxene diabase. The amygdales are surrounded by a rim of chlorite (black). White grains are quartz. Drill hole 14, 2 m from contact.

deriving from the rhombic pyroxene. Sparse olivine grains have totally changed to fine-flaked serpentine, which appears pale green in thin section.

In contrast to the mafic minerals, the plagioclase is usually quite well preserved. Nevertheless, within the immediate proximity of the calcite-quartz amygdales contained in the rock, it has undergone marked saussuritization or, starting from the cleavages, has been replaced, in many cases altogether, by very fine-grained chlorite. The original form of the plagioclase laths remains clearly recognizable, however, as does the ophitic texture of the rock.

The most characteristic component of strongly altered pyroxene diabase is, however, calcite, the content of which in places exceeds 15 Vol.-%. It occurs as round or as oval, 1—20 mm-long amygdales whose rims are usually quite fine-grained but whose cores, again, are coarser. In addition to calcite, the amygdales often contain idiomorphic quartz crystals as well as small scales of talc and serpentine, sometimes also pyrrhotite, chalcopyrite, pentlandite and pyrite (Fig. 6, p. 18).

The following result was obtained through an analysis of the material constituting the calcite-quartz amygdales described in the foregoing (P. Ojanperä):

TiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	1.72 %
MgO	2.10 »
CaO	38.39 »
CO ₂	32.40 »
Insoluble	24.87 »
	<hr/>
	99.48 %

According to the result of the analysis, the carbonate in this case, too, consists of practically pure calcite.

SULFIDE-BEARING OLIVINE DIABASE

As pointed out, above-described conspicuously altered pyroxene diabase is met with along both margins of the thick core of the diabase lens as a zone 4—8 m thick. It is not, however, directly bounded by the fine-grained border, for between them runs a thin zone of more mafic rock. It has an olivine content of 20—35 Vol.-% and in general is only weakly altered. It should further be noted that the rock consistently contains a slight amount of disseminated sulfides, mainly pyrrhotite, chalcopyrite and pentlandite. On the basis of its mineral composition (Fig. 3, 5, p. 14) and texture the rock type in question will here be termed sulfide-bearing olivine diabase.

The thickness of the olivine-rich zone is only 0.5—1 m in the lenticular middle part of the dike. Its sulfide content is also quite small, averaging about 1—3 Vol.-%. Toward the tapering southeastern end of the dike, however, the olivine-rich zone gradually grows ever thicker and simultaneously richer in sulfide. In cross-sections 4—7, 2—12—17 and 16 the diabase as a whole represents this type with the exception of the fine-grained border zones. In the cross-sections referred to, the dike is 4—9 m thick and contains the previously mentioned sulfide minerals to the extent that it can be regarded as nickel-copper ore, though, to be sure, rather poor of grade (Fig. 2, p. 12).

The sulfide-bearing olivine diabase is relatively fine-grained and its texture distinctly ophitic or poikilophitic, as shown in Fig. 7, p. 20. Its principal silicate minerals are plagioclase, diopsidic augite and olivine. The content of strongly serpentinized rhombic pyroxene amounts in a few thin sections to as much as 5—10 Vol.-%, but in the majority of samples none at all is to be found. The combined content of sulfides varies between 2 and 40 Vol.-%, the oxide minerals, on the other hand, accounting for only 0.5—3 Vol.-%. Additional minerals include a little biotite, calcite, alkali feldspars and quartz, with spinel and apatite as accessories. In spots, serpentine, chlorite and talc are met with, even in abundance. The mineral



Fig. 7. Thin section, $\times 10$, nic. +. Photo E. Halme. Olivine diabase containing small amount of sulfides. Augite as large crystals enclosing laths of plagioclase. Olivine as smaller roundish grains, full of cracks. Drill hole 14, 5 m from the contact.

composition of six typical samples has been presented in Fig. 8, p. 21. A silicate analysis has been made of only one sample (Table I, 1, p. 31).

The plagioclase, which, with the exception of the areas richest in olivine, serpentine and sulfide, is also one of the principal minerals of the diabase type in question, occurs as unoriented laths measuring between 0.2 and 2 mm in length. Especially the largest of them are distinctly zoned. According to the maximal angle of extinction determined from symmetrical sections, the anorthite content in the cores of the grains is An_{60-70} and at the margins An_{45-55} . Thus the plagioclase would seem to be somewhat richer in anorthite than in the more silicic diabase types previously described.

Among the mafic minerals of the rock, the most abundant is sometimes olivine, sometimes diopsidic augite. The former occur as roundish grains 1—4 mm in diameter, though only in rare instance are idiomorphic crystal faces visible. The optic sign of the olivine is in some grains positive, but mostly negative. Determinations made with a universal stage of three samples showed the axial angle $2V_x$ to vary between 84 and 89°. According to Winchell & Winchell (1951), these values correspond to 70—80 Mol.-% forsterite.

Like the olivine, the diopsidic augite occurs as grains that, measuring 1—5 mm in diameter, exceed the plagioclase laths in size. In contrast to

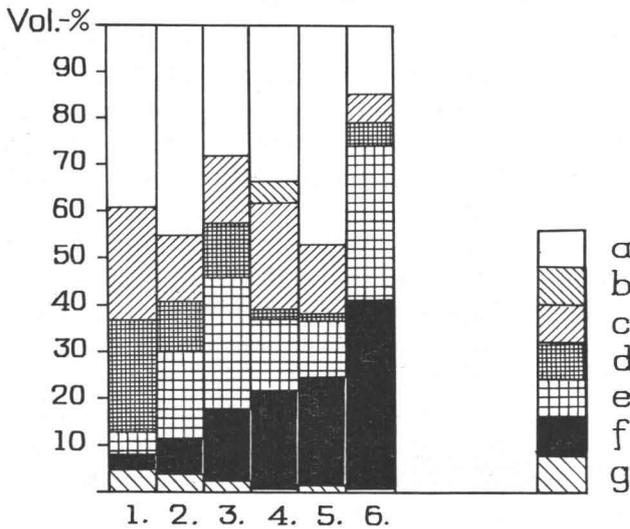


Fig. 8. Volumetric mineral composition in six samples, which represents typical sulfide-bearing olivine diabase. a. Plagioclase; b. Rhombic pyroxene; c. Diopsidic augite; d. Olivine; e. Serpentine; f. Ore minerals; g. Biotite, calcite, quartz, alkali feldspars and accessories.

the olivine, they poikilitically enclose plagioclase laths, proving that they had crystallized after the plagioclase. In thin section, the mineral in question is only a pale brownish color and not pleochroic. The optic sign is positive and $Z \wedge c = 36-40^\circ$. The axial angle $2V_z$ in the case of the majority of the grains measured with the universal stage is 45° , rising, however, in a few grains or parts of grains as high as 55° . On the basis of its optical properties, the pyroxene in question consists of iron-poor diopsidic augite (Winchell & Winchell, 1951), though there is considerable non-homogeneity in its composition. Besides variation in the axial angle, this is also revealed by the undulating extinction of the grains.

Rhombic pyroxene occurs in smaller amounts than any of the minerals mentioned in the foregoing — in all cases under 10 Vol.-%. Its mode of occurrence is practically the same as that of the olivine. Its optic sign is negative and $2V_z = 72-74^\circ$. The pleochroism is typical of rhombic pyroxene: $x =$ brownish red, $y =$ yellow and $z =$ grayish blue-green. According to the optical properties, the Mg-component, as in the case of olivine and monoclinic pyroxene, too, is in overwhelming excess compared to the Fe-component, here being about 90 Mol.-% $MgSiO_3$ (Winchell & Winchell, 1951).

As additional minerals, ore-bearing olivine diabase consistently contains some biotite and alkali feldspars, sometimes quartz and calcite as well.

Their combined content, 0.5—3 Vol.-%, however, is substantially lower than in other diabase types. The minerals mentioned, together with sulfides, constitute jointly the material of the rock that solidified last and fills the interstices of the main constituents of the rock (Fig. 17, p. 40).

As accessories, the olivine diabase contains small amounts of spinel and apatite. The former occurs as very small octahedral inclusions in the olivine and the rhombic pyroxene, whereas long prismatic apatite is met with as inclusions in all the silicate minerals. Both the spinel and the apatite evidently solidified at quite an early stage.

As the ore minerals will be dealt with later in greater detail, it suffices in this connection to mention that the sulfides, like the oxide minerals, occur for the most part as evenly disseminated grains and blebs. They apparently belong to the primary mineral assemblage of the rock, although, with the exception of the ilmenite and titanomagnetite, they obviously solidified later than the principal silicate minerals.

The autohydration has been considerably weaker in the sulfide-bearing olivine diabase than in the previously described ore-less pyroxene diabase. With the exception of slight remnants, the rhombic pyroxene, however, has totally changed to coarse bastite-like serpentine, which is geometrically oriented on the original pyroxene. Of the olivine, an average of about two-thirds has changed to fine-scaled serpentine, which in thin section is usually almost colorless, though rather intensely greenish or brownish varieties are sometimes met with. About a quarter of the serpentine in the rock consists of fibrous chrysotile, occurring as narrow veinlets cutting the silicate and sulfide minerals (Fig. 19, p. 43). In contrast to the olivine and rhombic pyroxene, the diopsidic augite has been preserved practically unchanged.

FINE-GRAINED BORDER ZONES OF THE DIABASE

The fine-grained border varies in thickness between a couple of dozen centimeters and a meter and a half. In the thin terminal parts of the dike, where the effect of the cold wall rock on the cooling magma had been more pronounced, the diabase is nevertheless of this rapidly solidified, fine-grained type throughout (see Fig. 2, p. 12).

The principal minerals of the chilled contact are plagioclase An_{60} , diopsidic augite, olivine and rhombic pyroxene. Of these the two last mentioned, however, have changed almost completely to serpentine. As in the other diabase types, the supplementary minerals include a slight amount of biotite, quartz, potash feldspar, albite, titanomagnetite and ilmenite. There is a conspicuous scantiness of sulfide minerals also in those portions where both inner and outer sides of the border zone are abundantly disseminated.

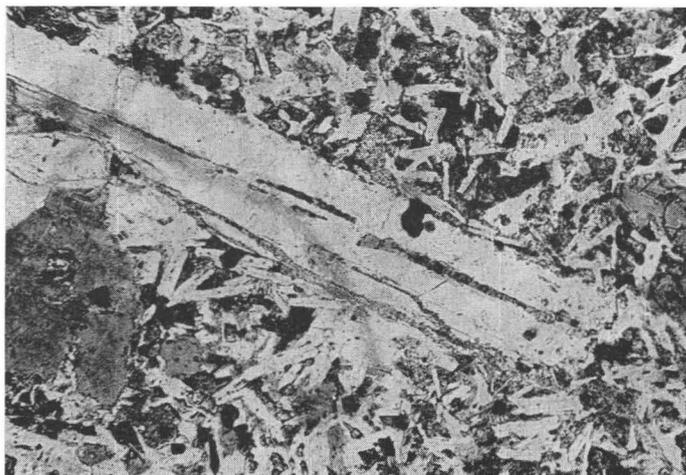


Fig. 9. Thin section, $\times 140$, nic. // . Fine-grained diabase, 0.2 m from the contact. As phenocrysts, plagioclase laths and rhombic pyroxene. The last-named has changed to coarse-grained serpentine. Drill hole 2.

The most abundant mineral of the rock, plagioclase, occurs as unoriented laths measuring between 0.1 and 0.2 mm in length. The augite occurs as even smaller xenomorphic grains, which in some cases form roundish radiating clusters. Strongly serpentinized rhombic pyroxene and olivine occur in the ophitic ground mass formed by the plagioclase and the augite as phenocrysts, some of them idiomorphic, measuring between one and five mm in diameter. Judging by the relict textures and mineral remnants, the rhombic pyroxene had been appreciably more abundant than the olivine. Some plagioclase is likewise present as lath-shaped phenocrysts 1—2 mm in length (Fig. 9, p. 23). The chemical composition of the rock is presented in Table I, 2 (p. 31) and its mineral composition in Fig. 3, 6, p. 14.

Deviating from the normal type of fine-grained border described in the foregoing, the marginal zones and, especially, thin terminal portions of the diabase contain — sometimes in abundance — drop-like quartz grains 1—5 mm in diameter as well as strongly corroded grains of oligoclase An_{17-20} measuring the same size. In drill hole 15, for instance, their total content in many spots rises as high as 20—40 Vol.-%, as shown in Fig. 10, p. 24.

The quartz and oligoclase grains usually form accumulations a few centimeters in diameter, the form of which, however, cannot be accurately determined from the core samples. The quartz grains, at the margins of which one often meets with a very fine-grained biotite- and chlorite-rich rim,

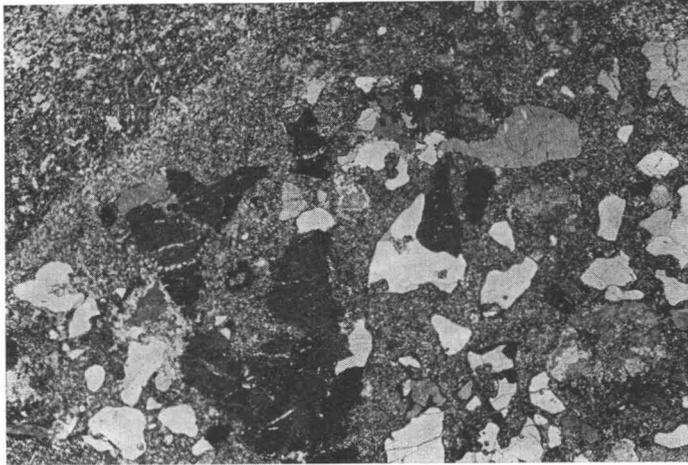


Fig. 10. Thin section, $\times 10$, nic. +. Photo E. Halme. Fine-grained diabase (in upper left corner) with remnants of a strongly assimilated xenolith of mica gneiss. Fine-grained material filling the interstices of the large oligoclase (grey) and quartz (black or white) grains consists of saussuritized plagioclase laths, biotite, chlorite, talc, carbonates, quartz and alkali feldspars. Drill hole 15.

ordinarily consist of a single, large crystal with a sharp extinction. In conjunction with the quartz, there sometimes occur radial aggregates of a mineral which, judging by its low refringence and birefringence, appears to be some mineral of zeolite group. The oligoclase likewise most usually occurs as separate, large-sized crystals, which in many cases are conspicuously sericitized. More rarely, a slight amount of epidote also occurs as an alteration product of the oligoclase.

Further characteristic of the fine-grained diabase containing large quartz and oligoclase grains is a relatively high graphite content. It most usually occurs as tiny flakes in the diabase material filling the interstices between the grains, though in places it is also found in larger, roundish aggregates, which in some cases are likely to measure over 2 cm in diameter.

Evidently the graphite represents, together with the corroded oligoclase and quartz grains, the remains of partially fused xenoliths, having been drawn into the diabase magma when it brecciated the surrounding mica gneiss; in places this wall rock contains considerable graphite and the composition of its plagioclase is practically the same as in the grains referred to. Since no intact fragments of mica gneiss are met with in the diabase, the assimilating effect of the diabase magma had evidently been quite strong.

The texture of the fine-grained material filling the interstices of large oligoclase and quartz grains is in most cases clearly ophitic. In addition to minute plagioclase laths, it contains fine scales of biotite, chlorite and talc as well as some large grains of calcite. Quartz, potash feldspar and albite occur as a granophyric intergrowth, which may amount to 10—30 Vol.-%. This brings out the fact that by xenolithic assimilation the diabase magma has become considerably more silicic than originally.

In the immediate proximity of the wall rock, the chilled border contains no large quartz or oligoclase grains whatsoever, but in some cases quite an abundant granophyric intergrowth of quartz and alkali feldspars, which lends the rock a light red color. One sample of such rock, taken 15 cm from the contact of the diabase, proved to have the following mineral composition:

Plagioclase	29.0	Vol.-%
Biotite	2.0	»
Chlorite	22.0	»
Talc	5.0	»
Granophyric intergrowth of quartz, potash feldspar and albite	39.5	»
Calcite	1.0	»
Ore minerals	1.5	»
	<hr/>	
	Total	100.0 Vol.-%

The main mafic mineral, chlorite, occurs as an alteration product of the biotite and of some idiomorphically developed mineral, probably monoclinic pyroxene. The plagioclase An_{55} , on the other hand, occurs in the granophyric ground mass only as weakly saussuritized laths, which give the rock distinctly the appearance of diabase. Still, in chemical composition the rock is probably more nearly like the granophyric wall rock of the diabase than like the diabase itself. Evidently this kind of hybrid rock has crystallized out of diabase magma which has strongly assimilated the wall rock.

It should be added that, e. g., Kahma (1951) exhaustively described similar contact phenomena in his study of the olivine diabase of Satakunta. The results arrived at by Kahma likewise indisputably demonstrate that basaltic magma solidifying under conditions of diabase facies is capable of assimilating its more silicic wall rock to a remarkable extent.

APHANITIC DIABASE APOPHYSES

An even denser type of diabase than that met with in the above-described border zones occurs in some diabase apophyses cutting across the mica

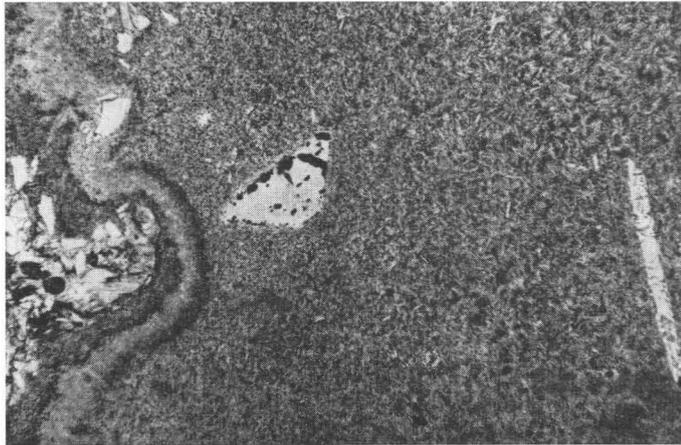


Fig. 11. Thin section, $\times 30$, nic. // . The contact between mica gneiss (on left) and an aphanitic diabase apophysis. In the apophysis, plagioclase (a lath on right) and serpentinized rhombic pyroxene (in middle) occur as phenocrysts. The apophysis has extremely dense border zone (light grey). Between this and mica gneiss, a rim rich in biotite (grey). Drill hole 15.

gneiss (see Fig. 2, p. 12). At the core of these 5—15 cm thick dikes, the length of the plagioclase laths is 0.02—0.05 mm, but diminishing in size steadily toward the dense margins. The other principal mineral, pyroxene, is so fine-grained that it cannot be accurately determined under the microscope. Strongly serpentinized rhombic pyroxene and olivine, as well as plagioclase and spinel, occur in the dense ophitic ground mass as phenocrysts, measuring less than a millimeter in length (Fig. 11, p. 26).

At the contact of the apophysis and the adjacent mica gneiss there is in places a biotite-rich reaction rim less than a millimeter in thickness. No other contact reactions can be detected either in the country rock or in the apophysis itself. The chemical composition of one diabase apophysis 10 cm thick is presented in Table I, 2, p. 31.

GRANOPHYRIC VEINS

In the majority of the drill holes at Petolahti, one meets with pale granophyric veins cutting the diabase. They vary in thickness from a few millimeters to nearly half a meter, and most of them are situated no more than a few meters from the contact of the diabase. One sample of such a vein proved to have the following mineral composition:



Fig. 12. Thin section, $\times 7$, nic. +. Photo E. Halme. The contact between diabase (on left) and a granophyric vein consisting mainly of fine-grained albite, quartz, potash feldspar and chlorite. The largest grains in the vein material are calcite. Near the contact the diabase is rich in alteration products, such as chlorite, sericite and quartz. Drill hole 8.

Albite An ₅	56.0	Vol.-%
Quartz	24.0	»
Chlorite	10.0	»
Calcite	9.0	»
Opaque minerals	1.0	»
	100.0	Vol.-%

The principal minerals of the veins, albite and quartz, as well as, in part, chlorite, occur mostly as a fine-grained granophyric intergrowth. The calcite, on the other hand, occurs as larger, separate grains as shown in Fig. 12, p. 27. A slight amount of potash feldspar generally is met with as a supplementary constituent, but in some cases it is totally lacking. Such an especially potash-poor ($K_2O = 0.08\%$) and at the same time sodium-rich ($Na_2O = 6.3\%$) type of vein is represented, e. g., by the one approximately 30 cm thick cutting across the diabase and the chemical composition of which is presented in Table I, 5, p. 31 and the mineral composition in the foregoing. Sporadically the veins also contain slight amounts of pyrrhotite, chalcopyrite and pyrite as well as pentlandite. Apatite is present as an accessory in appreciably greater abundance than in various diabase

types and the wall rock of the diabase, though nowhere does it exceed 1 Vol.-%.

