SUOMEN GEOLOGINEN TOIMIKUNTA || GEOLOGISKA KOMMISSIONEN I FINLAND

BULLETIN
DE LA
COMMISSION GÉOLOGIQUE
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N:o 114

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BY
PAAVO HAAPALA

WITH 21 FIGURES IN TEXT AND TWO MAPS

HELSINKI
MAY 1936

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CONTENTS.

PREFACE.

This work was begun already in 1930 on the initiative of Dr. H. Väyrynen. During prospecting work in the summer of 1930 some of the ultrabasic occurrences in Northern Karelia were visited and the collected specimens were later subjected to microscopical examination. In 1933 the investigation was continued under the guidance of Prof. Pentti Eskola. The field of the work was enlarged by including for investigation also the asbestos-bearing bodies of the westerly part of the region in question. The earlier material concerning these bodies was placed at my disposal by Prof. Eskola. Owing to the kindness of the Outokumpu Company I had an opportunity of making closer observations at Outokumpu, both underground and in the field, and also of studying the diamond drilling cores. Later on the abundant material was examined and the observations outside the Outokumpu ore field were made.

I wish to take this opportunity to express my gratitude to Prof. Pentti Eskola for his advice and encouragement during this work, as well as for his criticizm of this manuscript. To Dr. Heikki Väyrynen I am indebted for many helpful discussions of the problems. I also desire to thank Dr. Eero Mäkinen, of the Outokumpu Company, for his kind help during my work at Outokumpu.

Helsinki, May 1936.

Paavo Haapala.

HISTORICAL OUTLINE OF THE SERPENTINE STUDY.

Up to 1862 the opinions regarding the various problems connected with serpentines were greatly divergent. As early as 1831 the close connection of serpentine with olivine and pyroxene was noticed by Breithaupt (Zirkel 54 p. 378), who also considered it probable that serpentine as a rock might be a product of the alteration of other rocks. This idea was accepted by Rose (54) who went still further, in assuming that serpentine perhaps never represents a rock in its original form. Almost any rock found its place in the list of rocks which were believed to be able to change into serpentine, such as agglomerates, olivine-sands, sandstones etc.

Instead of these divergent views held during the early and middle decades of the 19th century its closing years and the commencement of the following century witness great unanimity of opinion with regard to the origin of the serpentine bodies. This development was made possible by the discovery of the anhydrous magnesian rocks in 1862 by Des Cloiseaux and Darmour. And, as Benson (6) states in his review of the literature dealing with serpentine rocks prior to 1918, a general agreement regarding the derivation of the serpentines from the peridotites and the intrusive character of the latter was soon obtained. It is now held that only exceptionally they may have been formed by the action of silicifying solutions upon magnesian limestones, producing olivine and other magnesian silicates; their subsequent hydration might occasionally have given rise to serpentine. But according to Hunt (cited by Benson) the characteristics of the serpentine of such derivation are different: It is less dense, it is poor in iron and contains neither chromite nor nickel.

This discovery by Des Cloiseaux and Darmour was followed by several other investigations and a great number of papers was published dealing with the actual process of serpentinization, its products and the minerals undergoing this process. Tschermak (54) described the typical mesh-structure of serpentine, showing its gradual development from olivine, and explained that the common association of serpentine and gabbro was not due to the serpentinization of the latter, but that it indicated an earlier close relationship of olivine rock and gabbro. Roth (54) wrote that not only olivine but all the anhydrous magnesian silicates poor in or free from alumina are capable of being converted into serpentine. Drasche (14) distinguished (1871) two different kinds of serpentine, the usual one with mesh-structure derived from olivine and another, »serpentine-like» rock, composed of a dagger-shaped variety of serpentine due to the transformation of pyroxene. Hussak (37) described in detail the various forms of pseudomorphs, particularly emphasizing that the dagger-shaped antigorite is formed at the expense of pyroxene, whereas Eichstädt (17), in his study of the serpentines of Northern Sweden, was led to the conclusion that the antigorite can also be formed from olivine, being supported in this view by Becke (5) and Bonney (8, 9). The latter in especial carefully discussed the question arriving at the result that the essential factor in the forming of antigorite is pressure. — »The most typical antigorite occurs when the rock is considerably affected by pressure». — Grubenmann also (29) (1910) believes that the antigorite is due to a higher pressure than the crysotilic variety of serpentine. Benson has found that in certain serpentines of New South Wales antigorite replaces the mesh-structure serpentine.