The diabase bounded by the granophyric veins, which is to some extent also present as fragments in the veins themselves, has usually altered markedly in their proximity. The mafic minerals, diopsidic augite in particular, have changed wholly to chlorite, serpentine and biotite. In conjunction with them, there is an abundance of quartz and calcite, which fill the interstices between the saussuritized plagioclase grains (Fig. 12, p. 27). In one diabase fragment studied under the microscope, the plagioclase laths had undergone marked albitization, their composition now being about An_5 . Other major constituents of the fragment are, in order of importance, quartz, chlorite and calcite.

Leucocratic veins are met with not only in the marginal parts of the diabase lens but also as veins a few millimeters thick cutting across the foliation of the wall rock of the diabase (Fig. 13, p. 29). In texture also these veins are granophyric and they consist of alkali feldspars, quartz, chlorite and calcite. Sporadically, the veins also contain slight amounts of chalcopyrite and other sulfides. In all the veins studied microscopically, the potash feldspar clearly exceeds the albite in abundance; accordingly, these veins appear to be considerably more potassic than the granophyric veins cutting across the diabase. An alkali determination (A. Heikkinen) made from a vein 0.8 cm thick yielded $Na_2O = 2.04\%$ and $K_2O = 6.20\%$.

The mode of occurrence, texture and composition of the granophyric veins cutting across the diabase and its wall rock — especially their sulfide and calcite content — afford grounds for assuming that they represent the final silicic residual liquids expelled from the almost completely consolidated diabase. On the basis of a number of observations, the veins cutting across the diabase appear to be highly sodic whereas at least some of the veins penetrating the wall rock of the diabase are rather potassic.

The same kind of residual injections, which have been interpreted along the same lines, have often been met with in conjunction with subsilicic intrusions comparable to the Petolahti diabase, as, for instance, the Skaer-gaard intrusion in Greenland (Wager and Deer, 1939), the diabase of the New Jersey Palisades (Walker, 1940), the diabases of eastern Fennoscandia (Eskola, 1925) and numerous Finnish diabases (Saksela, 1960, Meriläinen, 1961).

CONTACT-METAMORPHIC WALL ROCK OF THE DIABASE

Since the greatest thickness of the Petolahti diabase is as much as 70—80 m, the fact that it has caused considerable contact metamorphism in the surrounding mica gneiss is understandable. At the thick middle portion

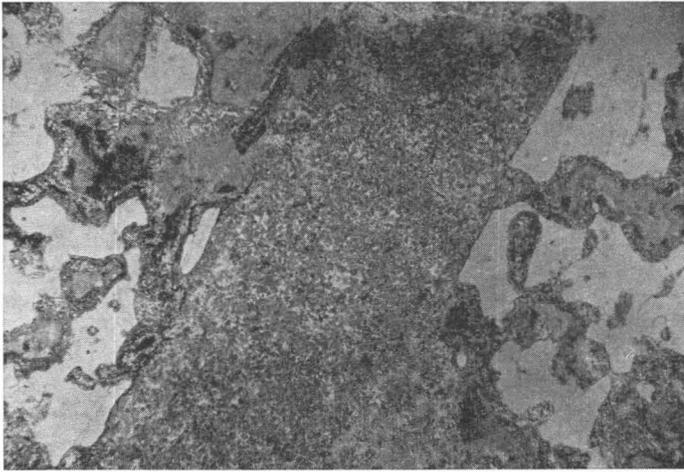


Fig. 13. Thin section, $\times 6$, nic. // . Photo E. Halme. Wall rock of the diabase, 5 meters from contact. Granophyric material occurring as a vein and as a rim between sericitized oligoclase (grey) and quartz (light grey) grains. Drill hole 5.

of the dike, clearly perceivable alteration of the wall rock has taken place at a distance of more than 10 m from the contact of the diabase. On the other hand, the thin terminal portions of the dike as well as the dense apophyses are bounded by practically unaltered mica gneiss. The outer boundary of the contact zone is marked in Fig. 2, p. 12.

In the outermost portions of the contact zone, the texture of the mica gneiss has been preserved unaltered, but under the microscope its principal mineral, oligoclase, exhibits relatively strong sericitization. In addition, the biotite has changed in part to chlorite. Toward the contact of the diabase, the mineral changes referred to gradually become more pronounced. At the same time there appears in the rock, gradually in increasing abundance, a granophyric substance composed of alkali feldspars, quartz and chlorite, which occurs partly as veins like those described in the foregoing and partly as a rim between the quartz and sericitized oligoclase grains, as shown in Fig. 13, p. 29. In the immediate proximity of the contact of the diabase, the granophyric substance in many cases also contains disseminated sulfides, of which chalcopyrite, pyrrhotite, pyrite, pentlandite and violarite are most prevalent (Fig. 22, p. 59).

The following mineral composition (left) was obtained by the point-counter method from a certain sample of the wall rock taken 0.5 m from the contact:

Oligoclase (sericitized) ..	26.0 Vol.-%	Oligoclase	40.0 Vol.-%
Chlorite	18.5 »	Biotite	18.0 »
Quartz	9.5 »	Quartz	35.3 »
Intergrown alkali feld-			
spars and quartz	42.0 »	Microcline	3.2 »
Calcite	2.0 »	Garnet	2.5 »
Sulfides	2.0 »	Accessories	1.0 »
	Total 100.0 Vol.-%		Total 100.0 Vol.-%

For the sake of comparison, on the right is presented also the mineral composition of a mica gneiss that has undergone weak migmatization but in which no changes, however, have taken place as a result of the influence of the diabase.

In the foregoing (p. 28) the assumption was presented that the granophyric veins cutting across the wall rock were due to the silicic, alkali-rich residual solutions emanating from the diabase. Evidently, also the sericitization of the oligoclase and the chloritization of the biotite took place through the influence of the same solutions. Also a part of the material of the granophyric rims bordering the oligoclase grains, notably the sulfides and potash feldspar, apparently derives from the interstitial solutions seeping from the diabase. Accordingly, the alteration of the wall rock would be, at least partially, metasomatic by nature.

On the other hand, it is evident that the heat generated by the diabase magma contributed to promote considerably the alteration of the wall rock; it is even quite possible that the materials of the wall rock had partially melted in the proximity of the contact, forming intergranular liquids of the eutectic composition of the quartz and alkali feldspars. The granophyric material filling the interstices of the quartz and oligoclase grains and also occurring as veins in the wall rock may partially derive from such re-molten materials, too.

CHEMICAL COMPOSITION OF THE DIABASE

In the foregoing, descriptions have been given of the mineral composition, texture and mode of occurrence of the different types of diabase met with in the Petolahti dike. The chemical composition of four of the main types as well as of a granophyric vein cutting across the diabase is presented in Table I, 1—5, p. 31. The different types of diabase constitute a typical differentiation series, the end members of which are the sulfide-bearing olivine diabase and the quartz diabase. Apparently, also the granophyric veins described on pp. 26—28 belong to the same differentiation series,

Table I. The chemical composition of the principal types of the Petolahti diabase (1—4) as well as of a granophyric vein associated with the diabase (5). For the sake of comparison, the table also includes the chemical composition of some rocks (6—9) and magma types (10—11) comparable to the diabase of Petolahti.

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	44.84	46.27	47.27	51.92	70.41	45.73	47.92	46.39	45.90	45	50
TiO ₂	0.78	1.04	1.22	1.05	0.28	3.00	1.40	1.77	2.0	—	—
Al ₂ O ₃	13.00	16.72	18.00	13.55	12.86	14.79	18.87	16.98	15.13	15	13
Fe ₂ O ₃	2.38	2.66	2.28	1.74	0.01	4.06	1.18	1.97	1.84	} 13	} 13
FeO	9.17	7.67	5.91	9.13	1.59	9.89	8.65	10.55	14.69		
MnO	0.19	0.19	0.15	0.20	0.05	0.13	0.11	0.19	0.14	—	—
MgO	14.71	9.61	8.46	6.32	1.20	6.50	7.82	7.59	5.69	8	5
CaO	7.95	8.55	9.42	10.35	3.22	7.50	10.46	9.69	8.66	9	10
Na ₂ O	1.55	1.76	2.12	2.40	6.31	2.39	2.44	2.70	2.85	2.5	2.8
K ₂ O	0.47	0.56	0.58	1.00	0.08	1.13	0.19	0.67	0.96	0.5	1.2
P ₂ O ₅	0.08	0.12	0.13	0.07	0.17	0.90	0.07	0.40	0.21	—	—
CO ₂	1.11	0.73	0.00	0.76	2.47	0.22	0.06	0.00	—	—	—
H ₂ O+	3.42	3.35	2.77	1.49	1.30	2.51	0.41	0.87	1.20	—	—
H ₂ O—	0.45	1.11	2.20	0.25	0.17	0.85	0.10	0.15	0.60	—	—
S	0.40	—	0.12	0.06	0.04	0.19	0.27	—	—	—	—
Ni	0.11	—	—	—	—	—	—	—	—	—	—
Cu	0.11	—	—	—	—	—	—	—	—	—	—
Total	100.72	100.34	100.63	100.29	100.16	99.79	99.95	99.92	99.87	93	95

- 1 — Sulfide-bearing olivine diabase, Petolahti (Anal. A. Heikkinen).
- 2 — Aphanitic diabase apophysis, Petolahti (Anal. I. Huhta).
- 3 — Fine-grained border zone of diabase, Petolahti (Anal. A. Heikkinen).
- 4 — Quartz diabase at core of dike, Petolahti (Anal. A. Heikkinen).
- 5 — Granophyric vein in diabase, Petolahti (Anal. A. Heikkinen).
- 6 — Olivine diabase from Ahlainen, Finland (Anal. I. Huhta).
- 7 — Chilled marginal olivine gabbro from intrusion at Skaergaard (Wager and Deer, 1939).
- 8 — Olivine diabase from Vaasa archipelago, Kobberget, Korsnäs, Finland (Anal. P. Ojanperä).
- 9 — Olivine diabase of Satakunta, Suontaka, Laitila, Finland (Kahma, 1951).
- 10 — Olivine-basalt magma-type (Kennedy, 1933, p. 241).
- 11 — Tholeiitic magma-type (Kennedy, 1933, p. 241).

representing the alkali-rich, siliceous residual solutions following the main crystallization of the diabase magma.

In comparing the chemical composition of the sulfide-bearing olivine diabase with that of quartz diabase (Table I, 1 and 4, p. 31), the former will be observed to be considerably poorer in SiO₂, Na₂O, K₂O and CaO than the latter. Its MgO content (14.71 %), on the other hand, is more than twice as great as that of the quartz diabase.

In further comparing the analytical results, it will be noted that the fine-grained border is distinctly richer in SiO₂ than the sulfide-bearing olivine diabase situated directly inside it, even if not so silicic than the principal rock forming the dike, the quartz diabase. Apparently, the fine-grained border, owing to its rapid crystallization, represents magma material remaining undifferentiated; accordingly, its chemical composition pro-

vides a rough picture also of the average composition of the entire diabase dike. It should be noted, however, that by marginal and xenolithic assimilation the border zone of the diabase has in places become distinctly more silicic and richer in Na_2O and K_2O than it was originally, as presented on page 25. Although no marks of assimilation could be detected in the portion analyzed, at least under megascopic examination, the process could have occurred there, too, to a slight extent.

On the other hand, between the aphanitic apophyses and their wall rock, scarcely any kind of contact reaction seems to have taken place. Since, owing to their thinness, no differentiation whatsoever appears to have taken place in the apophyses, one has good reason to assume that their chemical composition corresponds to the original composition of the magma even more closely than does that of the fine-grained border. In comparing the chemical composition of the apophyses with that of the border zone, one will observe that they are fairly similar (Table I, 2 and 3). The latter is just a bit more silicic and richer in Al_2O_3 , Na_2O and K_2O and at the same time poorer in FeO and MgO , which may very well be due to the above-mentioned assimilation.

Insofar as the chemical composition of the diabase apophyses may be regarded as representing the original, average composition of the diabase magma, it will be observed to closely approximate — in the light of the analytical results presented in Table I — the composition of the olivine-basaltic magma-type described by Kennedy (1933). It will likewise be observed to closely resemble, e. g., the composition of the fine-grained marginal type of the Skaergaard intrusion, which Wager and Deer (1939) have judged to represent the average composition of the whole intrusion. Very similar in composition, moreover, is the olivine diabase of the Vaasa archipelago, met with as major intrusions 20—40 km to the northwest from Petolahti. On the other hand, the olivine diabase of Satakunta, situated in an extensive area some 150 km to the south from Petolahti, is distinctly poorer in magnesium and richer in alkalis, approaching in this respect the composition of Kennedy's tholeiitic magma-type.

FORMATION OF THE DIABASE AND THE ORE

In order to comprehend the mechanism of the differentiation that occurred in the diabase of Petolahti, let us re-examine the picture obtained of the form of the diabase dike through the investigations carried out. In the light of the results achieved by means of gravimetric and magnetic surveys and, in particular, diamond drillings, the length of the dike may be estimated to be at least 600—700 meters, and its thickness in the terminal portions only 5—12 m but in the middle nearly 80 m. It is more

interesting in this connection, however, to know the shape of the dike vertically. This may be determined quite satisfactorily from all the cross-sections where the diabase has been pierced by numerous holes drilled to various depths (see Fig. 2, p. 12). In these cross-sections the diabase forms a cone which narrows downward, the sides of which intersect at a $6-8^\circ$ angle and which dips at a mean angle of 80° in a SSW direction. The cross-section formed by drill holes 2, 12 and 17, moreover, reveals that, having tapered to a thickness of 5—7 m, the diabase continues downward as a dike of fairly even thickness in which, owing to its thinness, differentiation has taken place only very slightly or not at all. This root portion of the dike, furthermore, contains sulfides only very scantily.

On the basis of the foregoing, it is to be assumed that the diabase dike tapers downward also in its thicker parts, e. g., around drill holes 1 and 8, thereby forming in its entirety a lens that tapers in a vertical plane downward and on a horizontal plane toward its ends. It is further evident that the original intrusion had continued above the present surface section, at least for a certain distance and constantly expanding. Accordingly, the part of the diabase now remaining would represent the cone-shaped base of the original, larger intrusion, at the edges and, especially, at the base of which the most mafic differentiation products of the magma and the sulfide material had in one way or another accumulated. This conception is illustrated in Fig. 14.

According to the petrographic observations made of the different parts of the diabase, the intrusion, crystallization and subsequent development of the sulfide-bearing diabase magma appear to have taken place by and large as follows:

— The parent olivine-basaltic magma intruded into a nearly vertical fissure or zone of weakness existing in the clearly older Precambrian bed-rock. Owing to the magmatic pressure, the middle part of the dike thereby swelled out into a lens-like knob about 80 m thick in the present surface section. Above this level, however, the dike had been perhaps considerably thicker. In addition to the main dike, the olivine-basaltic magma penetrated the adjacent rock also as 10—20 cm thick apophyses.

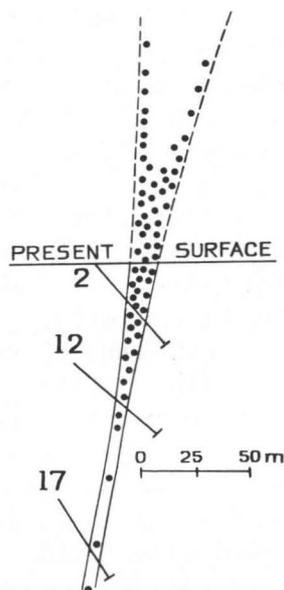


Fig. 14. Cross section of the diabase in the area of drill holes 2, 12 and 17 and the conjectured extension above the present surface. The spotted portion represents sulfide-bearing olivine diabase.

— In intruding, the magma brecciated its wall rock. Heavily assimilated fragments of it are met with in abundance, especially in the thin terminal portions of the dike. Possibly the wall rock was brecciated also at the thicker middle parts of the dike, but, owing to the greater mass and slower rate of cooling of the magma, the fragments of wall rock here became totally assimilated.

— On account of the rapid cooling caused by the cold wall rock, the crystallization of the magma started immediately after its intrusion. It led to the crystallization along the contacts of the dike as a fine-grained border zone which is 0.2—2 m thick and only slightly or not at all differentiated. The thin terminal parts of the dike are wholly of this type. The crystallization of the apophyses intruding beyond the main dike took place even more rapidly.

— Inside the fine-grained border, crystallization progressed considerably slower and thus quite distinct differentiation could take place, the course of which can be explained most readily on the basis of Bowen's (1928) classical theory of fractional crystallization differentiation: First to crystallize out of the magma were the magnesium-rich olivine and small amounts of rhombic pyroxene, which, owing to their greater density, sank down in the magma basin and thereby become highly enriched in the cone-like basal part of the magma basin and its margins. The likewise gravitational enrichment of the sulfide material separated at the same time from the diabase magma in a molten state was even more intense. The enrichment of olivine, rhombic pyroxene and sulfides led to the formation of disseminated olivine diabase. The remaining magma crystallized as ore-less pyroxene diabase and, finally, as quartz diabase which forms the core of the dike.

— The alkali-rich, silicic residual liquids remaining after the main stage of crystallization of the magma solidified as interstitial granophyric material. One part of this residual liquid filter-pressed out from the almost completely consolidated diabase, forming granophyric veins that cut across both the diabase and its wall rock.

— After the primary crystallization of the silicates, comparatively strong autohydration took place in the diabase, especially in its subsilicic marginal parts. The olivine and rhombic pyroxene had by then largely serpentinized and the augite partly changed to talc. These hydrous silicates were apparently produced by the action of the volatiles contained in the original diabase magma which became active only after the primary crystallization of the silicates. Besides water, the mineralizing substances also contained abundant silica and carbonates, the quartz and calcite that crystallized from them occurring in conjunction with serpentine as veins filling small fractures and as rounded or oval amygdales. The autohydration referred to was most marked in the intermediate pyroxene diabase

zone of the thick middle part of the dike. The same phenomena, especially the serpentinization of olivine, can be noted also in the sulfide-bearing olivine diabase, though far weaker.

— During or after crystallization, no tectonic deformation, excluding slight fracturing and shearing, took place in the diabase.

— Before and during the consolidation of the diabase, marked contact-metamorphic alteration took place in the invaded mica gneiss. The sericitization of the oligoclase and chloritization of the biotite as well as the formation of granophyric intergrowth of quartz and alkali feldspars are evidently brought about by the combined action of the heat and materials emanating from the diabase. This emanations contained small amounts of sulfides, too, which occur as disseminated, interstitial grains or blebs in the granophyric material near the contact of the diabase.

— The sulfide material separated and enriched from the diabase magma in a molten state as tiny drops began to crystallize at a markedly high temperature, yet clearly after the oxide minerals and the olivine and plagioclase. The last fraction of sulfides to solidify, enriched considerably by Cu, Ni and volatiles, was expelled from the interstices between the silicate grains and had injected into the fractures in the host rock.

— Subsequently, conspicuous secondary changes took place in the sulfides, apparently when acted upon by the same hydrothermal solutions as in the case of the mafic silicates, too.