As early as 1891 a new line of thought was opened by the assumption of Weinschenk (6 p. 700) that in the case of the serpentines of Stubachthal the antigorite is partly primary, the remainder being a result of the action of magmatic water upon olivine. The primary antigorite, if accepted at all, was held to be of very rare occurrence. In more recent times, however, some authors have regarded such an origin as the most probable one for certain occurrences of antigorite. Thus Gisolf (26), in his paper on the antigorite-olivine-magnetite-rocks of Doormantop in New Guinea, considers the antigorite to be primary, crystallizing as a first component from a hydrous magma. With regard to occurrences of antigorite in some ultrabasic rock complexes of South Africa a magmatic origin has been expressed by Daly (13) as possible.

The origin of the water required for the serpentinization has been and still is one of the most intricate problems of the serpentine study. The majority of the earlier workers regarded the process as being entirely a phenomenon of weathering (Schrauf, Teall etc.). Holland (36), from his survey concerning the distribution of anhydrous and hydrated ultrabasic rocks of the world, supposes that the hydration is due to the increase of waters circulating within areas which, like Europe, have been covered by sea, whereas in continental massifs where no such action has occurred, the ultrabasics are found to be anhydrous. Van Hise (35) ascribes the serpentinization to solutions which in part may be of magmatic origin, but believes, like Grubenmann that reactions leading to serpentine have played in the zone of weathering. According to Benson, Crosby and Julien regarded the serpentinization as due to a superficial action, as did Wagner (see Hall 30 p. 330) with regard to some serpentine occurrences of South Africa.

Merrill (39) was probable the first to emphasize the significance of magmatic water, pointing out that no proof of the meteoric origin of the water needed had ever been advanced. He thought the serpentinization to be connected with deep-seated processes due to vapours or waters coming from considerable depths, the agencies maybe even being constituents of the magma during its intrusion. Weinschenk's opinion mentioned above not only put forward the idea of primary antigorite, but at the same time it gave a very definite explanation for the origin of water. During the following years the role of magmatic water became more and more paramount. Benson, while noticing this evolution, does not wholly deny the significance of meteoric water which, however, must be of minor importance.

While the change from an anhydrous magnesian rock to serpentine involves an addition of water and usually also of silica, the latest differentiates, granitic and pegmatitic magmas, form a natural source for such a solution. In fact, serpentinization is in many cases connected with granites and pegmatites occurring in the neighbourhood of the serpentine bodies. According to Dresser and Graham (15, 28) this has occurred in the Canadian serpentines near Quebeck, where the ultrabasics, cut by veins of pegmatite and granite, were converted into serpentine by solutions which, according to Graham, entirely originated from granites, while Dresser supposes them partly to have been of meteoric character. Similar action on the part of granites is believed by Keep (see Read 42) to have occurred in South Africa and by Wilcockson and Tyler (48) to have taken place in Anglo-Egyptian Sudan.

Not infrequently, however, the circumstances are such that the alteration cannot be accounted for by any intrusion in the vicinity and must be ascribed to the ultrabasic rock itself. The papers of Weinschenk, Gisolf and Daly already referred to held the water to be a constituent of the ultrabasic magma. Krotow and Granagg have accepted (see Benson 6 p. 717) the same view regarding certain occurrences of serpentines in the Southern Urals and Carinthia. Lodochnikow (38) argues that the peridotite magmas must have contained at least 5—10 per cent of water. A most interesting discussion has lately arisen through the investigation of Hess (33) concerning serpentinization in general, where he arrives at the result that serpentinization is a deuteric process in the sense used by Sederholm, i. e. the changes have taken place in direct continuation of the consolidation of the magma of the rock. Phillips (40), with regard to the serpentines of Unst, also arrives at the conclusion that the alteration is autometamorphic, and Hiesleitner (34) has accepted the same explanation for the serpentines of Kumanovo in Southern Serbia.

Benson (7) has collected a large number of investigations concerning basic and ultrabasic rocks of the world in order to make a tectonico-petrographic classification of these rocks.

He distinguishes several groups of occurrences. Frequently the basic intrusive rocks associate with differentiates of more acid character. The different components of such a complex may show a more or less gradual transition to one another. In this laccolitic complex the ultrabasics form, in general, the peripheric zone. This first group is termed laccomorphic. In the second, Cordilleran type, the ultrabasics occur more separately, in a sill-like manner, being invaded by more acid members of the complex. The third mode of occurence comprises the ophiolitic rocks, an association of serpentines and gabbros with amphibolites and diabases in region of intense folding. The term used for this type is Alpine. In the fourth group the ultrabasics form lenticular masses with boundaries conforming to the structural features of the enclosing gneisses or schists. Regarding them Benson writes that »it is not always possible in such cases to state the conditions under which these masses were injected though it is not improbable that many are essentially intrusions of the Alpine or Cordilleran types and were erupted during orogenic movement.»

With regard to the countries of northern Europe the study of serpentine rocks followed the general outlines sketched above. Among the first investigators in Norway and Sweden there are to mention Kjerulf, Törnebohm, Svenonius, Pettersen and Eichstädt. Since their time interest seems to have slackened, as the papers published later are relatively few. An account of the peridotites of Norway was given by Carstens (11) in 1918, and as for Sweden, the serpentines have since been subjected to investigation by Backlund (4) and quite recently by Du Rietz (16).

As far as is known to the writer the first paper concerning serpentines in Finland was published by Lemberg in 1867. According to Zirkel the occurrence in question is an asbestos-bearing variety of serpentine, situated on the island of Suursaari. The neighbouring rock is a dark amphibolite, into which the serpentine gradually grades over. Some years later, in 1876, Wiik (47) described a bastite-bearing serpentine from Tyrvää. The eastern occurrences, the subject of the present study, were investigated and described by Frosterus, whose monograph was published in 1902 (22). Frosterus' work is the first in its branch and at the same time is the only one of a more detailed character ever published in this country. Its results may be summarized here. The author divides the ultrabasic rocks into three different groups according to their mineralogical composition: viz. olivine-, asbestos- and serpentine-felses, the first of which, most likely pyroxene-bearing, represents the rock nearest to the original one. It is supposed to have intruded in the form of veins into the surrounding gneisses and schists. Within the regions of intense folding the formation of asbestos and talc predominates. For the latter in especial, stress was essential, whereas in the areas of gentler folding, and where no younger intrusions of granite exist, the change has led to serpentine-felses, which have subsequently undergone carbonatization, giving rise to talc-magnesite-rocks. These two last alterations were ascribed to weathering. Later, in 1913, Frosterus (23) holds it more probable that the parent rock of the serpentines has been a gabbro rich in labradorite feldspar. In 1918, in the description of the geological map of the district, serpentines are again dealt with by Frosterus and Wilkman (24). A more detailed list of occurrences is given, but in general the earlier views of Frosterus have been accepted unchanged. The parent rock is gabbro or a »picrite-like» rock from which the evolution proceeds to olivine-fels and further in two directions to the actual serpentines and to varieties rich in asbestos. The hydration is due to superficial waters containing carbon dioxide. After the last-mentioned year the serpentines of this area have received rather scant attention from the geologists.

Farther north, in the continuation of the Karelian schist formation, there occur similar serpentine bodies which have been described by Wilkman (49) and Väyrynen (51). The former regards them as ultrabasic rocks which were hydrated under hydrothermal conditions. Väyrynen, while pointing out the difficulty of getting any reliable picture about their original state, is inclined to believe that they have been rocks of gabbroic composition and were changed into their present state by removal of the feldspar material and by the hydration of the remaining femic minerals.

I. THE GEOLOGICAL FEATURES.

The limits of the area within which the serpentines under examination occur do not enclose any geographical or geological unit. They surround a part of northern Karelia in eastern Finland consisting of the parishes of Heinävesi, Tuusniemi, Kuusjärvi, Kaavi, Juuka, Polvijärvi and Liperi.

The geology of the district has been studied by several authors among whom — without referring to the respective works or discussing the various questions dealt with — mention may be made of Frosterus, Sederholm, Wilkman, Eskola and Väyrynen. The brief sketch given here is chiefly based upon the geological map and upon the description of same published by Frosterus and Wilkman. Map I is a copy from the same map, somewhat simplified and slightly modified as regard the ultrabasic occurrences.

Three factors are essential to the general geology of the area. In the east, up to frontier of Russia, gneissic and granitic rocks domi nate. Of these areas only a narrow zone in the northern part and some solitary isles inside the schist formation are visible on the map. Upon these oldest rocks lie the roots of the Karelian mountain zone, extending in a general north north-west and south south-east direction far beyond the region in question. The western part is occupied by gneissose schists invaded by numerous granitic and pegmatitic intrusions, thus producing injection rocks of various types. During the latest phases of the Karelian orogenic epoch big masses of so-called Maarianvaara granite were intruded into these and into the westerly portion of the schist formation. Now these granites particularly characterize wide areas in the middle parts along the border of the schist formation.