THE ORE ASSOCIATED WITH THE DIABASE

CHEMICAL COMPOSITION OF THE ORE

No large amounts of Petolahti ore, which might give a fully reliable idea of its composition, have been analyzed. Numerous nickel and copper determinations made from core samples and especially the general sample taken from a continuous stretch of 14,5 meters from drill hole 4 and analyzed at the ore laboratory of the Geological Survey (A. Löfgren, K. Karhunen and P. Väänänen) nevertheless provide a relatively accurate picture of the composition of the ore. The analysis referred to yielded different metals and sulfur as follows:

Fe, total	12.3	%
Fe, soluble in HCl	11.8	»
Ni	0.65	»
Cu	0.70	»
Co	0.02	»
S	3.27	»
Ag	4	g/t
Au	0.12	»
Pt	0.1	»
Pd	0.6	»

The average composition of the pure sulfide phase can be calculated from the values recorded:

Pyrrhotite $Fe_{11}S_{12}$	56	%	Fe	47.4	%
Pentlandite $(Fe . Ni)_9S_8$	21	»	Ni	7.4	»
Chalcopyrite $CuFeS_2$	23	»	Cu	8.0	»
<u>Total</u>	<u>100</u>	<u>%</u>	Co	0.2	»
			S	37.0	»
			<u>Total</u>	<u>100.0</u>	<u>%</u>

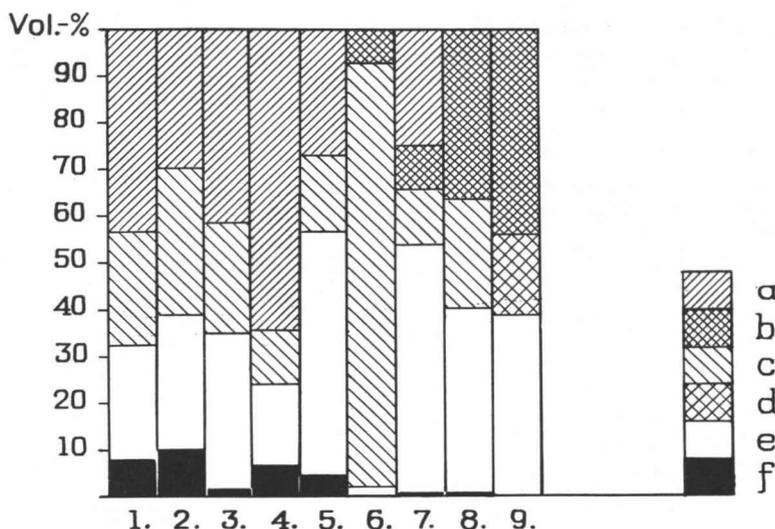


Fig. 15. Volumetric ratios of ore minerals in different ore types. a. Pyrrhotite; b. Pyrite; c. Pentlandite; d. Vioiarite; e. Chalcopyrite; f. Oxide minerals.

1—4. Disseminated olivine diabase.

5—6. Sulfide veins in the olivine diabase.

7—9. Disseminated wall rock of the diabase.

The sulfur content of the general sample, 3.27 % S, corresponds to about 9 Weight-% sulfides, given as pyrrhotite, pentlandite and chalcopyrite in the foregoing ratio.

In the light of the values recorded and the results of the volumetric analysis of the ore material presented in Fig. 15, p. 37, it may be stated that the Petolahti ore contains pentlandite and chalcopyrite in exceptional abundance compared to the content of pyrrhotite. In early magmatic nickel-copper-pyrrhotite ores the pyrrhotite content ordinarily exceeds that of pentlandite and chalcopyrite many times over (e. g., Schneiderhöhn, 1958), but at Petolahti the ratio pentlandite : pyrrhotite is roughly 1 : 2.7. The chalcopyrite content is usually 30—60 % that of pentlandite, but at Petolahti they occur in approximately equal abundance.

According to the analysis presented in the foregoing, the Petolahti deposit includes the ratio $\text{Cu} : \text{Ni} : \text{Co} = 108 : 100 : 3.1$ and the ratio $(\text{Cu} + \text{Ni}) : \text{platinum metals} = 19\,000 : 1$. When these are compared, e. g., with the corresponding values of the nickel-copper deposits presented in Table II, it will be noted that the relative cobalt content of the Petolahti ore is somewhat below par, whereas the relative content of platinum metals is substantially greater than in, for example, the ores of Sudbury and

Table II. The ratios Cu:Ni:Co and (Cu + Ni): platinum metals in a number of nickel-copper-pyrrhotite ores, according to different sources.

Occurrence	Cu : Ni : Co	(Cu + Ni): platinum metals
Sudbury, Canada (Schneiderhöhn, 1958)	65: 100: 2,5—6	20 000—222 000: 1
Ni-ores of Norway (Vogt, 1923)	25—75: 100: 6—12	175 000—260 000: 1
Alexo, Canada »	19: 100	55 000: 1
Hubertus, Germany (Ahlfeld, 1934)	100: 12,8	
Bottenhorn, Germany »	100: 12,4	
Merensky-Reef (Schneiderhöhn, 1958)		2 000— 5 000: 1
Igdlukúnguaq, Greenland (Pauly, 1958)	65: 100: 5,8	
Petolahti, Finland	108: 100: 3,1	19 000: 1

Norway, although considerably lower than in the exceptionally platinum-rich occurrences of Merensky-Reef.

On the basis of nickel and copper determinations made from core samples, the ratio of the metals mentioned appears to remain fairly constant throughout the ore body. A clear exception to this, however, is represented by those parts of the ore body where the disseminated mineralization extends a few score centimeters also to the wall rock. In such places the copper has been enriched greatly in relation to the nickel (Fig. 16, p. 39).

No determinations of the zinc, lead, arsenic or antimony were made in the analyses presented in the foregoing. On the other hand, these metals were determined spectrographically (A. Löfgren) — cobalt being included as well — from three ore concentrates made with a superpanner apparatus, two of them (a and b) representing the core of the ore body and the third (c) the disseminated wall rock of the diabase:

	a	b	c
Co	0.37 %	0.28 %	0.1 %
Zn	<0.1 »	<0.1 »	~0.1 »
Pb	<<0.01 »	<0.01 »	<0.01 »
As } Sb }	not detected		

The cobalt, an average of 0.2 % of which is contained by the pure ore material in drill hole 4, has, according to the foregoing results, been enriched fairly clearly into the middle parts of the ore body richer in nickel. In all parts of the ore, the content of zinc, lead, arsenic and antimony is very scanty and only in the case of zinc can a slight enrichment into any particular part of the ore body be observed to have occurred — i. e., into the disseminated wall rock of the diabase. This could also be established in microscopic examinations of the different ore types (see p. 60).

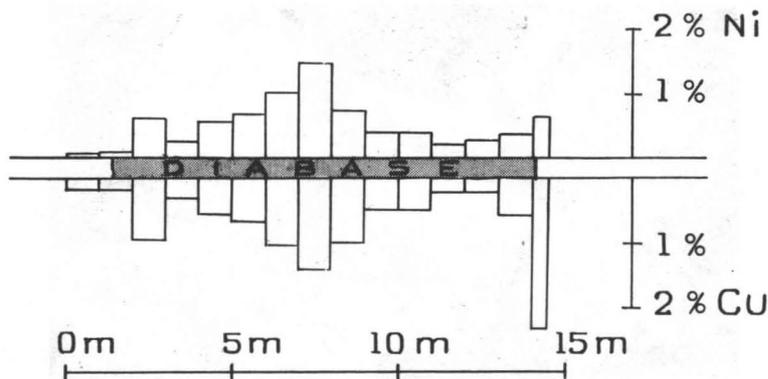


Fig. 16. Variation in the nickel and copper contents in drill hole 4.

ORE MINERALS AND ORE TYPES

As mentioned previously in connection with the petrographic description of the diabase, the Petolahti ore represents for the greatest part disseminated ore contained in serpentinized olivine diabase. The sulfide minerals are usually present in it as quite formless clusters, measuring 0.2—4 mm in diameter, which fill the interstices of previously crystallized silicate minerals. In the sulfide clusters all three principal sulfides are almost invariably present, and they are in most cases arranged in such a way that the core of the cluster consists of pyrrhotite and the margins of chalcopyrite and pentlandite, accompanied by a slight amount of secondary magnetite (Figs. 17, p. 40 and 18, p. 41). More rarely the sulfides occur as roundish blebs 4—10 mm in diameter, in which the previously described rim-like arrangement of the sulfides can often be distinctly observed (Fig. 19, p. 43). Ilmenite and titanomagnetite occur evenly disseminated throughout the rock. They also are present to some extent in the sulfides as inclusions. In contrast to the pure magnetite, both the ilmenite and the titanomagnetite crystallized well before the sulfides. The ratio of the ore minerals in four typical samples representing disseminated olivine diabase is presented in Fig. 15, 1—4, p. 37.

A small portion of the sulfides, estimated at 5—10 %, occurs as 1—10 mm thick veins injected into fractures in the diabase. In addition to the ore minerals, these veins usually also contain serpentine and calcite, in some cases also a slight amount of quartz. And they contain, on the average, clearly a greater abundance of pentlandite and, especially, chalcopyrite, than the disseminated sulfides does. Correspondingly, the pyrrhotite content is scantier and in certain veins it is lacking altogether. In lieu of it, pyrite

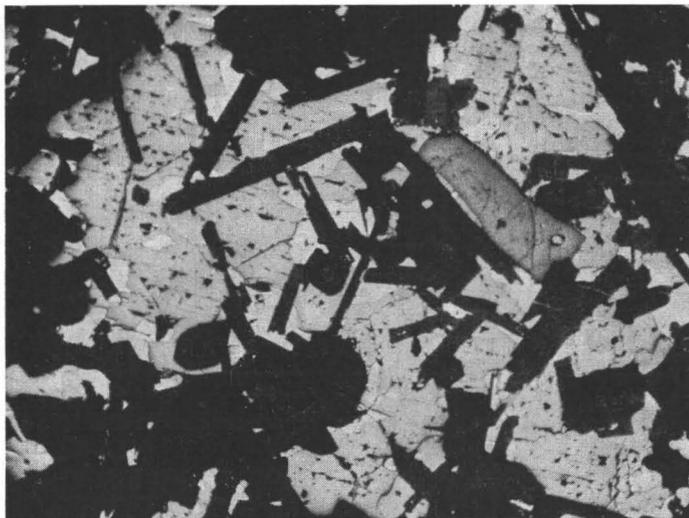


Fig. 17. Polished section, $\times 30$, nic. // . Pyrrhotite (light grey) enclosing laths of plagioclase (grey) and rounded grains of olivine (nearly black) and an ilmenite crystal (medium grey). On the boundaries between pyrrhotite and silicates, chalcopyrite and pentlandite (light). Drill hole 2.

is sometimes present. The mineral composition of two veins is presented in Fig. 15, 5—6, p. 37.

The amount of sulfides in the wall rock of the diabase is very slight, not more than about 5 % of the total amount of the ore. The sulfides occur mainly as roundish blebs 1—10 mm in diameter in which, however, the above-described rim-like texture is not evident. The ore minerals, and their ratios as well, are practically the same as in the sulfide veins cutting across the diabase. However, there is even a greater abundance of pyrite. In addition to pentlandite, violarite, too, occurs as a nickel mineral. The mineral composition of three of the samples is presented in Fig. 15, 7—9, p. 37.

In line with the foregoing, the following three ore types may be distinguished in the Petolahti deposit:

- disseminated olivine diabase
- sulfide veins in the olivine diabase
- disseminated wall rock of the diabase

Inasmuch as the mode of occurrence, proportionate contents and textures of the ore minerals distinctly deviate from each other in these three types,

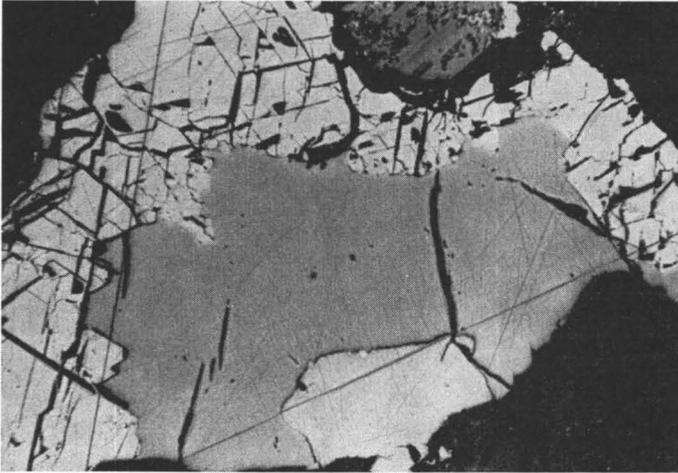


Fig. 18. Polished section, $\times 80$, nic. // . A typical sulfide bleb in olivine diabase. From the top downwards, titanomagnetite (grey), pentlandite, pyrrhotite (in middle) and chalcopyrite. Drill hole 1.

the occurrence of each ore mineral in the three ore types will be dealt with separately in the detailed description to follow.

The following ore minerals are met with in the Petolahti ore:

Pyrrhotite,

chalcopyrite and pentlandite as exsolution bodies. Marcasite, pyrite, magnetite and non-reflective material occur as alteration products.

Chalcopyrite,

pyrrhotite, cubanite and pentlandite as exsolution products, as well as material broken up into a fine-grained intergrowth of pyrrhotite, chalcopyrite, pentlandite and magnetite.

Pentlandite,

chalcopyrite and pyrrhotite as exsolution bodies and bravoite as an alteration product.

Sphalerite,

very scantily present in all ore types. Chalcopyrite as exsolution product.

Pyrite,

as primary crystals only in some sulfide veins and in the disseminated wall rock.

Violarite,

only in the disseminated wall rock.

Galena,

very scantily present in some sulfide veins.

Silver,

uncertain, occurring in conjunction with galena.

Titanomagnetite,

evenly disseminated throughout the rock.

Ilmenite,

evenly disseminated throughout the rock.

Magnetite,

occurs in part like titanomagnetite and ilmenite, in part as a secondary mineral in conjunction with sulfides.

Hematite and limonite,

in small quantities in some magnetite and serpentine veins.

ORE MINERALS IN THE DISSEMINATED OLIVINE DIABASE**PYRRHOTITE**

Of all the ore minerals contained in the disseminated olivine diabase, pyrrhotite is obviously the most abundant, although its share of the total ore material — averaging about 55 % — is exceptionally small as compared to numerous other early magmatic sulfide ores.

The pyrrhotite occurs, like the pentlandite and chalcopyrite, as grains or as grain clusters measuring 0.05—5 mm in diameter, the form of which depends entirely on the shape of the surrounding, previously solidified silicate minerals. The largest pyrrhotite grains, in especial, often contain plagioclase laths as inclusions, resulting in a clearly poikilophitic texture. More rarely does one encounter ilmenite, titanomagnetite and olivine, too, as inclusions, the last-mentioned usually being conspicuously serpentinized (Fig. 17, p. 40).

Further characteristic of the pyrrhotite of the disseminated ore is the total lack of any signs of deformation. Likewise scarce are primary replacement textures. Occasionally one meets with cases of chalcopyrite that has slightly replaced the pyrrhotite and the pentlandite. The pyrrhotite for its part, together with the chalcopyrite and the pentlandite, in some cases replaces the magnetite component of the exsolved titanomagnetite. On the other hand, the alteration of pyrrhotite mainly to pyrite and marcasite is quite a common occurrence, in many cases being very marked. It will be described in more detail, together with the alterations of other ore minerals as well, on pages 61—63. However, most characteristic of the pyrrhotite of the disseminated ore are exsolution bodies of chalcopyrite and pentlandite, which occur in it in places quite abundantly.



Fig. 19. Polished section, $\times 6$, nic. // . Photo E. Halme. Sulfide blebs 1—8 mm in diameter in serpentized olivine diabase. Centers of blebs are pyrrhotite; at borders there is a rather regular chalcopyrite-pentlandite rim, which however is hard to distinguish in picture. Veins cutting sulfide blebs are mainly serpentine. Drill hole 12.

CHALCOPYRITE LAMELLAE ALONG PRISM AND PYRAMID PLANES OF PYRRHOTITE

In certain parts of the ore, notably in drill holes 7 and 16, the pyrrhotite is often found to contain abundant chalcopyrite in a triangular network of shuttle-shaped lamellae 2—20 μ thick and 10—100 μ long. Around the lamellae there frequently occurs an abundance of flame-like exsolution bodies of pentlandite, which, as is usual, are oriented parallel to the basal plane of the pyrrhotite (Pl. I, 1). The texture plainly reveals that the chalcopyrite lamellae antedated the pentlandite flames and that they are oriented according to either the prism or pyramid planes of the pyrrhotite. In sections that, to judge by the lack of cleavages // (0001) and the very weak anisotropy, run fairly parallel to the basal plane of the pyrrhotite, these lamellae intersect at an angle of just about 60° as shown in Pl. II, 1.

An attempt was made, furthermore, to determine the angle at which the chalcopyrite lamellae intersect the basal plane of the pyrrhotite. Finding sections suitable for this purpose running perpendicular to the basal plane on the polished sections proved, however, to be very difficult. In the section shown in Pl. II, 2, the pentlandite flames oriented parallel to the basal plane of pyrrhotite are very straight and narrow, just as are the marcasite bands running in the same direction, judging by which the section is fairly perpendicular to the basal direction of the pyrrhotite. The lenticular chalcopyrite lamellae either run perpendicular to the direction (0001) indicated

in the section referred to by the pentlandite flames and marcasite bands or intersect it in pairs symmetrically at 80—85° angles. Accordingly, it is evident that the chalcopyrite lamellae are in this case oriented partly in conformity to the prism planes and partly to the sharp pyramid planes. Judging by the mode of occurrence of the lamellae, it is further evident that they are true exsolution products of pyrrhotite.

Where the exsolution bodies of chalcopyrite described in the foregoing are met with, they vary in quantity within a broad range. Most usually they account for 15—30 % of the total quantity of intergrowth, but all the other mixture ratios are also to be observed. In the cases where chalcopyrite occurs as by far the most prevalent component, pyrrhotite is present as tiny angular grains, whose form and arrangement exhibit no distinct regularity. With crossed nicols, however, it may be noted that the pyrrhotite grains are oriented in the same way throughout the intergrowth.

The mutual proportion of pyrrhotite and chalcopyrite usually remains fairly unchanged throughout the entire intergrowth, but also numerous such cases could be observed as where pure pyrrhotite gradually passes over into an intergrowth containing ever-increasing amounts of chalcopyrite, which for its part runs without any distinct boundary into pure chalcopyrite. This suggests that the pyrrhotite and the chalcopyrite had, in unmixing, strongly tended to separate from the intergrowth into pure grains.

Triangular chalcopyrite lamellae of the kind considered in the foregoing have recently been described by Pauly (1958) from the nickeliferous pyrrhotite deposit of Igdlukúnguaq. In spite of many thorough microscopic investigations, none have been met with, however, in other ores containing chalcopyrite and pyrrhotite — at least, none have been described in the literature.

Pauly (op. cit.) divides the chalcopyrite lamellae found by him in the pyrrhotite of Igdlukúnguaq into two categories, rectilinear and flame-like, assuming the former to have unmixed at about 700° C along the prism and pyramid planes of the pyrrhotite. In regard to the latter, Pauly deems it possible that they exsolved from the pyrrhotite likewise along the prism and pyramid planes but, in contrast to the former, only at approximately 550° C and originally as chalcopyrrhotite, which subsequently passed over to chalcopyrite, the excess of FeS being transferred to the surrounding pyrrhotite host. Pauly bases his assumption on the fact that the pyrrhotite undergoes transformation between 550 and 575° C (Roberts, 1935) and that Borchert (1934) had perceived in pyrrhotite during laboratory tests the same kind of chalcopyrite lamellae, which formed at a temperature of about 550° C.

As for the triangular chalcopyrite lamellae of Petolahti, they resemble in texture and mode of occurrence most closely the rectilinear chalco-

pyrite lamellae described by Pauly, on the evidence of which it is conceivable that their exsolution had also taken place at approximately the same temperature, or around 700° C. At any rate, it is clear that the texture in question formed at an exceedingly high temperature by the unmixing of an extensive solid solution of pyrrhotite and chalcopyrite.

CHALCOPYRITE LAMELLAE PARALLEL TO THE BASAL PLANE OF PYRRHOTITE

Chalcopyrite lamellae forming a triangular network, as described in the foregoing, are met with in only a few portions of the ore. On the other hand, in nearly all the specimens representing disseminated olivine diabase, the pyrrhotite contained chalcopyrite lamellae following the basal direction of the host. The length of the lamellae varies between 100 and 400 μ and the breadth between 10 and 70 μ ; accordingly, they are distinctly larger than the triangular chalcopyrite lamellae. They are, however, substantially smaller in quantity, at most about 10 % of that of the host mineral. Around the lamellae, especially their terminal parts, there occurs in many cases an abundance of pentlandite flames running in the same direction, as shown in Pl. I, 2. The construction clearly reveals that, also in this instance, the chalcopyrite represents a true exsolution product and that it had exsolved prior to the pentlandite, or above the temperature range of 310—425°, which is generally considered to be the exsolution temperature of pentlandite flames (see p. 47).