The schist formation consists of rocks of mainly sedimentary origin. Beginning from the east, where the border against the older formations is sharp, one finds conglomerates and quartzites in almost unmetamorphosed state. They are followed by phyllites, more metamorphosed quartzites and mica-schists, which grade over into micaceous gneisses and gneissose schists farther west. In addition to these bands of dolomite and amphibolite occur in the peripheric parts of the formation.

In this environment of rocks a great number of ultrabasic bodies occur in various stages of metamorphism, although the majority belong to the serpentines. Their distribution is restricted to the mica-schists and to the zones of quartzite within the latter, and also to the contiguous parts of the westerly gneisses. A most conspicuous feature of all these ultrabasic bodies is their general mode of occurrence as discontinuous belts, following the structural lines of the enclosing country rocks. The regularity or irregularity of a belt depends upon the conditions of the latter. In the west the distribution of the outcrops is more haphazard than within the schists of gentler folding, where the belt may have a length of some tens of kilometres. The size of the bodies varies greatly. Within the gneiss territory the dimensions in general are smaller, ranging from 200 metres to 20 metres in length and having correspondingly lower figures of width. In the easterly occurrences again a single body may have a length of several kilometres and a width of hundreds of metres. The form is always more or less that of a lens, especially as regards the smaller occurrences, but the larger bodies often give the impression of a sheet. The most striking feature is the complete lack of other more acid differentiates in connection with them, the only exception being the Nunnanlahti formation, where the serpentines are associated with amphibolites.

The contacts against the country-rock are seldom exposed and thus there are not many data for the determination of the mutual relationship. Frosterus and Wilkman (24) described an occurrence at Polvijärvi, where they had discovered fragments of quartzite in serpentine. Further, they state that at Outokumpu veins of serpentine are traversing quartzite. During the canal works at Varistaipale the contact between serpentine and gneiss was visible and was studied by Wilkman. He observes that the pegmatitic dikes of the gneiss are cut by the ultrabasic body, showing its eruptive character and indicating that it is younger than the granite from which the dikes originate. At no place where the present writer has had the opportunity of making observations at contacts, e. g. at Outokumpu in especial, were features of that kind noticed; on the contrary, the ultrabasic body follows in strong conformity the enclosing rock.

Though the outcrop of the younger granite are common enough in the neighbourhood of the serpentine, the contacts between them have rarely been observed. Wilkman mentions three places where the granite is found to traverse serpentine, namely, at Petrumajärvi, Outokumpu and Luikonlahti. The first of these, near lake Petrumajärvi, at Heinävesi, has earlier been described by Frosterus. There are two outcrops of dark serpentine rock near each other and between them a body of a grey even-grained granite, the contact between this and the southernmost serpentine body being fairly well visible. In the vicinity of the contact the granite contains black, irregular patches composed chiefly of black mica and hornblende. According to Wilkman they represent fragments of serpentine from the time of the intrusion of the granite. It is worthy of note, however, that the parts of the main mass of serpentine adjacent to the granite do not show traces of any action of a similar kind. Apart from the fact that the body (next to the granite) is amphibole-bearing — a colourless asbestos-like variety — with needle-formed pseudomorphs of talc, the zone contiguous to the contact greatly resembles the serpentine of the other body, with no direct evidence of any contact action on the part of the granite.

More distinct are the relations at Outokumpu. The nearest greater outliers of Maarianvaara granite occur about five kilometres to the northwest of Outokumpu. The places where the pegmatites were found to traverse the serpentine have most probably been met with during the diamond drilling, though Wilkman does not mention this. The underground operations of recent years, however, have exposed new contacts which show with certainty that the serpentines are older than the pegmatites. The relations are fairly visible in the eastern drift on 165 metres' level, about 200 metres from the Central Shaft. Two practically vertical dikes of about one metre in thickness cut the serpentine bodies underlying the ore. The dikes are brecciated to some extent and composed of rather coarse potash feldspar and quartz, often with pale brown or white mica. More rarely, crystals of pink garnet are studded into it, found so far only in those parts which are enclosed by serpentine. The contact zone next to the granite is made up of biotite, which soon grades over into chlorite, followed by a zone of talc. The thickness of these layers is only a few dms. The amount of talc, with some carbonate, is still considerable in the contiguous grey parts of serpentine and continues for some dms gradually decreasing meanwhile.

As a rule, the serpentine rock is resistant against weathering. It forms small abrupt hills which, where not covered by soil, are often very barren of vegetation. The brown zone of weathering has usually only a depth of about 1 cm, though most striking exceptions may occur. Thus, for instance, at Luikonlahti the whole rock is fallen into pieces, forming not a rocky hill, but a heap of debris, from which solitary ridges of more solid material rise up.

For the more detailed description of the different types and occurrences a division into two major groups is made. The areal distribution is preferred as a basis instead of that used by Frosterus, though the zones of the present division roughly correspond to Frosterus' types, only the olivine rocks have not any areal importance, because most of them belong to the serpentine rocks of mesh-structure. It is just the heterogeneity of the »olivine-felses» and »asbestos-felses» which justifies the preference of the present way of description.

II. THE OCCURRENCES.

THE EASTERN ZONE.

This zone of serpentines extends, slightly arching, some 30—40 kms along the easterly margin of the area in which the ultrabasics occur. The dotted line on map I shows its western border. It is sharply determined in the northern and middle parts by the adjacent bodies of the serpentine belt of Mihkali, but farther south, near Lake Viinijärvi, the border is less easy to draw, due to the fact that the occurrences of Horsmanaho and Makumäki, as far as is known to the writer, are talc-carbonate-rocks and all definite features relating to their serpentinous phase, if they ever had any, are lacking. Horsmanaho, however, bears so great a resemblance to the talc-magnesite-rocks of the other occurrences of this zone that it is taken into this group.

The following occurrence belong to this zone: Solansaari, Sola, Juttusuo, Horsmanaho, Kylynlahti, Louhiinsalo, Vasaralahti, Haaralanniemi, Revonkangas, Hovinaho and Nunnanlahti. Characteristic of them all is that they are composed of the antigoritic variety of serpentine, as already mentioned by Frosterus, or at least that antigorite is the prevailing serpentine mineral. Excluding the occurrences of the Nunnanlahti area the similarities are not restricted solely to this. The distinctions are so uniform that a description of one of these occurrences gives a reliable picture of the others also.

Solansaari. The neighbouring rocks of this occurrence are mica-schists, but the immediate areas around the serpentine outcrop are covered by soil, so that the contacts are not visible. The outcrop shows a brown surface of weathering, often deeply pitted. The depth of the action of the atmospheric agencies is only a few centimetres, as is best discernible on the westerly margin, where some open pits have been made in the talc-magnesite-rock. In fresh sample the rock is of a bright green colour, having a rather strong lustre when compared with the mesh-structure serpentine.

The mineralogical composition and the microscopical structure show but small variations, if any, in different portions of the outcrop. The main bulk of the rock is composed almost entirely of the dagger-shaped variety of serpentine, antigorite. It forms irregular areas of somewhat uniform dimensions of blades, surrounded or penetrated by others of different sized individuals. The greatest laths measure up to a few mms. The arrangement of the crystals is mostly haphazard, though in places the structure resembles that described, for instance, by Hussak, the blades occurring in two directions nearly perpendicular to each other. More seldom, the structure is nearly spherulitic (fig. 1), as observed for instance by Bonney (9) in the antigorite rocks from Griffin Range, Hokitika, and by Phillips in the Unst bodies. The blades are quite colourless in thin section, showing a cleavage along the direction of elongation. The optic axial angle is fairly large, and the elongation of the laths is invariably positive. The index of refraction was determined by immersion, $\gamma = 1.573$. The birefringence, measured by Berek's compensator, is 0.004—0.005.

As further components talc, magnesite and pyrrhotite are met with. A noteworthy fact is that the magnetite is quite subordinate in

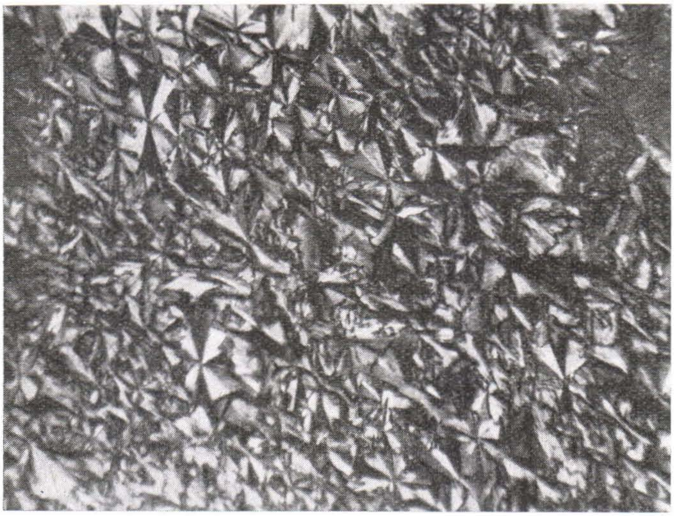


Fig. 1. Antigorite serpentine from Solansaari.
+ nic. Magnified 40 x.