Like the triangular chalcopyrite lamellae, also the lamellae oriented along the basal plane usually have a sharp boundary against the surrounding host mineral. One polished section, however, revealed at the edges of some chalcopyrite lamellae // (0001) a thin rim of quite fine-grained pyrrhotite, which, judging by its mode of occurrence, derives from the original exsolution. It is therefore apparent that, at least in this case, the exsolution did not take place initially as chalcopyrite but as some component containing more FeS, which subsequently passed over into chalcopyrite and the fine-grained pyrrhotite surrounding it. The component richer in FeS had possibly been chalcopyrrhotite, which has been reported to remain stable between about 255° and 550° C and which above the latter temperature forms solid solutions with pyrrhotite. The solid solution of these two minerals begins to unmix at about 550° C (Borchert, 1934). In accordance with the experimental results obtained by Borchert, the unmixing temperature of the chalcopyrite lamellae surrounded by the fine-grained pyrrhotite rim may be readily set at about 550° C, or the same temperature at which Pauly (op. cit.), on pretty much the same grounds, assumes the so-called flame-like chalcopyrite lamellae to have unmixed.

Only one polished section, as pointed out already, revealed the presence of fine-grained pyrrhotite along the margins of chalcopyrite lamellae running parallel to the basal plane. It is conceivable that the excess FeS separated from the assumed chalcopyrrhotite had elsewhere transferred completely to the surrounding pyrrhotite, just as Pauly assumes to have occurred during the formation of the flame-like chalcopyrite lamellae of the Igdlukúnguaq ore. On the other hand, it is equally possible that part of the chalcopyrite lamellae situated parallel to the basal plane had unmixed directly as pure chalcopyrite, another part, again, as an iron-richer material comparable to chalcopyrrhotite. The exsolution temperature was probably in each case, however, very nearly the same, or approximately 550° C.

Chalcopyrite lamellae parallel to the basal plane of pyrrhotite have not been described previously from natural occurrences, so far as is known; accordingly, together with triangular chalcopyrite lamellae, they must be considered an exceedingly rare phenomenon. On the other hand, Hewitt (1938), for example, has observed in laboratory tests that in pyrrhotite-chalcopyrite ore rapidly cooled after being heated near the melting point the precipitation of the last-mentioned takes place at about 600° C as lamellae parallel to the basal direction of pyrrhotite. This clearly shows that exsolution bodies of chalcopyrite may form at a high temperature in connection with rapid cooling — a fact that fits in well with what has been observed regarding exsolution bodies of chalcopyrite of the Petolahti pyrrhotite.

PENTLANDITE FLAMES IN PYRRHOTITE

Pentlandite flames oriented in the basal direction of pyrrhotite, as observable in most other nickeliferous pyrrhotite ores, are met with quite regularly also in the disseminated ore of Petolahti, although their quantity even in different parts of the same pyrrhotite grain varies greatly. They occur in greatest abundance around the above-described chalcopyrite lamellae as well as near the edges of the grains, especially at such points as where the pyrrhotite lies adjacent to a free pentlandite grain. The exsolved pentlandite is in cases of the last-mentioned kind often so abundant that the boundary between the minerals referred to is hard to distinguish even under a microscope (Pl. III, 1). Such a texture distinctly shows that the precipitated pentlandite has diffused to the grain boundaries of the pyrrhotite and segregated as larger, unified grains. Evidently, on account of the rapid cooling, the diffusion process had been interrupted and a considerable portion of the pentlandite remained in the pyrrhotite as exsolution bodies.

The pyrrhotite has in some cases included 20—30 % — and even as much as 40 % — pentlandite exsolved from it, as measured in relation to the total quantity of the intergrowth. Since it has been noted that pentlandite will dissolve in pyrrhotite to the extent of about 40 % at temperatures above 425—450° C (Newhouse, 1927 and Hewitt, 1938), it is evident that also the mix-crystals of pyrrhotite and pentlandite from Petolahti must have formed above the temperature range mentioned. On the basis of chalcopyrite lamellae met with in the same exsolution intergrowths, crystallization may have taken place even above 700° C. The unmixing of pentlandite from pyrrhotite is assumed by, e. g., Hawley, Colgrove & Zurbriigg (1943) as well as Pauly (1958) to occur within the temperature range of 310 and 425° C, possibly at about 315—318° C in the main, where pyrrhotite undergoes a sudden reversible transformation (Roberts, 1935). As the amount of pentlandite unmixed from pyrrhotite at Petolahti has in some cases been unusually large, several dozen per cent, in fact, its unmixing in these cases had evidently started at the upper end of the temperature range, or at about 425° C.

No other exsolution bodies besides those of the chalcopyrite and pentlandite described in the foregoing were met with in the pyrrhotite. For its own part, the pyrrhotite occurs as exsolution bodies in the pentlandite and cubanite, as will be set forth in greater detail in connection with the descriptions of them.

CHALCOPYRITE

The amount of chalcopyrite contained in the disseminated olivine diabase averages about one-half the amount of pyrrhotite. For the most part, it occurs at the margins of the considerably coarser-grained pyrrhotite in conjunction with pentlandite and secondary magnetite. In some cases, chalcopyrite has replaced both the pyrrhotite and the pentlandite, less often also the plagioclase and the pyroxene. The chalcopyrite contains exsolution bodies of cubanite and pentlandite as well as an extremely fine-grained intergrowth of pyrrhotite, chalcopyrite, pentlandite and magnetite, probably formed by the breakdown of primarily exsolved chalcopyrrhotite.

EXSOLUTION LAMELLAE OF CUBANITE IN CHALCOPYRITE

The most common of the minerals unmixed from chalcopyrite is cubanite, which usually accounts for about 10 % of the total amount of the intergrowth, in some cases as much as 20—30 %. The cubanite occurs as characteristic rectilinear lamellae running evidently in the (111) directions of the chalcopyrite host.

As shown in Pl. III, 2, IV, 1 and VIII, 1, abundant pyrrhotite has unmixed from the thicker cubanite lamellae, in particular, as small blades, some of which run parallel to the longitudinal direction of the cubanite lamellae while others form two or more sets of diagonal intersecting blades. A nearly identical cubanite-pyrrhotite intergrowth has been described by Newhouse (1931) from Frood Mine, Sudbury, and by Ödman (1933) from Kaveltorp.

Certain of the pyrrhotite blades found in the cubanite lamellae proved to contain tiny, unoriented grains of an isotropic mineral softer than pyrrhotite and with a high reflectivity. Judging by the mode of occurrence and properties of the mineral, it is evidently pentlandite unmixed from pyrrhotite and representing the third unmixing generation.

As pyrrhotite unmixed from cubanite is present in many cases in nearly the same abundance as the host mineral, it appears that the cubanite could contain as a solid solution quite an appreciable FeS-surplus, whereupon it approaches in composition chalcopyrrhotite broken up into various mineral mixtures, to be dealt with later on. On the other hand, the amount of NiS likewise contained in the original cubanite as a solid solution has been very slight.

According to Ramdohr (1960), the unmixing of cubanite from chalcopyrite takes place between 300° C and 250° C. Apparently, also the unmixing of the cubanite of the Petolahti ore should be placed within this temperature range. The abundant excess of FeS in the cubanite, along with the smaller amount of NiS, justifies the assumption that the unmixing took place at the upper end of the temperature range in question, or approximately 300° C.

AREAS OF FINE-GRAINED INTERGROWTHS OF PYRRHOTITE, CHALCOPYRITE, PENTLANDITE
AND MAGNETITE IN CHALCOPYRITE

Besides cubanite lamellae, a fair abundance of fine-grained, shuttle-shaped inclusions, the chief component of which is without exception a very fine-grained pyrrhotite, is met with in the marginal parts, especially, of chalcopyrite grains. Regular additional components of the inclusions are chalcopyrite and magnetite, both of which most usually occur as lamellae running parallel to the longitudinal direction of the shuttle-shaped inclusions. The average share of each is 10—25 % of the total quantity of the mineral mixture. On the other hand, the share of the likewise very fine-grained pentlandite occurring at the edges of the shuttles is ordinarily much smaller, in some cases, however, nearly 20 % (Pl. IV, 1 & 2).

The fine-grained shuttles vary in length between 50 and 150 μ , the thickness being 10—50 μ . They distinctly differ in orientation from the

cubanite lamellae, judging by which the fine-grained material in question was not formed by the breakdown of cubanite but rather genetically represents quite a different phase.

The fine-grained mixture of pyrrhotite, chalcopyrite, pentlandite and magnetite is often met with not only as shuttle-shaped inclusions, as described in the foregoing, but also as thin rims along the margins of chalcopyrite grains. In such cases, the magnetite sometimes occurs as a regular octahedral network in the fine-grained substance, offering evidence that this substance must once have been a homogeneous phase with a isometric crystal structure (Pl. V, 1).

To judge by the mineral composition and mode of occurrence of the fine-grained substance, it is quite probable that it originally formed as the homogeneous Fe—Cu—Ni-sulfide unmixed from the chalcopyrite. On the basis, e. g., of the relative abundance of the various components of the mixture, it seems quite possible that this homogeneous Fe—Cu—Ni-sulfide could have been chalcopyrrhotite, which, according to Ramdohr, is a isometric CuFeS_2 —FeS mix-crystal produced at a high temperature and varying in composition. It usually contains NiS as well, which would seem to have a significant effect on the permanence of the mix-crystal (Ramdohr, 1960). According to Borchert (1934), chalcopyrrhotite is stable between 255° C and 550° C and forms a solid solution with chalcopyrite above 450° C. On cooling, the solid solution begins to unmix at 450° C, and unmixing is complete at about 255° C, below which temperature the chalcopyrrhotite disintegrates, depending on the circumstances, into various mixtures containing chalcopyrite, pyrrhotite, cubanite and vallerite.

On the basis of the results presented by Borchert (*op. cit.*), the fine-grained pyrrhotite-chalcopyrite-pentlandite-magnetite mixture met with in the Petolahti chalcopyrite may be assumed to have formed as follows: at a temperature of about 450° C a nickeliferous chalcopyrrhotite started to unmix from the chalcopyrite and in unmixing it had a strong tendency to diffuse toward the margins of the host mineral. After the temperature had dropped to around 255° C, the chalcopyrrhotite broke down into pyrrhotite, chalcopyrite and pentlandite. Evidently, in conjunction with the disintegration, there regularly formed in the mineral mixture magnetite, too, as described in the foregoing. In this connection, it is interesting to note that a description has been given from among the sulfide ores of Kaveltorp of lamellar magnetite occurring in practically the same way as a disintegration product of cubanite together with pyrrhotite and chalcopyrite (Ödman, 1933). Both Ödman and Ramdohr (1960) regard the occurrence of magnetite in this connection as evidence that the disintegration of cubanite has in some way been connected with oxidation. Apparently, the disintegration of the chalcopyrrhotite of Petolahti likewise took place under

oxidizing conditions. However, it is further possible that the original chalcopyrrhotite contained more iron than the sulfides occurring as its disintegration products and that this excess of iron has been deposited as magnetite.

EXSOLUTION BLADES OF PENTLANDITE IN CHALCOPYRITE

In a number of chalcopyrite grains containing the above-described exsolution products in greater than ordinary abundance, pentlandite was also observed here and there as narrow blades, measuring 40—200 μ in length and 2—30 μ in thickness, and having the same orientation as the fine-grained pyrrhotite-chalcopyrite-pentlandite-magnetite shuttles (Pl. III, 2 and Pl. IV, 1).

Judging by the mode of occurrence of the pentlandite lamellae, it would seem that what we have here, too, is a true unmixing texture. Furthermore, it may be noted from numerous polished sections that the cubanite lamellae break off where the pentlandite lamellae are situated — evidence indicating that the cubanite unmixed after the pentlandite. In other words, the unmixing temperature of the pentlandite must have been above at least 300° C, the temperature at which the cubanite is believed to have unmixed.

It is apparent from the above-described unmixing textures that, in addition to the abundant FeS excess, the chalcopyrite could also have contained a smaller amount of Ni-sulfide, accounting for at most a few per cent of the total, which unmixed in part as pure pentlandite blades, in part, at about 450° C, as chalcopyrrhotite containing 1—20 % pentlandite components, and finally, at about 300° C, as cubanite containing a very small amount of NiS. Since chalcopyrite can evidently contain as a solid solution substantially more Fe-sulfide than Ni-sulfide, it is highly probable that of the exsolution products mentioned the pentlandite blades formed at the highest temperature of all; accordingly, their unmixing temperature must also be placed above 450° C.

In this connection, it is interesting to note that Pauly has described from Igdlukúnguaq chalcopyrite crystallized at a remarkably high temperature and presumably containing a small amount of pentlandite components as solid solution (Pauly, 1958, p. 84). The observations made at Petolahti indicate that such mix-crystals of chalcopyrite and pentlandite really can exist at high temperatures, thus strongly supporting Pauly's view.

PENTLANDITE

As already stated, the ore of Petolahti contains an exceptional abundance of pentlandite. Its content in the disseminated ore is practically equal to that of chalcopyrite, or nearly one-half the pyrrhotite content (Fig. 15,

p. 37). For the most part the pentlandite occurs as roundish grains 0.1—2 mm in diameter situated along the margins of pyrrhotite grains of a somewhat greater coarseness together with chalcopyrite. A small part of the pentlandite occurs as exsolution products, described in the foregoing, in the pyrrhotite and the chalcopyrite, both of which, in turn, are present as unmixed minerals in pentlandite.

One spectrographic cobalt, copper and arsenic determination made from a pentlandite grain about 4 mm in diameter yielded the following result: Co = 0.55 %, Cu = 0.5 %, As = 0.1 % (A. Löfgren). In view of the fact that even the largest magnification of the analyzed sample revealed no cobalt or arsenic minerals, the metals in question must be concealed in the pentlandite structure. On the other hand, the copper content may be attributed, at least in part, to the chalcopyrite, which in some cases occurs in pentlandite as small inclusions and veinlets. According to the analysis herein presented, the pentlandite of the disseminated ore is relatively poor in cobalt — just as is the ore as a whole. To cite an example for the sake of comparison, the average cobalt content of the pentlandite in certain of the Sudbury ores is 0.85 % (see p. 56).

EXSOLUTION BODIES OF PYRRHOTITE IN PENTLANDITE

In all the thin sections in which the pentlandite has been only slightly or not at all bravoitized, high magnification reveals the presence of pyrrhotite as extremely small (1—10 μ), roundish inclusions, which in most cases consist of numerous pyrrhotite crystals oriented in different ways. Owing to the tiny size of the crystals, their orientation in relation to the pentlandite cannot, however, be accurately determined. Often there is a fair abundance of these pyrrhotite inclusions, amounting to approximately 5—15 % of the quantity of pentlandite, and they are distributed as an even emulsion throughout the host, as shown in Pl. V, 2.

Pyrrhotite inclusions of the kind described in the foregoing have occasionally been met with in considerable abundance, as, e. g., in the pentlandite of some Sudbury ores. Ramdohr (1960), among others, interprets them as exsolution products indicating the extraordinarily high crystallization temperature of pentlandite. In heating and crystallization experiments carried out with both natural and artificial sulfide mixtures, it has been noted that at high temperatures pentlandite can dissolve into its structure a substantial FeS excess, which unmixes as pyrrhotite when the temperature falls (Hewitt, 1938, and Hawley, Colgrove & Zurbrigg, 1943). The rare occurrence of pyrrhotite exsolution products in natural pentlandites may be due, according to, e. g., Hewitt (op. cit.), to the fact that the unmixing takes place at high temperatures where diffusion is rapid and the segre-

gation of the minerals referred to, especially in slowly cooled natural occurrences, is consequently complete.

Judging also by the mode of occurrence of the pyrrhotite exsolution products found in the pentlandite of Petolahti, it is evident that they formed by unmixing from pentlandite containing a 5—15 % FeS excess. Like numerous other exsolution products, they suggest, in addition to a high crystallization temperature, also a rapid cooling of the ore.

EXSOLUTION BODIES OF CHALCOPYRITE IN PENTLANDITE

Besides bleb-like pyrrhotite exsolution products, the pentlandite more seldom contains rectilinear chalcopyrite lamellae, which are oriented according to some particular crystallographic direction — perhaps (111) — of the pentlandite. The lamellae measure only 1—5 μ in thickness, their share of the total intergrowth being approximately 10 % (Pl. VI, 1). Somewhat more commonly, chalcopyrite is present in the pentlandite as roundish inclusions or as vein-like, irregularly oriented lamellae, as shown in Pl. V, 2. Since the vein-like chalcopyrite bodies do not extend beyond the pentlandite, it is probable that, just like the above-mentioned oriented chalcopyrite lamellae, they have formed by the unmixing of chalcopyriteferous pentlandite. It should be added that chalcopyriteferous pentlandite of the kind referred to has almost without exception become situated along the borders of pyrrhotite grains.

One pyrrhotite grain was found to contain a pentlandite-chalcopyrite intergrowth, occurring as a roundish inclusion, in which the chalcopyrite was present in exceptional abundance, or about 25 % of the total. Roughly half the chalcopyrite occurs as an irregular rim around the edges of the inclusion, the rest as an intimate lamellar intergrowth with pentlandite (Pl. VI, 2). Judging by the texture and mode of occurrence of the intergrowth, it is evident that it formed during the unmixing of an originally homogeneous pentlandite containing in this case about 25 % chalcopyrite as a solid solution. Upon unmixing, about one-half the chalcopyrite migrated into the boundaries of the original mix-crystal, the other half remaining as a lamellar network in the pentlandite.

Exsolution bodies of chalcopyrite of the kind described in the foregoing are apparently quite rare in natural pentlandite. Recently, however, Pauly (1958) has described similar textures from the nickeliferous pyrrhotite of Igdlukúnguaq. The intergrowth of pentlandite and chalcopyrite occurs here partly as roundish inclusions in pyrrhotite, partly as so-called pore material. In each instance, Pauly assumes the intergrowth to have formed by the breakdown of a solid solution of pentlandite with 10—15 % chalcopyrite. Terming it chalcopentlandite, Pauly believes it to have unmixed

from pyrrhotite at a temperature of approximately 850° C. Upon the temperature's falling further, to perhaps around 600° C, the chalcopentlandite disintegrated for the most part into pentlandite and chalcopyrite, some of it remaining as a non-exsolved mix-crystal.

Comparing the intergrowths of pentlandite and chalcopyrite met with in the Petolahti ore with corresponding ones occurring at Igdlukúnguaq, it becomes evident that a phase warranting the designation of chalcopentlandite has also evolved at Petolahti, though in far smaller quantity than at Igdlukúnguaq. Since, to judge, for example, by the triangular exsolution networks of chalcopyrite met with in the pyrrhotite, the Petolahti ore started to solidify at a remarkably high temperature — evidently above 700° C, — it is quite possible, too, that in certain rare cases there could have unmixed from the pyrrhotite some chalcopentlandite as well, which to a certain extent was left as inclusions in the pyrrhotite but mostly migrated to the grain boundaries of the host. Conceivably, the unmixing took place at around 850° C, as, according to Pauly, in the case of the Igdlukúnguaq ore.

OXIDE MINERALS

In addition to sulfides, the Petolahti ore contains small amounts of titanomagnetite, ilmenite, magnetite, hematite and limonite. The first two, as well as the magnetite, to some extent, occur apart from the sulfides as finely disseminated grains, accounting for only about one per cent of the total ore minerals. Titanomagnetite, ilmenite and magnetite are sometimes present also as inclusions in the sulfides. Since, moreover, the sulfides have in many instances conspicuously replaced them — notably the magnetite component of the titanomagnetite —, it is plain that the titanomagnetite and the ilmenite as well as a portion of the magnetite crystallized before the sulfide minerals (Pl. VII, 1). As regards the texture of the oxide minerals, it should be remarked that the unmixing of the titanomagnetite has generally produced an extremely fine-grained lattice intergrowth of magnetite and ilmenite. In certain instances, the fine-grained exsolution matter grades over by degrees into pure ilmenite or, then, into a nearly isotropic substance, which is apparently non-exsolved titanomagnetite (Pl. VII, 2). According to Ramdohr (1960), non-exsolved titanomagnetite is generally met with in effusive rocks; accordingly, its occurrence also in the Petolahti diabase is altogether possible.

For the most part, the magnetite contained in the ore under consideration occurs, in contrast to the oxide minerals described in the foregoing, which solidified at an early stage, as a thin band between the sulfides and silicate minerals and is thus distinctly younger than the sulfides. Under the microscope, one can distinguish in the magnetite band variously colored

or differently pigmented zones, as shown in Pl. VIII, 1. Since, moreover, the magnetite often contains as inclusions the sulfide it borders, it is clear that the magnetite must have formed here at the expense of the sulfides. The oxygen of the magnetite apparently derives from the residual mineralizing solutions, whereas the iron in the magnetite could easily have derived from replaced sulfides. Evidently at the same stage and in the same way, magnetite formed also in cleavages and fractures of pyrrhotite, pentlandite and chalcopyrite (Pl. VIII, 2).