amount. The typical ore powder of many occurrences of the chrysotilic variety is wholly lacking, only irregular patches of coarse magnetite are occasionally met with, filling the space between the laths of antigorite. Not a grain of chromite could be found, though searched for with special care. The presence of the chrome-bearing silicates, such as fuchsite, in the neighbourhood of some serpentine bodies indicates, however, a content of chromite in some parts, as shown, in fact, by analyses published by Frosterus and Wilkman (24).

Towards the periphery of the body the content of talc and magnesite becomes more and more pronounced, forming at last, as already mentioned, a talc-magnesite-rock. The talc occurs in coarse flakes of random orientation or, in the schistose parts, as smaller blades of roughly parallel arrangement. The magnesite occurs as big grains up to 1 cm in diameter, and is leached out and disintegrated into patches of reddish brown ferric oxide near the surface. The laths of antigorite often pierce the carbonate into pieces of similar orientation and their sharp-edged forms also penetrate into the flakes of talc.

The origin of the serpentine and the sequence of minerals is discussed later.

The following analysis, made by miss Elsa Ståhlberg, illustrates the composition of the pure antigorite rock.

Table 1. Analysis of antigorite rock from Solansaari by Elsa Ståhlberg.

	Weight per cent.	No. Mol.
SiO_2	43.81	0.7265
TiO_2	trace	—
Al_2O_3	1.46	0.0143
Fe_2O_3	1.12	0.0070
FeO	5.18	0.0721
MgO	35.06	0.8696
CaO	0.91	0.0162
MnO	trace	—
Na_2O	0.35	0.0057
K_2O	0.09	0.0010
$+H_2O$	10.94	0.6037
$-H_2O$	0.18	—
Cr_2O_3	0.32	0.0021
NiO	0.26	0.0035
	99.68	

Sola. The Sola formation is composed of several separate bodies of serpentine associated with quartzites and carbonate rocks. Of these the Kuikkalampi outcrop in the southeastern corner of the formation deserves special attention. It forms a barren, rocky hill with an irregular network of pits on its brown surface. The fresh rock is of a mottled appearance owing to the dark, nearly black areas carved out as pits in the surface enclosing those of bright green colour. The passage between them is gradual. Seen under the microscope the green portions are found to be composed of blades of antigorite with the properties described above. The black spots are made up of the mesh-structure serpentine, in which still fresh-looking remains of olivine occur. Big grains of coarse magnesite are scattered throughout the rock, as well as flakes of talc, though the talc seems to prefer the border parts of the fields of antigorite serpentine. In addition to these, a fine-grained carbonate occurs among the laths of antigorite. Magnetite forms irregular grains of various sizes within the mesh-structure serpentine in and around the magnesite crystals and only occasionally occurs in the adjacent parts of the antigorite area. The blades of antigorite penetrate into the field of the green or yellowish mesh-structure serpentine, but do not come into direct contact with olivine. By and by the chrysotilic serpentine is replaced by antigorite and the rock passes over into the typical serpentine of this zone. According to these observations the sequence of minerals is: olivine — chrysotile and magnetite — magnesite (with talc) — antigorite. Probably the cycle was in part repeated so that the recrystallization of serpentine was followed by a second carbonatization and formation of talc, which strongly attacked the antigorite portions. This repetition possibly explains the circumstances noticed in the talc-carbonate-rock of the same outcrop, where big, rectangular pseudomorphs of mesh-structure serpentine are embedded in a ground-mass of talc and carbonate. The primary mineral has most likely been olivine, though not a grain of it can any longer be found. The pseudomorphs have a length of several cms with haphazard orientation and with sharp boundaries against the ground-mass. Occasionally ghostly outlines of pyramidal faces are discernible. Grains of carbonate are met even within the pseudomorphs.