The occurrence of magnetite as bands like those described in the foregoing between sulfides and silicates is fairly general in various sulfide ores, having been described by, among others, Ödman (1933) from Kaveltorp and Saksela (1938) from Nivala. Ödman, too, thinks that the magnetite formed in the reaction between sulfides and oxidizing hydrothermal solutions, which evidently have been ascendent in origin.

Characteristic of the above-described magnetite occurring along the edges and in the cracks of sulfides is the fact that the bordering sulfides have not altered in the least. This may be regarded as indicative of the fact that the magnetite in question had formed at a relatively high temperature, possibly immediately after the solidification of the sulfides. The magnetite occurring as fracture veins grades over, however, without any distinct border into magnetite of obviously later derivation, which evolved as an alteration product of pyrrhotite along with pyrite and marcasite (see pp. 61—63).

Hematite and limonite are sporadically met with in conjunction with magnetite filling cracks in the sulfides. In addition, hematite occurs as the sole ore mineral in a number of serpentine veins cutting the diabase.

ORE MINERALS IN THE SULFIDE VEINS

Sulfides also occur in conjunction with the above-described disseminated ore as hair-thin veinlets, which for the most part follow fractures in the rock or cleavages in the silicate minerals. In these veinlets, the pentlandite and, especially, chalcopyrite are much more abundantly represented, as compared to the pyrrhotite, than in the disseminated ore proper. The enrichment of these minerals is even more clearly to be seen in the sulfide veins, in most cases fairly compact, measuring between 1 and 10 mm in thickness and injected into the rectilinear fractures of the diabase. Some of the veins contain no pyrrhotite whatsoever. In lieu of it one sometimes runs across pyrite in small amounts as iron sulfide. In addition to the sulfide minerals mentioned, the veins regularly contain a few percentages of magnetite. Serpentine and carbonate, on occasion quartz, too, are met with in varying amounts as gangue minerals. The mineral composition of a few of the sulfide veins is presented in Fig. 15, p. 37.

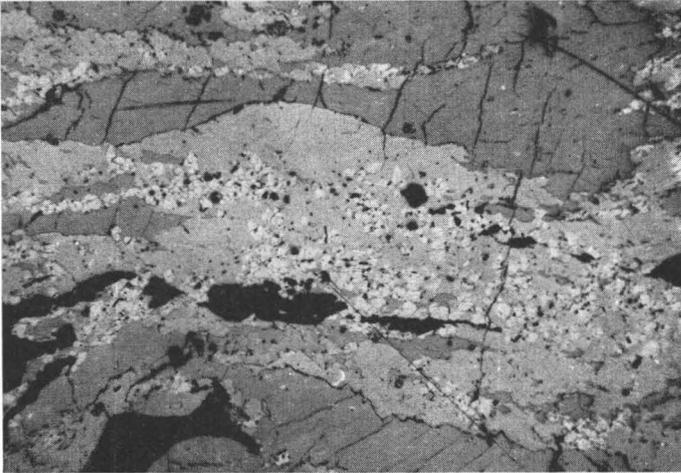


Fig. 20. Polished section, $\times 70$, nic. //, oil immersion. Banded texture in a sulfide vein. Pentlandite (light) and chalcopyrite (light grey) as fine-grained bands, pyrrhotite (grey) as larger, deformed crystals. Drill hole 4.

PYRRHOTITE

In the sulfide veins, the pyrrhotite most usually occurs as a fine-grained mosaic in conjunction with chalcopyrite and pentlandite, which in such cases are often arranged in bands running parallel to the longitudinal direction of the vein (Fig. 20, p. 55). Less often the pyrrhotite occurs also as larger grains, nevertheless measuring less than 1 mm in diameter, in which a bending in the cleavages (0001) and translation along basal plane can in numerous instances be observed. Such clear signs of deformation are totally lacking in the pyrrhotite of the disseminated ore. On the other hand, the pentlandite and chalcopyrite exsolution bodies characteristic of the last-mentioned are not met with at all in the pyrrhotite contained in sulfide veins.

PENTLANDITE

The pentlandite of sulfide veins is often brecciated into small angular pieces (Fig. 21, p. 56) or granulated into an exceedingly fine-grained mosaic, occurring in such cases as mentioned in connection with the description of the pyrrhotite. Exsolution bodies are not found in the pentlandite any more than in the pyrrhotite.

In contrast to the pyrrhotite, the pentlandite forms a number of nearly monomineral veins 1—10 mm thick. The mineral composition determined

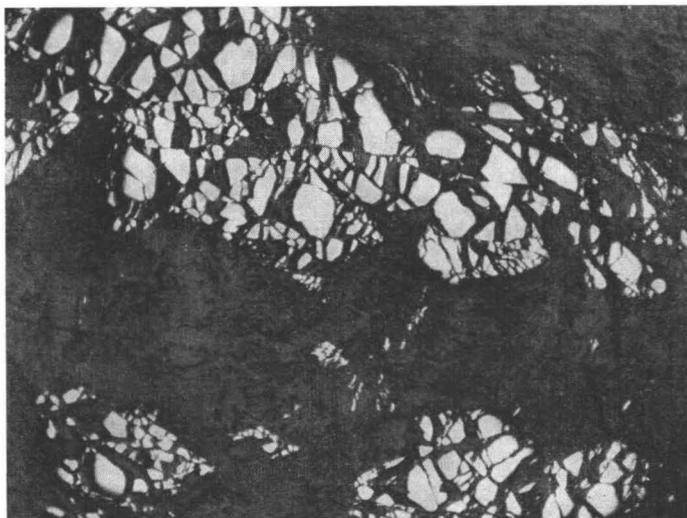


Fig. 21. Polished section, $\times 50$, nic. // . Fractured and brecciated pentlandite in a serpentine vein. Drill hole 12.

from one of these veins is presented in Fig. 15, p. 37. An analysis made from the same vein yielded the following result (Column 1, analyzed by A. Heikkinen, K. Karhunen and P. Väänänen):

	1	2	3
Cu	0.0 %	—	—
Fe	28.4 »	30.1 %	31.85 %
Ni	34.2 »	34.7 »	35.35 »
Co	0.5 »	0.85 »	—
S	36.9 »	33.21 »	32.8 »
	100.0 %	98.86 %	100.0 %

Column 2 gives the average composition of the pentlandite analyzed from three ores from the Sudbury area (Frood, Greighton and Copper Cliff), according to Dickson (1904), and Column 3 the theoretical composition of pentlandite on the basis of the formula $(\text{Ni} \cdot \text{Fe})_9\text{S}_8$ and the ratio $\text{Ni} : \text{Fe} = 11 : 10$.

Comparing the analytical results, one will note that the pentlandite of Petolahti contains sulfur somewhat in excess of the theoretical formula. This probably is partly because there was a slight amount, about 5 %, of pyrite in the fractures of the analyzed pentlandite. Further noteworthy in the composition of the pentlandite under consideration is its small co-

balt content in comparison with the pentlandites of Sudbury. The (Fe + Co) : Ni ratio in the analyzed material = 10 : 11.8. Since a small part of the iron is bound in the pyrite present as an impurity, the ratio 10 : 12 probably better corresponds to the composition of pure pentlandite. In the majority of natural pentlandites, this ratio varies, according to Ramdohr (1960), between 10 : 10 and 10 : 11, so that the pentlandite analyzed from Petolahti may be considered slightly richer in nickel than is usual.

CHALCOPYRITE

The chalcopyrite, which is on the average the most abundant ore mineral of the sulfide veins, is most frequently likewise totally free of exsolution products. In a certain 10 mm-thick vein coarser of grain than usual are nevertheless to be found numerous rectilinear cubanite lamellae containing an abundance of lenticular pyrrhotite exsolution bodies. Quite a similar unmixing texture has been previously described in connection with the chalcopyrite of the disseminated ore (see p. 48).

PYRITE

In the disseminated olivine diabase, pyrite occurs only as a secondary alteration product of pyrrhotite (see pp. 61—63). On the other hand, it is met with in a number of sulfide veins as thin veinlets in the fractures of the pyrrhotite and the pentlandite. Pyrite occurring in this way has evidently crystallized primarily after the pyrrhotite and the pentlandite.

GALENA

Some of the sulfide veins contain very small amounts of a light bluish grey isotropic mineral distinctly softer than the chalcopyrite. It occurs in the chalcopyrite — in some instances also in the pyrrhotite — as bleb-like inclusions 5—30 μ in diameter. The powder photograph of this mineral revealed clear galena lines (K. Neuvonen). Also the etch reactions of the mineral (HNO_3+ , $\text{HCl}+$, FeCl_3+ , $\text{KCN}-$, $\text{KOH}-$ and HgCl_2-) fit galena well, as does also its reflectivity (green 23 %, orange 23 % and red 22 %), as measured with a photometer ocular in an oil immersion.

SILVER

In the sulfide vein with the greatest abundance of the above-described galena, also some grains measuring 1—10 μ in diameter of a very bright and soft mineral were observed. It occurs as bleb-like grains mostly in

conjunction with galena but also alone in the chalcopyrite. The etch tests yielded the following results: HNO_3+ , $\text{HCl}+$, $\text{KCN}+$, FeCl_3+ , $\text{KOH}+$, HgCl_2- . The reflectivity obtained with a photometer ocular in an oil immersion was as follows: green 65 %, orange 68 % and red 70 %. Although the results cited cannot be regarded as completely reliable on account of the smallness of the grains, they do indicate, as does also the fact of the mineral's occurring in conjunction with galena, that, however, what is involved is metallic silver, 4 g/t of which the ore contains on the average.

MAGNETITE

Only magnetite among oxide minerals is met with in the sulfide veins, varying in amount between one and five per cent. Magnetite occurs most usually as a thin rim along the edges of the veins, less often as tiny grains between the sulfide grains or as inclusions in the sulfides. The sulfides frequently are met with as filling in fractures in the magnetite; indeed, certain of the magnetite grains have become nearly completely replaced by sulfides. Accordingly, it is reasonable to conclude that the magnetite here solidified in toto before the sulfides differing in this respect distinctly from the magnetite found in the disseminated ore (see pp. 53—54).

ORE MINERALS IN THE DISSEMINATED WALL ROCK OF THE DIABASE

As previously pointed out, the rather low-grade mineralization met with in the wall rock extends at most a few dozen centimeters from the contact of the diabase. The sulfides occur here partly as finely disseminated grains in a granophyric intergrowth of feldspars, quartz and chlorite, but mainly as roundish or elongated blebs 1—10 mm in diameter, in which no regularity in the arrangement of the ore minerals can be detected (Fig. 22, p. 59). Instead of the paragenesis pyrrhotite + pentlandite + chalcopyrite one runs in places across the paragenesis pyrite + violarite + chalcopyrite, which reveals a more abundant content of sulfur. Oxide minerals are almost totally lacking in the disseminated wall rock.

PYRRHOTITE

Both pyrrhotite and pyrite are present in the disseminated wall rock as iron sulfide. There is usually a greater amount of the former, though in spots pyrite is the only iron sulfide present. To a certain extent, pentlandite flames parallel to the basal plane of pyrrhotite are met with as

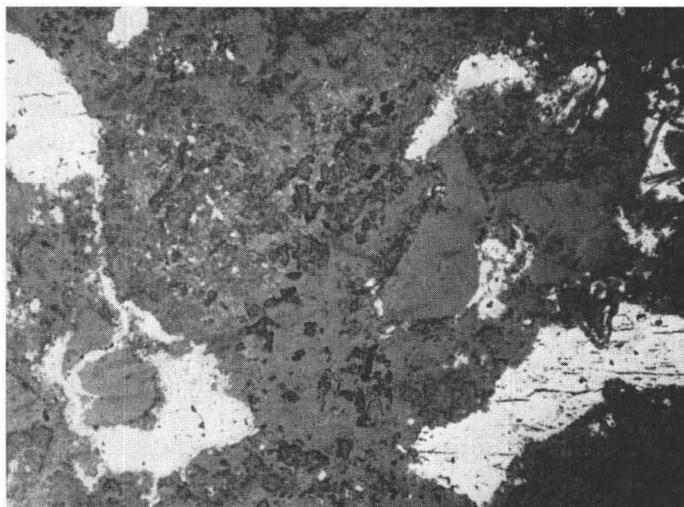


Fig. 22. Polished section, $\times 10$, nic. // . Photo E. Halme. Disseminated wall rock of the diabase. Pyrrhotite, chalcopyrite and pentlandite (light) are situated in the granophyric alkali feldspar-quartz-chlorite intergrowth surrounding roundish quartz blebs (grey, flat). Drill hole 4.

exsolution products, as are chalcopyrite lamellae oriented in the same direction. Both of them occur in quite the same way as in the pyrrhotite of the disseminated olivine diabase. The amount of exsolution bodies, however, is many times smaller in the wall rock (see pp. 45—47).

PYRITE

The pyrite occurs as large, rarely idiomorphic grains, which appear under the microscope to be wholly or almost wholly isotropic. A certain amount of pyrite occurs also as thin veinlets cutting through the sulfides and silicates. No signs could be detected in either these or the large independent pyrite grains of the pyrite's being a secondary alteration product of pyrrhotite, as is the case in the disseminated olivine diabase.

PENTLANDITE

Like the pyrrhotite and the pyrite, the pentlandite also occurs mostly as rather large, independent grains. Bleb-like exsolution bodies of pyrrhotite characteristic of the pentlandite present in the disseminated olivine diabase were met with in only a few grains and even then in slight amounts. The same was true of exsolution lamellae of chalcopyrite.

VIOLARITE

In the places where the pyrite occurs as the dominant iron sulfide, the nickel constituent is a coarse-grained isotropic mineral which takes a polish rather poorly and which shows an octahedral cleavage like pentlandite but differs from it distinctly on account of its reddish hue. Also compared with bravoite, the color of this mineral is redder. Especially in the marginal parts of the larger grains, measuring 1—2 mm in diameter, a peculiar lamellar structure may often be noted.

The mineral's resistance to polish is somewhat higher than that of chalcopyrite but distinctly lower than that of pyrite. Measured with a photometer ocular, its reflectivity in oil (green 43 %, orange 44 %, red 45 %) is slightly less than that of the pentlandite but corresponds closely to the values given, for example, the linnaeite group of minerals (cf. Uytendogaardt, 1951, p. 20).

From the mineral under consideration, the following metals were determined spectrographically:

Ni, Fe and S	abundant, not accurately determined
Co	0.65 %
Cu	0.4 »
As	0.1 »

On the basis of the powder photograph taken of the mineral the lattice parameter $a_0 = 9.42 \pm 0.02 \text{ \AA}$ was calculated (A. Vormaa). The value obtained corresponds well to the a_0 -values given for violarite in the literature.

CHALCOPYRITE

The chalcopyrite, which is distinctly the most abundant of the ore minerals of the disseminated wall rock, occurs partly as large, separate grains and partly along the borders and within the fractures of pyrrhotite, pyrite, pentlandite and violarite. In the last-mentioned case, the chalcopyrite has replaced, to a considerable extent effectively, the sulfides mentioned. No exsolution products whatsoever were met with in the chalcopyrite.

SPHALERITE

Comparatively a trifle more sphalerite is present on the wall rock side of the diabase than in the disseminated olivine diabase and the intersecting sulfide veins, where it is almost totally absent. The amount, however, is quite modest here, too, as the zinc content, about 0.1 %, also of a pure ore concentrate clearly indicates (see p. 38).

Sphalerite occurs as small, independent grains, mainly along the borders of chalcopyrite. In some cases, it contains unoriented, bleb-like chalcopyrite inclusions, which are apparently exsolution bodies characteristic of sphalerite crystallized at a relatively high temperature. According to Buerger (1934), the unmixing takes place at between approximately 350 and 400° C.

ALTERATION OF ORE MINERALS

Magnetite replacing sulfides and occurring at the borders and in fractures of sulfides was described in the foregoing (pp. 53—54), the assumption being that it had formed under the influence of ascending hydrothermal solutions. In addition, numerous other, later changes took place in the sulfides, of which the most common are the bravoitization of pentlandite and the alteration of pyrrhotite into various aggregates containing pyrite, marcasite, magnetite and non-reflective substances. These alterations are connected without any distinct boundary to the formation of the above-mentioned hypogene magnetite, while, on the other hand, they apparently belong, at least in part, to pure weathering phenomena.

The pyrrhotite has most commonly changed, starting from the middle parts of the grains, into an exceedingly fine-grained substance composed of idiomorphic pyrite crystals 1—20 μ in diameter and magnetite filling their interstices. As may be seen in Pl. IX, 1, the pyrite crystals have become oriented in a certain way, possibly so that their (111) direction runs parallel to the basal plane of the pyrrhotite. Less often, secondary pyrite occurs also as larger grains, measuring nearly a millimeter in diameter, in which the cleavages // (0001) of the original pyrrhotite has been well preserved.

In all the cases where the last-mentioned alteration has taken place, shuttle-shaped magnetite lamellae parallel to the basal plane are also met with in abundance in the pyrrhotite. The pyrrhotite bordering on the lamellae is in some instances quite unaltered, but mostly there has formed around the magnetite a thin rim of an extremely fine-grained mineral colored light grey and possessing a high reflectivity (Pl. IX, 1). The mineral is slightly harder than pyrrhotite and under crossed nicols it shows strong anisotropism with intense color effects. On the basis of its properties, the mineral approximates ordinary marcasite.

In places more than half of the pyrrhotite has changed to a striped substance which takes a poor polish and consists of very fine-grained marcasite bands parallel to the basal plane of the pyrrhotite and a non-reflective material filling their interstices. The latter cannot be accurately determined under the microscope. Possibly the substance in question, consisting of marcasite and a non-reflective material, corresponds to the »hydropyrro-

tite» described by Saksela (1947), which consists of marcasite and hydrous sulfides — according to Lokka's analysis (1943), it may have as high an H_2O content as 7.95 %, the Fe : S being 1 : 2.27. In conjunction with banded marcasite there often occurs coarse-grained pyrite in which the cleavages // (0001) of the original pyrrhotite can sometimes still be recognized, as shown in Pl. IX, 2.

Particularly susceptible to change appears to have been the pyrrhotite containing triangular chalcopyrite lamellae. The most common alteration product is banded marcasite (Pl. X, 1), but in many cases at the expense of the pyrrhotite component there formed pyrite, which now occurs as idiomorphic crystals oriented in a specific way in unaltered chalcopyrite (Pl. XI, 1). In some cases, again, the pyrrhotite has changed as a whole to a non-reflective substance while the triangular chalcopyrite network has remained quite unaltered, as shown in Pl. X, 2.

Everywhere that the alteration of pyrrhotite described in the foregoing has taken place, the pentlandite has also partly altered, starting from the borders and cleavages of the grains, into a sulfide containing more sulfur, in the present case into bravoite. Also in conjunction with bravoitization, magnetite or non-reflective substances have formed in varying amounts. In some cases, however, they are totally lacking.

In contrast to the pyrrhotite and pentlandite, the chalcopyrite exhibited no secondary alteration whatsoever. On the other hand, the cubanite unmixed from the chalcopyrite has often disintegrated into a non-reflective substance, whereas the pyrrhotite blades unmixed from the cubanite before its disintegration have been preserved totally unaltered (Pl. VIII, 1).

As mentioned, the alterations of the sulfides described in the foregoing are quite common in the disseminated olivine diabase. On the other hand, the sulfides in the wall rock of the diabase have remained almost totally unaltered, suggesting that the alteration of the sulfides had taken place particularly under the influence of the oxidizing residual solutions deriving from the diabase. It is noteworthy, in addition, that the serpentine occurring as veins in the diabase has in many cases replaced the sulfides and their alteration products selectively in such a way that only the most resistant marcasite, occurring as bands along the basal planes of original pyrrhotite, has partially been preserved (Pl. XI, 1 and XII, 1). It is evident that the marcasite bands have in such instances formed prior to the serpentine veins. For the most part, the alteration of the sulfides probably took place under the influence of the same ascending hydrothermal residual solutions as in the case of the alteration of the mafic silicates of the diabase into serpentine and other hydrous minerals. Apparently, the alteration of the sulfides, however, continued during a very late stage, joining to an extent the weathering phenomena induced by descending solutions. According to

Ramdohr, the alteration of pyrrhotite into various intergrowths of pyrite and magnetite takes place under the influence of ascending or descending water solutions. The reaction may be regarded, for example, as oxidation taking place according to the formula $6 \text{FeS} + 4 \text{O} = \text{Fe}_3\text{O}_4 + 3 \text{FeS}_2$ (Ramdohr 1960, p. 559).

CRYSTALLIZATION, UNMIXING AND ALTERATION OF ORE MINERALS IN DIFFERENT ORE TYPES

In the following will be presented in summary the textures of ore minerals in different ore types together with a view of the factors that have led to the formation of the textures observed.

DISSEMINATED OLIVINE DIABASE

The first ore minerals to have crystallized in this main ore type of Petolahti are titanomagnetite and ilmenite, which occur in the ore, as in other diabase types, too, as sparce, evenly disseminated grains. Part of the magnetite also belongs in this group of oxide minerals that had crystallized at an early stage.

Although the disseminated sulfides are distinctly younger than the oxide minerals referred to, their solidification also started at a remarkably high temperature, possibly already above about 850° C. On account of their high crystallization temperature, the pyrrhotite, pentlandite and chalcopyrite could form among themselves unusually broad, if not complete, mix-crystals. The exsolution of the mix-crystals gave rise to numerous rare high-temperature exsolution textures, the order of formation of which is schematically represented in the accompanying figure (Fig. 23, p. 64). In places the separation of the components exsolved from the mix-crystals has been almost complete, resulting in the formation of a so-called rim-texture. In this texture, commonly met with in all parts of the ore, the pentlandite and chalcopyrite exsolved from the pyrrhotite occur as a more or less regular rim along the borders of the coarser-grained pyrrhotite. In the main, however, such a rim-like arrangement is probably due to the order of crystallization of the sulfides: The first to crystallize from molten sulfide drops was the pyrrhotite, with a considerable part of the pentlandite and chalcopyrite in solid solution. Next, out of the nickel- and copper-rich sulfide melt remaining outside the mix-crystal there crystallized at the borders of the pyrrhotite grains and in their interstices, in ever-increasing amounts, first the pentlandite and immediately thereafter the chalcopyrite. Like pyrrhotite, also the pentlandite and chalcopyrite have contained an abund-

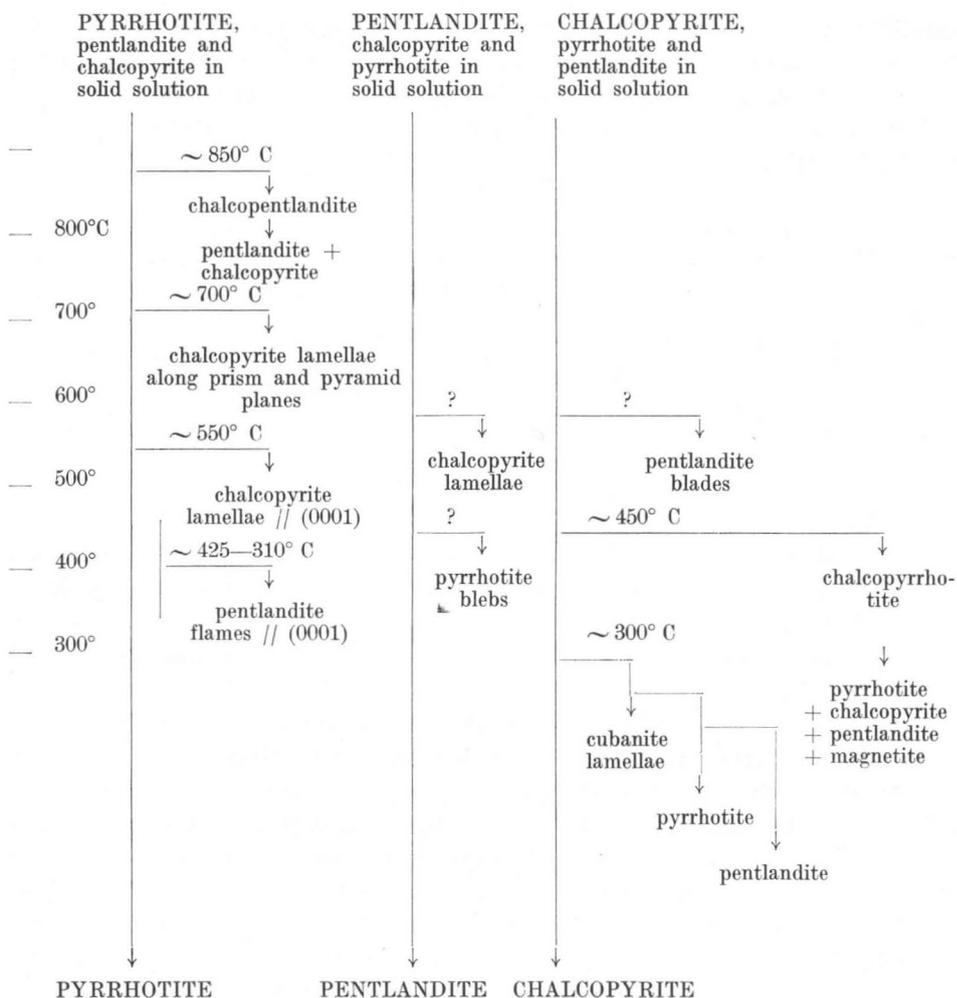


Fig. 23. A sketch representing the succession of the exsolutions in the pyrrhotite, pentlandite and chalcopyrite.

ance of foreign matter — in many instances between 10 and 25 % of the total — the unmixing of which also has led to the formation of numerous unusual exsolution textures (Fig. 23, p. 64).

As will be elucidated in the final section of this paper, the exceptionally high crystallization temperature of the sulfides of the Petolahti ore is due ultimately to the fact that during the initial stage of solidification the sulfide melt contained only very small amounts of volatiles acting to lower the crystallization temperatures. This, again, has a natural enough expla-

nation in the circumstance that the sulfides, like the diabase as a whole, had solidified under hypabyssal conditions, wherein the external pressure and, consequently, also the steam pressure of the volatiles are relatively low. In accordance with hypabyssal conditions, corresponding most nearly to the diabase facies, the cooling of the ore had likewise been rapid, which, for its part, promoted the preservation of apparently quite unstable exsolution intergrowths formed at high temperatures.

After the crystallization and unmixing of the sulfides, there formed through the reactions between them and the residual mineralizing solutions secondary magnetite, which occurs as a thin rim between the sulfides and silicates or as narrow veinlets in the fractures of the sulfides. Also, under the influence of the final oxidizing hydrothermal solutions deriving from the diabase, there took place noteworthy alterations in the sulfides. In places, over half the pyrrhotite underwent alteration into various aggregates containing pyrite, marcasite, magnetite and non-reflective substances. The bravoitization of the pentlandite was nearly of equal strength, but the chalcopyrite, on the other hand, has remained nearly totally unchanged. In part, the alterations are probably connected with weathering phenomena brought about by descending water solutions.

SULFIDE VEINS IN OLIVINE DIABASE

The 1–10 mm-thick sulfide veins cutting across the olivine diabase probably represent the last part to be left in a molten state of the sulfide phase separated from the diabase magma, a part substantially enriched by copper, nickel and volatile constituents as well as, to some extent, sulfur. Evidently, it was expressly the volatiles that augmented the mobility of the fraction in question sufficiently to enable it to intrude into the fractures of the olivine diabase.

The banded texture characteristic of the majority of the sulfide veins investigated, the deformation of the pyrrhotite and the brecciation of the pentlandite clearly demonstrate that the veins had been subjected to shearing movements either during or after their deposition. No exsolution textures whatsoever were met with in such veins; this may be partly due to the fact that the possible exsolution bodies escaped from the deformed sulfides in connection with the movements, and partly to the fact that, owing to the abundance of volatiles, the pyrrhotite, pentlandite and chalcopyrite had crystallized at a temperature relatively low from the very beginning as separate, fairly pure phases. It is noteworthy, however, that in one coarse-grained, only slightly disturbed vein, the chalcopyrite was found to contain an abundance of cubanite lamellae. The occurrence of cubanite exsolution bodies indicates that at least part of the sulfide veins

crystallized at a temperature above the 250—300° C range. Judging by the replacement textures, the ore minerals of the sulfide veins crystallized in the following sequence: magnetite-pyrrhotite-pentlandite-chalcopyrite-pyrite.

DISSEMINATED WALL ROCK OF DIABASE

Like the sulfide veins, the disseminated wall rock of the diabase also contains relatively a good deal more chalcopyrite than the disseminated olivine diabase does. Since one meets with the paragenesis pyrite + violarite + chalcopyrite in places in the wall rock in lieu of the paragenesis pyrrhotite + pentlandite + chalcopyrite, it is evident that in addition to copper also sulfur became enriched in the sulfidic material that traveled, presumably as aqueous interstitial fluids, from the diabase over to the wall rock. There the sulfides became disseminated in a granophyric material surrounding sericitized oligoclase grains, the principal components of this material being alkali feldspars, chlorite and quartz. In certain instances pyrite, occurring as idiomorphic grains, has also grown into bleb-like quartz grains.

The sulfides occur in the ore type in question quite irregularly arranged as free granular aggregates. Together with the slight quantity of exsolution products, this makes evident that the sulfides had solidified at the very beginning as nearly pure mineral species. Judging by the chalcopyrite and pentlandite exsolution bodies sometimes met with in small amounts in the pyrrhotite as well as by the pyrrhotite exsolution bodies in the pentlandite, the solidification process started here, too, however, at a relatively high temperature, evidently above around 550° C.

The formation of secondary magnetite and the subsequent alteration of the sulfides are conspicuously weak in the wall rock of the diabase, probably being due to the fact that the influence of the solutions deriving from the diabase which caused the alterations under consideration had not appreciably extended over into the wall rock.

COMPARISON WITH OTHER DEPOSITS

Inasmuch as it became evident in connection with the study made of the Petolahti deposit that the formation of the high-temperature exsolution textures met with in the sulfide minerals is due primarily to the crystallization taking place in hypabyssal conditions and to the nearly total lack of subsequent movements, I have tried to find suitable comparative material from ore deposits associated expressly with diabases or with comparable rocks. With this in mind, I have acquainted myself with a Finnish and some German nickel-copper deposits all of which have as the primary ore mineral paragenesis pyrrhotite + pentlandite + chalcopyrite. However, the mode of occurrence and primary textures of the sulfides in these deposits are practically identical to those of nickel-copper ores crystallized under ordinary plutonic conditions, so, accordingly, sulfides do not provide many of the exsolution textures I have been seeking, either. On the other hand, the deposit of Igdlukúnguaq, with its variety of exsolution products, affords quite interesting points of comparison, as was remarked in several connections during the foregoing description of the Petolahti ore.

THE NICKELIFEROUS PYRRHOTITE OF IGDLUKÚNGUAQ, GREENLAND

The nickeliferous pyrrhotite deposit of Igdlukúnguaq is associated with a Tertiary basaltic dike. In magnitude it is many times smaller than the Petolahti ore. The thorough microscopic studies carried out by Pauly (1958) of this Greenlandic ore prove incontrovertibly that the greatest portion of the ore's pentlandite and chalcopyrite content had originally been present as a solid solution in the pyrrhotite structure.

The major part of the nickel content of the mix-crystal had, according to Pauly, exsolved at approximately 850° C as chalcopentlandite, which is a high-temperature mix-crystal of pentlandite with 10—15 % chalcopyrite. A portion of the chalcopentlandite remained as roundish exsolution bodies in the pyrrhotite, another portion having migrated as so-called pore material into the interstices of the uniform pyrrhotite areas. With a further drop

in temperature, the largest part of the chalcopentlandite unmixed to form an intimate intergrowth of pentlandite and chalcopyrite. A considerably smaller portion of the nickel unmixed in the form of pentlandite sparks and flames.

The chalcopyrite likewise abundantly unmixed from the pyrrhotite of Igdlukúnguaq forms lamellae oriented along the prism and pyramid planes of the host. Pauly places these lamellae into two categories, rectilinear and flame-like, assuming the former to have formed at about 700° C and the latter at about 550° C. In regard to the flame-like chalcopyrite lamellae, Pauly further considers it possible that the unmixing had initially taken place as chalcopyrrhotite, which only at a subsequent stage passed over to the chalcopyrite, the excess of FeS being transferred to the surrounding pyrrhotite host.

Comparing the deposits of Igdlukúnguaq and Petolahti, it may be remarked first that the solid miscibility of pyrrhotite, pentlandite and chalcopyrite has been considerably more extensive in the case of the former, which is at the same time a clear token of the ore's higher crystallization temperature. From all the evidence, at Petolahti there has formed very little chalcopentlandite, the phase to have unmixed first from the pyrrhotite of Igdlukúnguaq. On the other hand, the pyrrhotite of Petolahti contains a distinctly greater abundance of ordinary pentlandite flames, which evolve under lower thermal conditions, than does that of Igdlukúnguaq.

The unmixing of chalcopyrite from pyrrhotite has led in both ores to the formation of triangular chalcopyrite lamellae. It is not possible, however, to divide the triangular lamellae met with in the pyrrhotite of Petolahti into two categories, for they are assumed to have evolved *in toto* in the higher temperature — i. e., approximately 700° C — suggested by Pauly. In addition, there unmixed from the pyrrhotite of Petolahti a slight amount of chalcopyrite, which forms shuttle-shaped lamellae running parallel to the basal plane. In this case, the unmixing appears to have taken place, at least in part, as a phase originally containing a greater abundance of FeS, possibly as chalcopyrrhotite. The exsolution product is thus comparable particularly to the flame-like chalcopyrite lamellae depicted by Pauly.

THE SULFIDE-BEARING DIABASE OF AHLAINEN, FINLAND

This brief review is largely based on unpublished data I have received from Dr. Juhani Seitsaari, Associate Professor of Geology, University of Helsinki. Prof. Seitsaari has generously also made available to me a few specimens from which I have made a number of microscopic observations of my own.

The diabase of Ahlainen is located in western Finland, on both sides of the boundary between the communes of Ahlainen and Merikarvia. The predominant rock of the near surroundings is a Precambrian mica gneiss of the same kind as in the Petolahti area, some 140 kilometers to the north. Like the diabase of Petolahti, that of Ahlainen cuts across the structure of the mica gneiss, giving proof of its being distinctly younger than the latter, or postorogenic. Judging by the clearcut magnetic anomaly caused by the diabase, it measures about three kilometers in length and between about twenty and fifty meters in thickness over the greatest part of the dike. At one end the diabase dike swells out into a knob approximately 200—300 meters thick and 700 meters long, also marked by a few exposures.

The greatest part of the rock in the exposures is a medium-grained diabase with an ophitic texture. The principal minerals of the rock are plagioclase An_{55} and monoclinic and rhombic pyroxene. In addition, the rock in most cases contains an abundance also of olivine or, as an alteration product of it, serpentine, so that it might be termed olivine diabase. As additional minerals, the rock has slight amounts of biotite, quartz and potash feldspar. Alteration products of the mafic minerals include — usually in abundance — serpentine, talc and chlorite, as in the sample whose chemical composition is presented in Table I, 6, p. 31. The sample analyzed, which probably gives an approximate picture of the composition of the diabase as a whole, is distinctly richer in iron and alkalis but poorer in magnesium than the apophyses and fine-grained contacts representing the average composition of the Petolahti diabase. On the other hand, the composition of the sample is practically the same as that of the olivine diabase of Satakunta, which occurs as numerous large dikes and sills a few dozen kilometers south of Ahlainen (see the analyses in Table I, p. 31).

In the olivine diabase described in the foregoing, which exhibit comparative variety both in composition and in stage of alteration, rather small portions of ultrabasic differentiates finer of grain than the rest of the rock are met with to some extent, too. In addition to olivine and rhombic pyroxene, they contain only a few per cent plagioclase.

The diabase of Ahlainen consistently contains slight amounts of ilmenite and titanomagnetite as ore minerals. In spots there occur disseminated sulfides in non-economic amounts, the quantitative order being pyrrhotite, pyrite, pentlandite, chalcopyrite.

Pyrrhotite occurs as grains measuring 1—2 mm in diameter and in some cases revealing a slight bending of the cleavages as well as translation twinning. A large proportion of the pyrrhotite has changed to pyrite, the cleavage // (0001) of the pyrrhotite still being recognizable. Pyrite occurs abundantly not only as pseudomorphs after the pyrrhotite but also as separate idiomorphic grains, which evidently are primary. Fine-grained

chalcopyrite has been evenly distributed in the disseminated rock. The pentlandite, on the other hand, which in most cases is markedly bravoitized, regularly appears as small grains at the margins of the pyrrhotite. It is also present as flame-like exsolution bodies in very small amounts in the pyrrhotite. No other exsolution products were met with in the samples taken from the exposures of the diabase.

Besides the economically quite insignificant ore prospects met with in the bedrock, some olivine diabase boulders richer in sulfide have been found in the vicinity, having apparently originated from the above-described diabase dike or some other still untraced deposit of the same type. The sulfides are present in these boulders in the way described in the foregoing, but in addition certain exsolution textures are to be observed in them that warrant closer examination in this connection.

Besides pentlandite flames, the pyrrhotite of the boulders referred to contain chalcopyrite shuttles between 50 and 150 μ long running parallel to them and in many cases surrounded by pentlandite flames (Pl. XII, 1). On the basis of the mode of occurrence of the shuttles, it is evident that they correspond to the chalcopyrite lamellae oriented parallel to the basal plane of the pyrrhotite in the Petolahti ore, which were assumed to have unmixed at around 550°C. Wherever the pyrrhotite has changed to pyrite, the chalcopyrite and pentlandite exsolution bodies have been partially preserved. The latter, to be sure, have in such cases totally bravoitized (Pl. XII, 2).

In the same boulders, the pentlandite for the most part occurs as small grains at the margins of the pyrrhotite, which gives grounds to assume that it has unmixed, at least in part, from the pyrrhotite. On the other hand, in some instances a comparative abundance of pyrrhotite has unmixed from the pentlandite, occurring in it as an exceedingly fine-grained emulsion, just as in the Petolahti ore. In addition to the FeS-excess, the pentlandite has also contained a very small amount of copper. It has not, however, unmixed as chalcopyrite as in the Petolahti pentlandite but as vallerite, which is present in the host mineral as small, unoriented flakes. Vallerite has likewise unmixed in small amounts from chalcopyrite, where some exsolution lamellae of cubanite were observed in addition.

Of the exsolution products referred to, the pentlandite, cubanite and vallerite ones are relatively common in high-temperature sulfide deposits (Ramdohr, 1960). By contrast, considerably rarer are chalcopyrite exsolution bodies in pyrrhotite and pyrrhotite exsolution bodies in pentlandite, indicating also in this case the unusually high crystallization temperature of sulfides. The textures suggesting the even higher crystallization and exsolution temperatures characteristic of the Igdlukúnguaq and Petolahti ores are, however, totally lacking in the sulfides met with in the Ahlainen diabase.

ENWUCH AND OTHER SULFIDE-BEARING OLIVINE DIABASES OF THE
DILLMULDE AREA, GERMANY

Several modest nickel-copper-pyrrhotite deposits have been known to exist in the Dillmulde area since the last century. Just as Mosebach (1932) and Ahlfeld (1934) have reported, they are associated with small syn-orogenic olivine diabase intrusions, all of which are characterized by very marked serpentinization, dolonitization, calcitization and silicification as well as a partial — in some cases even total — replacement of the primary ore-mineral paragenesis pyrrhotite + pentlandite + chalcopyrite by younger parageneses, including pyrite, chalcopyrite, bravoite, millerite, gersdorffite and other purely hydrothermal sulfides. The most prominent of the deposits in question are Bellnhausen, Bottenhorn, Hilfe Gottes, Hubertus and Enwuch.

In the summer of 1961, the present writer had the privilege of becoming acquainted with the Enwuch occurrence on the spot through the kindness of Prof. R. Mosebach, Justus Liebig-Universität, Giessen. Consequently, in the following detailed attention will be given only the Enwuch occurrence.

The original ophitic texture and primary mineral assemblage olivine + augite + plagioclase of the Enwuch olivine diabase are, according to Mosebach (op. cit.), still in places clearly recognizable, though for the most part the diabase has changed to a rock mainly composed of serpentine, carbonates and quartz, and penetrated with serpentine, carbonate and quartz veins. For example, all the hand specimens I collected on the spot and studied microscopically have been completely of this extremely altered type.