The abrupt border may be explicable by a selective replacement during which antigorite was destroyed while chrysotile was preserved. Corresponding features have been noticed at Hovinaho, with the difference that instead of the talc carbonate ground-mass a similar one composed of antigorite occurs. The acceptance of the second carbonatization and the formation of talc subsequently to that of antigorite is further favoured by the fact that the serpentines of the Mihkali belt adjacent to Hovinaho differ from it only in having the areas corresponding to those of antigorite occupied by talc and sparse carbonate, though without any trace of antigorite.

The other outcrops, Paljakka and Repovaara, are about one kilometre to the north of Kuikkalampi. Contiguous to Repovaara there occurs a narrow zone of steeply dipping quartzite containing chrome-bearing tremolite and fuchsite, accompanied by pyrite in abundance. Towards the serpentine the quartzite becomes richer in amphibole which at the same time turns to a shade darker. The contact zone is formed of actinolite-schist, in places with radiating groups of coarse amphibole and with alternating layers of quartzite. The serpentine body is conformable to the structural lines of the schists everywhere, where visible, though the exact border between them can not be drawn with certainty owing to the schistosity and to the presence of amphibole in the adjoining parts of the serpentine.

This serpentine belongs to the antigoritic variety with properties similar to those described before. Only small brown dots here and there indicate a content of mesh-structure serpentine. The amounts of magnesite and talc are small. The index of refraction of the antigorite, measured by immersion, was found to be: $\gamma = 1.576$ and that of magnesite $\omega = 1.720 \pm 0.003$, corresponding, according to Winchell (50), to a content of about 16 mol. per cent. of $FeCO_3$.

Juttusuo was not visited, but the specimens of talc-magnesite-rock obtained from there show that it belongs to the type in question.

Horsmanaho. Actual serpentine rocks are not known to the writer as occurring here, but, as mentioned before, talc-carbonate-rocks bordered by zones of actinolite-schist outcrop in an environment of mica-schist, quartzites and black, graphite-bearing schists. They were not studied microscopically.

At *Kylynlahti* only two outcrops exist. The serpentine body by the Joensuu road is of the usual type, practically a pure antigorite rock, while the other body, exposed in a cut of the same road, is composed entirely of talc. The contacts are nowhere exposed. A prospecting pit in the neighbourhood shows the presence of graphite-bearing schist and the abundance of boulders of quartzite with chrome-bearing silicates and patches of pyrite indicate quartzites similar to those at Sola.

Louhiinsalo. Serpentine occurs together with steeply dipping black-schists and quartzites. The latter contain bands of chrome-bearing tremolite and are exceptionally rich in pyrite. The richest part, a real pyrite ore, has so far been met with only as boulders in the vicinity. The serpentine itself consists of antigorite and scattered crystals of magnetite. Veins of ice-green, coarse talc are common.

Vasaralahti. The outcrops are in mica-schist. The distance between the outcrops of serpentine and its country-rock is in places only about one metre, but the actual contact is covered. The mica-schist shows no action on the part of the serpentine, being composed as usual of rather coarse mica and quartz, with some traversing veins of quartz, but these are common in all parts of the mica-schist formation. In the footwall the schist is graphite-bearing, with small patches of pyrrhotite and chalcopyrite. — The serpentinous parts are composed of antigorite. Talc and carbonate occur.

Haaralanniemi is a direct continuation of the occurrence of Vasaralahti. The outcrops of serpentine are greater in number, associated with quartzites, mica-schists and sulphide-bearing, steep black-schists of platy habit. The most conspicuous feature is the abundance of talc-magnesite-rocks. Their mode of occurrence does not differ from those described earlier, nor is the mineralogical composition different. The index of refraction of magnesite was measured by immersion: $\omega = 1.725 \pm 0.003$, corresponding to a somewhat higher content of $FeCO_3$ than in the case of the Sola occurrence.

Fig. 2. Antigorite serpentine surrounding an isle of chrysotilic serpentine in which grains of olivine are still visible. Haaralanniemi. + nic. Magnified 24 x.

Towards the centre of the body the amount of talc and carbonate diminishes and the rock passes gradually into the serpentinous core, consisting mostly of antigorite.

A few grains of olivine were found in a slice made from a specimen of apparently pure antigorite. They were embedded into a green serpentinous material of fibrous, chrysotilic character with no direct contact with the blades of antigorite. Occasionally these green areas are bordered by an unknown mineral of low relief and of rather high birefringence. The optic axial angle is small, with a negative sign. It has a rather strange pleochroism varying from a faint reddish colour perpendicular to the cleavage to colourless parallel to it.