The sulfides occur in the diabase exclusively as weak dissemination. According to Mosebach, the oldest of the them, pyrrhotite, pentlandite and chalcopyrite, often replace the serpentine present as pseudomorphs after the olivine and have, therefore, crystallized only after the serpentinization of the olivine. Pentlandite flames are met with to a slight extent in the pyrrhotite as exsolution products. Mineral formation did not, however, cease at this point, for subsequently — apparently in connection with the deformation and attendant carbonatization and silicification of the rock — the largest part of the pyrrhotite underwent a change to porous pyrite. At the same stage, new pyrite also crystallized, appearing as idiomorphic grains at the margins of the porous pyrite or quite apart from it. As the pyrrhotite changed, the pentlandite also in most instances disappeared altogether. In lieu of it, there occurs a recrystallized, grainy millerite, which together with chalcopyrite fills the pores in the pyrite or, then, forms quite separate grains.

Unfortunately, the specimens at the disposal of the present writer showed only the paragenesis pyrite + millerite + chalcopyrite, produced at a

purely hydrothermal stage. The sulfides appear in these samples wholly in accordance with Mosebach's description, as reported in the foregoing and shown in Pl. XI, 2. In one polished section, however, no millerite whatsoever was noted; rather is there to be seen in its stead a highly reflective isotropic sulfide revealing quite the same mode of occurrence. The powder photograph taken of the mineral revealed clear pentlandite lines (K. Hytönen). With a $\text{CrO}_3 + \text{HCl}$ solution (Gaudin, 1935) the mineral becomes brilliant blue in color, so that what is involved is evidently ordinary pentlandite.

As the primary pyrrhotite, pentlandite and chalcopyrite in the Enwuch ore crystallized only after the serpentinization of the mafic silicates (Mosebach, *op. cit.*), apparently owing to the abundance of the volatile constituents dissolved in the molten sulfide, it is quite understandable that high-temperature exsolution textures characteristic of the Petolahti ore are not met with at all in them. On the other hand, the Enwuch occurrence provides an interesting example of the alteration of the mineral assemblage pyrrhotite + pentlandite + chalcopyrite at a purely hydrothermal stage. Under such conditions, the minerals cited are no longer in a permanent state but are recrystallized, forming the paragenesis pyrite + millerite + chalcopyrite. In some cases, the recrystallized pentlandite is likely to occur in lieu of millerite.

THE SULPHIDE-BEARING PROTEROBASE DIKE OF SOHLAND AN DER SPREE, GERMANY

According to the descriptions given by Beck (1903) and Oelsner (1954), the economically insignificant nickel-copper-pyrrhotite deposit of Sohland a. d. Spree is associated with a basic dike about ten or twenty meters thick and 1 500 meters long. The texture of the main rock type of the dike, termed biotite proterobase by Beck, is hypidiomorphic and its primary principal constituents are, in order of abundance, augite, plagioclase, brown hornblende and biotite. Secondary minerals include — in some spots in considerable amounts — talc, pale green amphibole, serpentine, chlorite, epidote and sericite.

Abundant deposition of ore minerals has taken place only in the immediate vicinity of one of the contacts of the dike. The ore minerals, pyrrhotite, pentlandite, chalcopyrite and magnetite, occur partly as compact veins following the fractures, but mostly, however, evenly disseminated in the altered proterobase surrounding the veins. In places the disseminated sulfides are also met with in the granitic wall rock of the proterobase. Both Beck (*op. cit.*) and Oelsner (*op. cit.*) emphasize particularly the fact that the sulfides replace the secondary minerals of the proterobase, talc and

pale green amphibole. This is clearly observable also in the few samples at the disposal of the present author. The only exsolution products met with in the sulfides are occasional pentlandite flames in the pyrrhotite.

On the basis of the mode of occurrence of the sulfides, both Beck (*op. cit.*) and Oelsner (*op. cit.*) deem it demonstrated that the sulfides crystallized from high-hydrothermal solutions emanating from deeper down. This conclusion strikes the present writer, too, as well justified. As I see it, the ore formed when volatiles lowering the crystallization temperature and increasing mobility dissolved into the molten sulfide separated from the proterobase magma to the extent that it could inject into the zones of weakness in its host rock. Thus, the ore would be closely comparable in respect to its formation to, e. g., the sulfide veins and disseminated wall rock of the diabase at Petolahti.

CONCLUSIONS

As J. H. L. Vogt's (1918, 1923) classical studies show, molten silicates and sulfides dissolve in each other only at very high temperatures. In waterless melts a nearly total separation takes place already between 1 500 and 1 300° C. Volatile substances, notably water, however, promote solubility to a considerable degree, and in natural, regularly hydrous magmas the separation of silicate and sulfide melts is probably not complete until temperatures of 1 200° C to 1 000° C have been reached. Moreover, the presence of water significantly lowers the crystallization temperatures of both the silicates and the sulfides. To what extent the volatiles remain dissolved in the magma depends primarily on the prevailing external pressure.

A highly illuminating example of the powerful influence of water pressure is offered by the experiments performed by Bowen & Tuttle (1950) with crystallization in the system $\text{NaAlSi}_3\text{O}_8$ — KAlSi_3O_8 — H_2O . At temperatures of crystallization from dry melts (1 063° to 1 150° C), soda and potash feldspars form a complete solid solution series with a minimum temperature of 1 063° C on the liquidus. During cooling, immiscibility begins at about 660° C and the break widens as the temperature falls further. With increasing water pressure, the temperature of crystallization is lowered markedly. At a water pressure of 2 000 bars, the low-temperature point of the liquidus is about 770° C, and at 5 000 bars water pressure (Yoder, Stewart and Smith, 1956), compatible with plutonic conditions, the lowest temperature on the liquidus lies at 695° C, which is within 35° C of the solvus, determined by Bowen and Tuttle (1950) at about 1 000 bars pressure.

Although no corresponding tests have been made regarding the crystallization of sulfides, it is nevertheless quite obvious that the influence of volatiles, particularly water, toward reducing the temperature of crystallization is here at least as marked as in the examples concerning the crystallization of alkali feldspars. As a matter of fact, this is made quite clear also by the crystallization of the paragenesis pyrrhotite + pentlandite + chalcopyrite under volcanic, hypabyssal and plutonic conditions, i. e., conditions characterized by a low, medium or high water pressure.

A remarkable example of ore crystallized under volcanic conditions — that is, with low water pressure prevailing — is the Igdlukúnguaq occurrence associated with a basaltic dike. As Pauly (1958) has explained, the pyrrhotite, pentlandite and chalcopyrite crystallized in this ore at a very high temperature, above about 850° C, as mix-crystals, outside which only a small part of the ore's chalcopyrite has remained. In other words, the isomorphous miscibility of the sulfides mentioned was nearly total under the prevailing conditions of crystallization. The exsolution of the mix-crystals began at about 850° C with a unmixing of chalcopentlandite, followed by the unmixing of chalcopyrite as two systems along prism and pyramid planes of pyrrhotite at temperatures of approximately 700° C and 550° C.

As is well known on the basis of numerous microscopic studies, the exsolution bodies mentioned are quite foreign to sulfide ores formed under ordinary plutonic conditions — that is, at high water pressure. This may be considered evidence of the fact that the sulfides crystallized in the ores in question at a lower temperature, where the isomorphous miscibility of pyrrhotite, pentlandite and chalcopyrite is quite limited and the extensive mix-crystals required to produce the exsolution textures under consideration could not, accordingly, evolve at all.

In the ore at Petolahti, described in the present report, textural features characteristic of both the Igdlukúnguaq ore and ores crystallized under ordinary, plutonic conditions are met with, a fact altogether in accord with the hypadyssal nature of the deposit. The exsolution textures met with clearly demonstrate that the isomorphous miscibility of the pyrrhotite, pentlandite and chalcopyrite has been quite extensive in certain parts of the ore, though not to as high a degree as at Igdlukúnguaq. Of the extensive solid solutions formed, quite an abundance of chalcopyrite unmixed, presumably at a temperature of about 700° C, along the prism and pyramid planes of the pyrrhotite. On the other hand, exceedingly little of the chalcopentlandite unmixed first, at about 850° C, from the pyrrhotite of the Igdlukúnguaq ore has formed at Petolahti. In most cases, also the triangular chalcopyrite lamellae are totally missing, their place being taken by textures indicating a more limited solid solution and a lower unmixing temperature (about 550° C). In places, also these exsolution textures are lacking, with the exception of pentlandite flames in the pyrrhotite, whereupon the ore receives features characteristic of ores formed under plutonic conditions to an ever greater degree.

Finally, the Petolahti ore also contains sulfide veins that, judging by their mode of occurrence and the almost total lack of exsolution products, crystallized from the hydrous remnants of the sulfide melt at a relatively low temperature, perhaps at about 300—400° C. In the ores of Sohland

an der Spree and Enwuch, described as comparative examples, volatile substances apparently became enriched in the sulfide melt to the extent that the entire sulfide material did not crystallize until temperatures approaching a high-hydrothermal stage had been reached. It is thus apparent that under hybabyssal conditions the crystallization of pyrrhotite, pentlandite and chalcopyrite is likely to continue at relatively low temperatures. On the other hand, however, it is equally evident that crystallization may begin under these conditions corresponding to average water pressure at a temperature nearly as high as in volcanic conditions.

SUMMARY

This report deals with the diabase of Petolahti and its associated nickel-copper-pyrrhotite ore. The deposit is located in the commune of Petolahti, in the region of Etelä-Pohjanmaa, western Finland. On the basis of investigations carried out in the years 1957—1958, the ore reserves of the deposit are less than 100 000 tons and the tenor of ore, too, is so modest (Cu = 0.70 %, Ni = 0.65 %, Co = 0.02 %) that the deposit has no commercial significance.

The report is divided into two parts: the first deals with the diabase and its associated ore as a petrographic whole, and the second concentrates on describing the ore minerals and interpreting the textures observed in them.

The Petolahti diabase occurs as a lenticular, nearly vertical intrusion and is clearly younger than the Precambrian mica gneiss surrounding it, being possibly Jotnian in age. Even megascopically it is possible to detect in the diabase the following main types, occurring in the form of concentric zones: fine-grained contact zone, sulfide-bearing olivine diabase (the ore), pyroxene diabase and quartz diabase. Of these the three last mentioned are interpreted as differentiation products of the olivine-basaltic parent magma, whereas the fine-grained contacts and the dense apophyses intruded into the wall rock of the diabase appear to have crystallized from the undifferentiated parent magma. In respect to its mechanism, the differentiation is assumed to have been gravitational crystallization differentiation. On the part of the sulfides, the enrichment into the marginal and basal portions of the magma basin took place, however, in a molten state, so that the ore is purely liquid-magmatic in respect to its primary formation. In order to make graphic the mode of occurrence of different diabase types, numerous cross-sections of the diabase lens based on drilling results have been presented.

The pyrrhotite of the main ore type of Petolahti, disseminated olivine diabase, in some cases contains a considerable abundance of pentlandite and chalcopyrite as various exsolution bodies. Correspondingly, the primarily crystallized pentlandite and chalcopyrite have also in some instances

contained as a solid solution 15—30 % — or fair abundance of — foreign substances, the unmixing of which has likewise led to the formation of numerous unusual, high-temperature exsolution textures. The pyrrhotite, pentlandite and chalcopyrite have thus been able to form among themselves quite extensive, if not complete, mix-crystals, which clearly demonstrates that the crystallization of the sulfides started at an exceptionally high temperature. The high temperature of crystallization, again, is believed to be due primarily to the fact that the crystallization took place under relatively low water pressure corresponding to hypabyssal conditions.

With the advance of crystallization, the volatiles, together with the copper and sulfur, became strongly enriched into the residual sulfide melt. Principally owing to the influence of the volatiles, it became mobile to such an extent as to be able to travel as a sort of interstitial solution over to the side of the wall rock of the diabase or inject as narrow veins into the fractures of the diabase. In each case, the sulfides for the most part did not crystallize until temperatures were reached that approach the high-hydrothermal stage.

The high-temperature exsolution textures met with in the sulfides of the Petolahti ore resemble in many respects the textures described from the nickeliferous pyrrhotite associated with a basaltic dike at Igdlukúnguaq. In addition to Igdlukúnguaq, a brief comparative reference has been made toward the end of the report to a few nickel-copper-pyrrhotite ores associated with small hypabyssal intrusions. In all these cases, the sulfides had crystallized at relatively low temperatures and are thus closely comparable to the portions of the ore that crystallized last at Petolahti.

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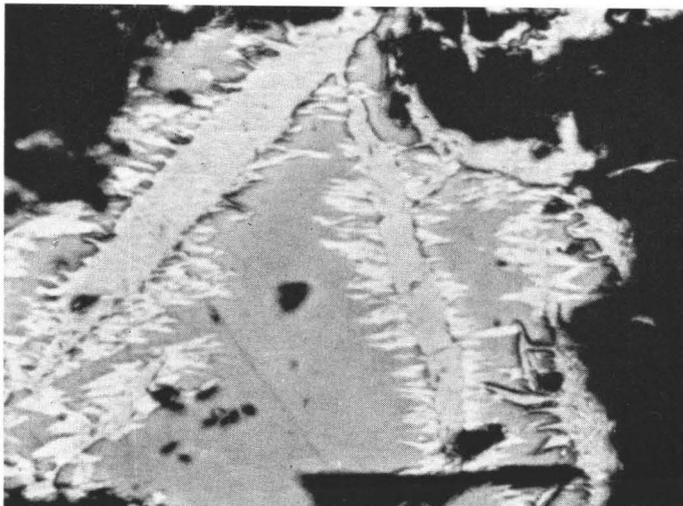


Fig. 1. Polished section, $\times 750$, nic. \perp , oil immersion. Exsolution lamellae of chalcopyrite (light grey) in the prism or pyramid planes of pyrrhotite (grey). The chalcopyrite lamellae are surrounded by pentlandite flames (light) oriented along the basal plane of pyrrhotite. Drill hole 7.

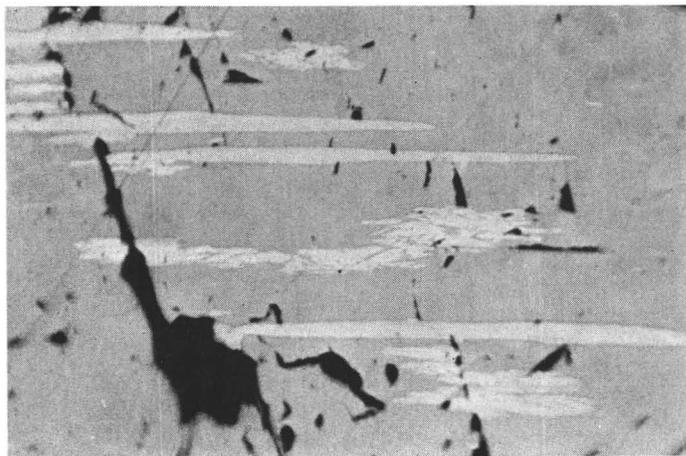


Fig. 2. Polished section, $\times 190$, nic. \parallel , oil immersion. Exsolution lamellae of chalcopyrite and smaller pentlandite flames, both along basal plane of pyrrhotite. Drill hole 4.

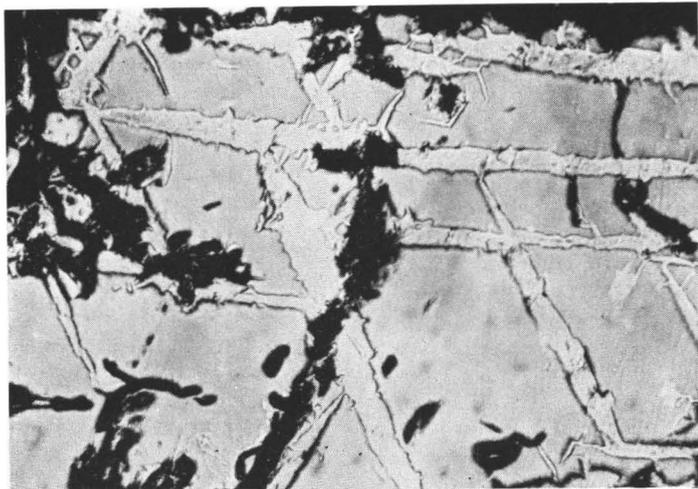


Fig. 1. Polished section, $\times 620$, nic. /, oil immersion. Triangular exsolution network of chalcopyrite in pyrrhotite in a section nearly parallel to the basal plane of the pyrrhotite. The chalcopyrite lamellae cut each other at a 60° angle. Drill hole 7.

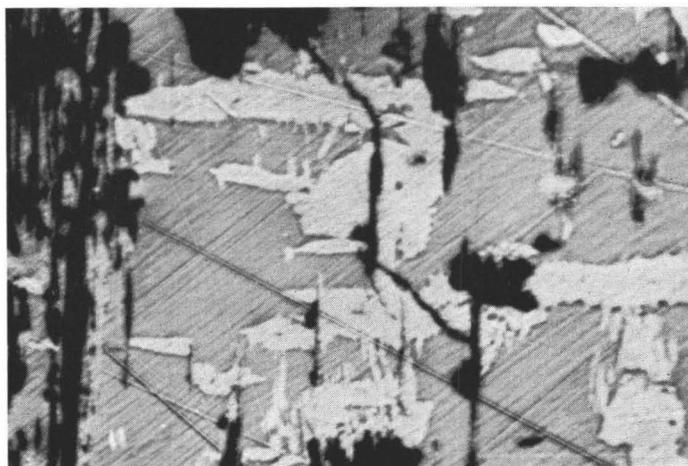


Fig. 2. Polished section, $\times 500$, nic. /, oil immersion. Chalcopyrite lamellae in a section nearly at right angles to the basal plane of pyrrhotite. Basal plane of pyrrhotite is indicated by marcasite bands and pentlandite flames (vertically in picture). Drill hole 7.

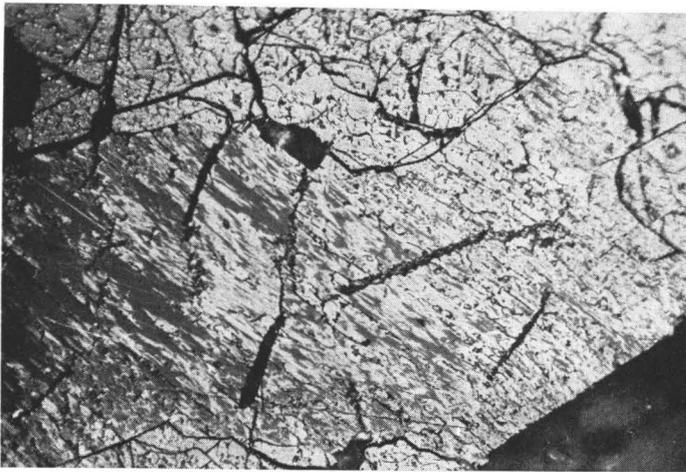


Fig. 1. Polished section, $\times 200$, nic. +, oil immersion. At top and bottom, slightly bravoitized pentlandite; in middle, pyrrhotite with abundant pentlandite exsolution bodies. Figure clearly shows that pentlandite has tended strongly to migrate toward borders of the pyrrhotite host. (Note the cleavage // (0001) of pyrrhotite).
Drill hole 7.

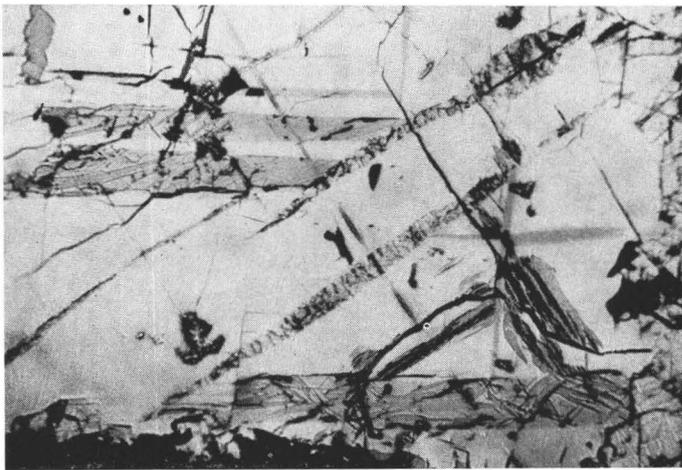


Fig. 2. Polished section, $\times 380$, nic. /, oil immersion. Various exsolution products in chalcopyrite. In horizontal position, some cubanite plates with small blades of pyrrhotite. In the middle, three pentlandite blades. In the same position or at right angles to them, lens-shaped areas of fine-grained pyrrhotite-chalcopyrite-pentlandite-magnetite intergrowth (near the lower left corner). Drill hole 4.

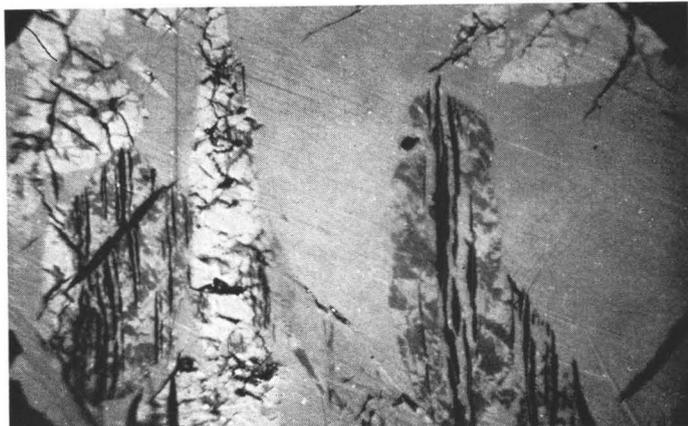


Fig. 1. Polished section, $\times 900$, nic. +, oil immersion. Various exsolution bodies in chalcopyrite. Vertically, two pentlandite blades (light) and two lens-shaped areas of fine-grained pyrrhotite-chalcopyrite-pentlandite intergrowth with magnetite lamellae (black). According to crossed nicols, the texture of the fine-grained material is obvious. Obliquely, one plate of cubanite with pyrrhotite blades.
Drill hole 4.

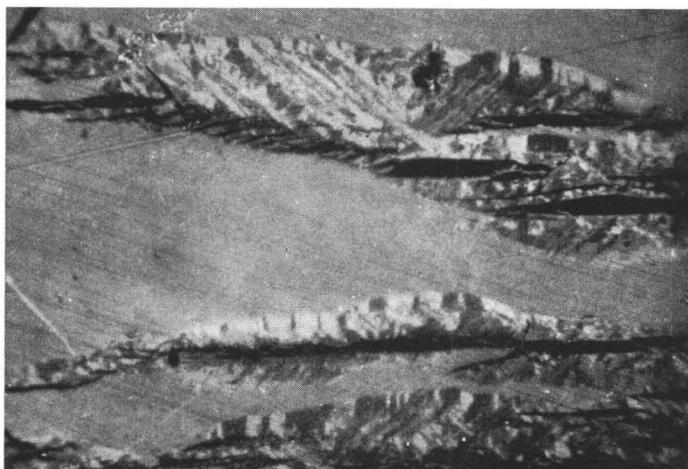


Fig. 2. Polished section, $\times 900$, nic. +, oil immersion. Fine-grained lenses of pyrrhotite in chalcopyrite. Some of the light grains on the boundaries of the pyrrhotite lenses are pentlandite. Dark lamellae are magnetite. Drill hole 4.

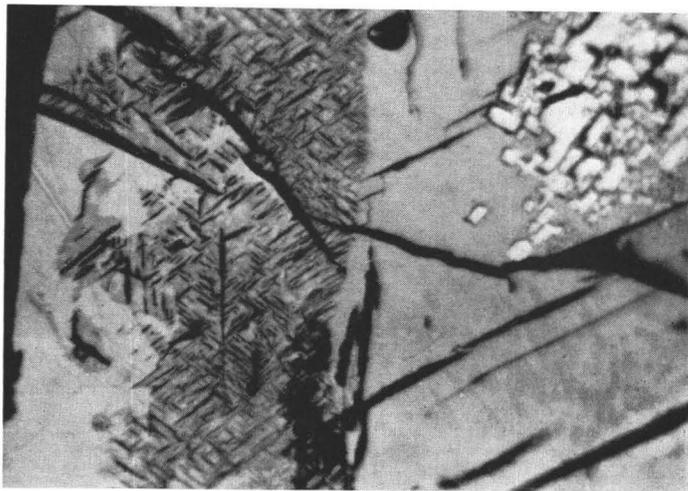


Fig. 1. Polished section, $\times 1000$, nic. /, oil immersion. On the grain boundary of chalcopyrite (light, on left), a rim of fine-grained intergrowth of pyrrhotite, chalcopyrite and magnetite, the last-named occurring as an octahedral network. On right, pyrrhotite exhibiting incipient alteration to fine-grained pyrite intergrown with magnetite (black). Drill hole 4.

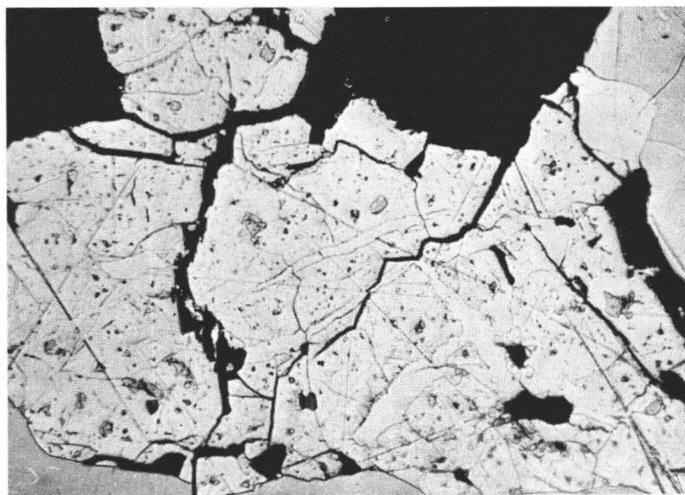


Fig. 2. Polished section, $\times 500$, nic. /, oil immersion. Rounded blebs of pyrrhotite (grey, relief) and vein-like bodies of chalcopyrite (light) in pentlandite. On right and at bottom, pyrrhotite. Drill hole 16.

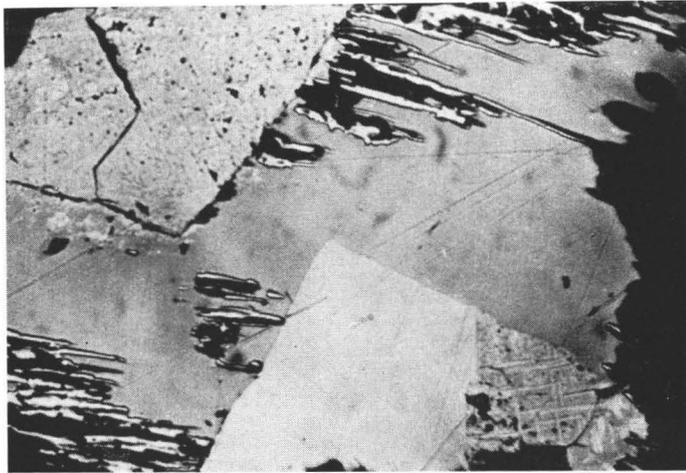


Fig. 1. Polished section, $\times 350$, nic. /. At top, pentlandite; in middle, pyrrhotite with banded marcasite; at bottom, chalcopyrite. Near lower right corner, pentlandite with lamellar network of chalcopyrite. Drill hole 14.

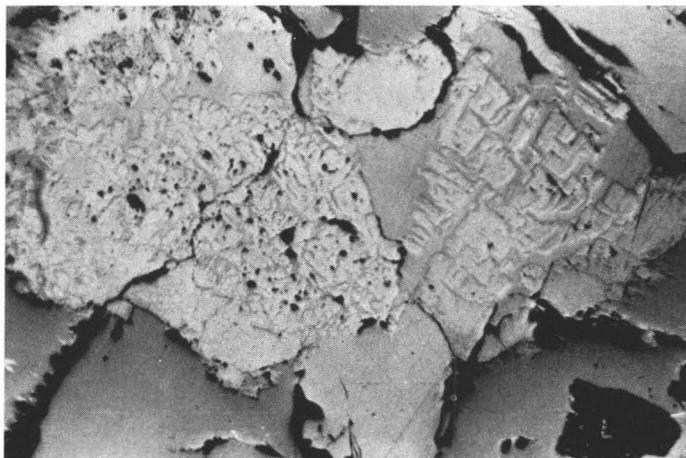


Fig. 2. Polished section, $\times 400$, nic. /. Intergrowth of pentlandite (light, relief) and chalcopyrite resulting from the unmixing of solid solution of these two minerals. The intergrowth is surrounded by pyrrhotite. Drill hole 2.

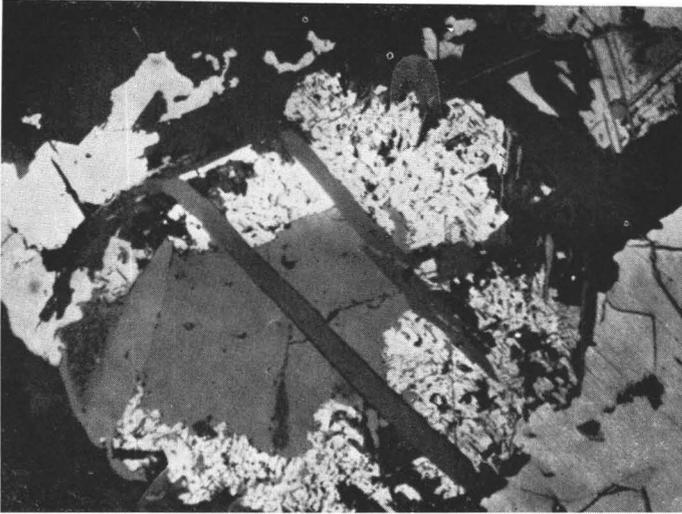


Fig. 1. Polished section, $\times 60$, nic. +. Pentlandite (light, in the middle) and chalcopyrite (light, in the upper right corner) replacing magnetite (grey), but not the ilmenite lamellae in it (dark grey).
Drill hole 2.

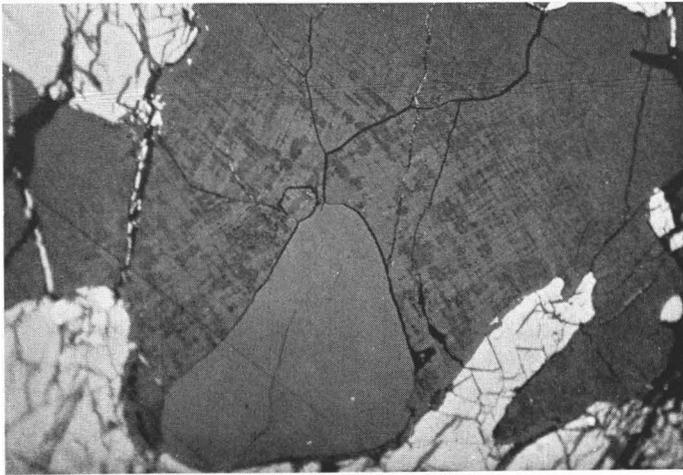


Fig. 2. Polished section, $\times 280$, nic. +, oil immersion. Ilmenite (in middle) surrounded by lattice intergrowth of ilmenite and magnetite, which grades over into non-exsolved titanomagnetite.
Drill hole 4.

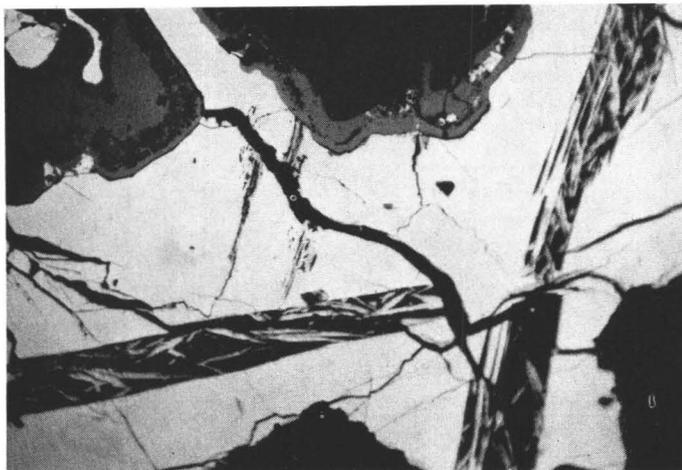


Fig. 1. Polished section, $\times 300$, nic. /. Two cubanite lamellae in chalcopyrite. Cubanite has changed to non-reflective material but the exsolved pyrrhotite blades have remained unaltered. On the upper boundary of the chalcopyrite, a rim of zonally pigmented magnetite with slight remains of chalcopyrite. Drill hole 4.



Fig. 2. Polished section, $\times 80$, nic. /. Magnetite veins (dark grey) in the fractures and cleavages of the pentlandite (on left) and the chalcopyrite. Drill hole 4.

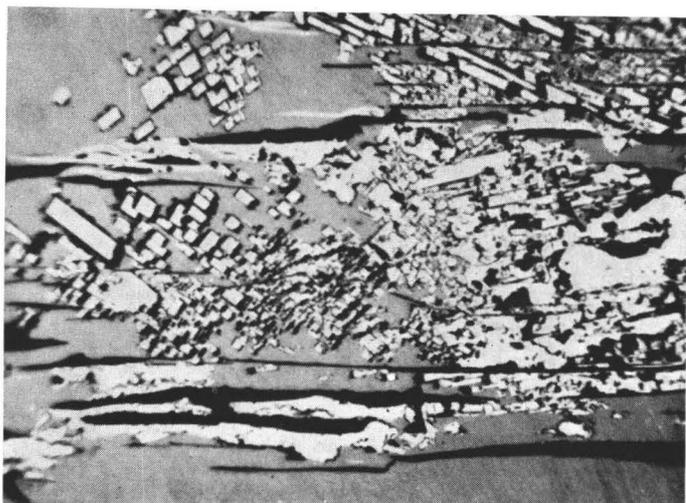


Fig. 1. Polished section, $\times 900$, nic. /, oil immersion. Incipient alteration of pyrrhotite to fine-grained pyrite (light, idiomorphic crystals) intergrown with magnetite (black). Along basal plane of pyrrhotite (in horizontal position) lens-shaped magnetite lamellae, surrounded by extremely fine-grained marcasite (light, flat). Drill hole 4.



Fig. 2. Polished section, $\times 120$, nic. /, oil immersion. Alteration of pyrrhotite (grey) to non-reflective material (black), pyrite (light) and marcasite. The last-named as bands along basal plane of pyrrhotite. Drill hole 16.

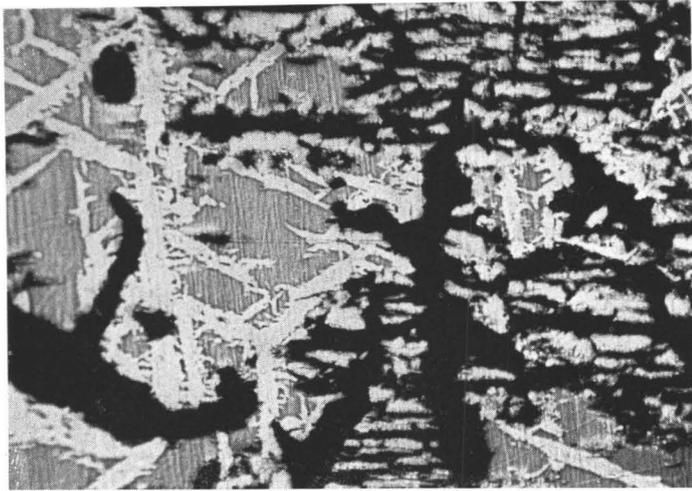


Fig. 1. Polished section, $\times 180$, nic. /, oil immersion. Triangular exsolution network of chalcopyrite in pyrrhotite. Around the chalcopyrite lamellae, minute pentlandite flames. On the right, pyrrhotite with its exsolution products has changed to banded marcasite intergrown with non-reflective material. Drill hole 7.

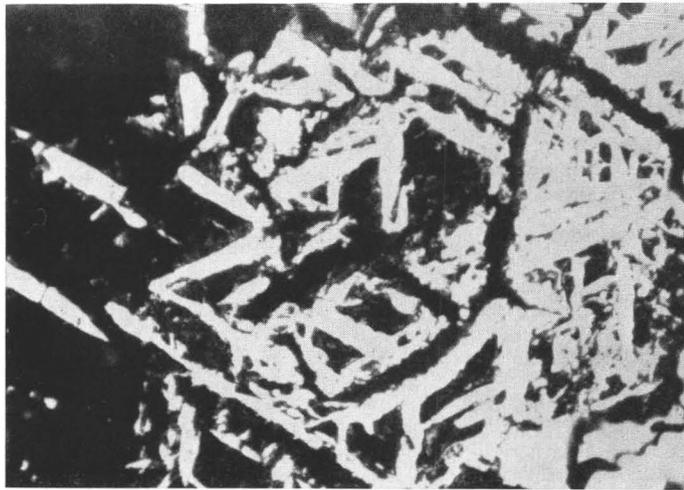


Fig. 2. Polished section, $\times 180$, nic. //. Triangular network of chalcopyrite in non-reflective material, supposed to be pyrrhotite in origin. Drill hole 7.



Fig. 1. Polished section, $\times 140$, nic. // . Conspicuously altered ore of Petolahti. On the left, original exsolution intergrowth of pyrrhotite and chalcopyrite has changed to oriented intergrowth of pyrite and chalcopyrite. In the middle, exsolution intergrowth of pyrrhotite and chalcopyrite with bands of marcasite and non-reflective material. On the right, a pyrite pseudomorph (light) after pyrrhotite. The light grey areas in the pyrite are marcasite. Serpentine (black veins in middle) replaces sulfides. The most resistant marcasite bands have been partially preserved. Drill hole 7.

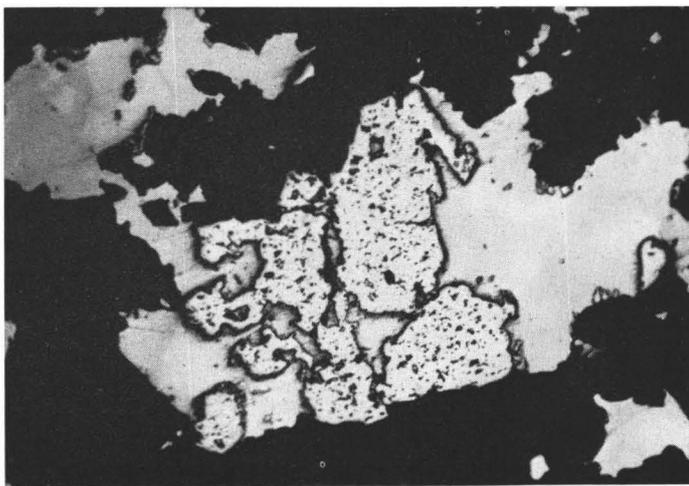


Fig. 2. Polished section, $\times 70$, nic. // . Millerite (light) and chalcopyrite (slightly more greyish) filling the pores of pyrite (light, relief). Strongly altered olivine diabase, Enwuch, Germany.

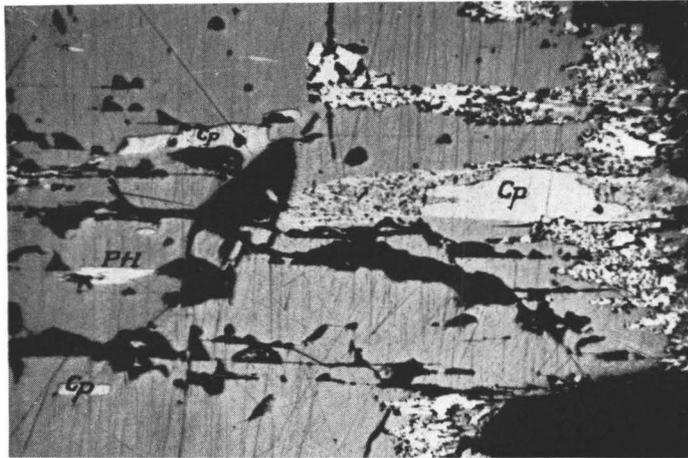


Fig. 1. Polished section, $\times 150$, nic. // . Pyrrhotite with minute pentlandite (ptl) flames and larger chalcopyrite (cp) shuttles, both along basal plane of pyrrhotite (in horizontal position). Along the grain boundaries of pyrrhotite incipient alteration to pyrite. Sulfide-bearing olivine diabase, a glacial boulder from Ahlainen, Finland.



Fig. 2. Polished section, $\times 300$, nic. /, oil immersion. Pyrite pseudomorph after pyrrhotite. Original pentlandite flames along basal plane of pyrrhotite have changed to bravoite (dark grey). Gangue minerals (black) replacing pyrrhotite (now pyrite) but not the pentlandite flames (now bravoite). Sulfide-bearing olivine diabase, a glacial boulder from Ahlainen, Finland.