Revonkangas resembles most closely the occurrence of Louhiinsalo, at least as regards those serpentine bodies which contain nests and veins of ice-green flakes of talc and minute grains of magnetite studded into the antigorite. The weathered grains of magnesite form brown patches on the rock surface. The indices of refraction of magnesite are, determined by immersion: $\omega = 1.722$ and $\varepsilon = 1.522$.

The contacts are not exposed. Farther west there occur rocks which belong to the serpentine formation. Among them are carbonate-tremolite-rocks and schists containing considerable amounts of fuchsite which, in fact, may occur as a chief component in some parts. Its presence indicates chromite in the serpentines, but this was not found.

Hovinaho. The actual outcrop is not known. According to an oral communication made by Dr. Väyrynen, its position as indicated on the geological map is not correct. During prospecting work in the summer of 1935 its approximate position was determined by the presence of boulders met with in abundance on the place marked, but which cannot be discovered farther north. They represent the same type as met with at Kuikkalampi, i. e. both antigoritic and chrysotilic varieties occur together. Their mutual relations are also the same, antigorite replacing the mesh-structure serpentine, though sometimes the border between them is sharp and hence the direction of the change less easy to decipher. Olivine was not met with, but most likely it is still in existence, as only one slice was made and studied.

Summary of the observations.

A summary of the observations gives many distinctions common to all the occurrences: 1) The serpentines occur as resistant rocky hills. 2) They are mostly associated with graphite-bearing schists and quartzites containing abundant pyrite and chrome-bearing silicates, tremolite and fuchsite. 3) The stage of metamorphism is amazingly constant throughout the whole zone. As a rule the bulk of the rock is composed of antigorite and as minor constituents magnesite and talc are general, becoming more important towards the periphery of the bodies, in places totally replacing the serpentinous material. The two exceptions, Kuikkalampi and Hovinaho do not alter the general picture, but instead help to find out the way and the direction of the changes. Though olivine was not found in every occurrence, its presence in an apparently pure antigorite rock, e. g. at Haaralanniemi, makes it probable that slight amounts of it are generally distributed, a further evidence for the regional metamorphism of these rocks being uniform throughout. Some additional features may still be pointed out. Chromite was not found, though its presence is most probable. The absence of magnetite dust and of chlorite within the fields of antigorite is general and worthy of attention.

The primary structure and composition are but little in evidence. Accepting the olivine as a primary mineral and taking into consideration that in general olivine is most readily serpentinized, the presence of this mineral and the lack of other anhydrous magnesian silicates suggest olivine as a sole component of the premetamorphic rock. The order of the events during their metamorphic history as indicated by the microscopical observations is: the hydration of olivine was followed by the formation of carbonate and talc. Subsequently the recrystallization of serpentine occurred, during which antigorite to a great extent replaced the mesh-structure serpentine and even penetrated into the field of magnesite. The carbonatization and the formation of talc were probably repeated.

According to the laboratory tests of Wells (46) serpentine may be formed at the expense of magnesium carbonate by the action of silicifying solutions. Väyrynen (5) has observed that in the serpentines of Kainuu carbonate has undergone serpentinization. As to the formation of antigorite, Benson (6) is of the opinion that in certain cases antigorite is a later product than chrysotile. This is stated also by Du Rietz (16) in the serpentines of Northern Sweden.

The Nunnanlahti—Mölönjärvi formation.

Apart from the aforementioned places there occurs in the northeasterly corner of the area a belt of serpentine bodies trending from lake Mölönjärvi for some eight kilometres up to the village of Nunnanlahti. Still farther north a zone of peridotite has been met with, east of the highroad near the church village of Juuka.

The various interesting features of the geology of the district combined with the economic importance of the soapstones occurring there have made it the subject of keen investigation. Both Frosterus and Wilkman have described it in detail in their publications already referred to. By the aid of the geologic maps of Wilkman and Eskola the writer made a short excursion through the district in order to make some comparisons with the serpentines farther west. Some observations in addition to those of earlier investigators are given here, though these occurrences are outside the original scope of this work.

The most conspicuous difference is the abundance of amphibolites intimately associated with serpentine rocks and soapstones. Their mutual field relations, as seen, for instance, in the Kärenvaara quarry, are as follows: On the side of the foot-wall the outcrop most remote from the soapstone body consists of massive antigorite serpentine. Towards the quarry it becomes more and more schistose, but no remarkable change in other respects can be noticed. The passage into soapstone is not wholly exposed but as far as is visible the transition is gradual. The soapstone itself is somewhat schistose (fig. 3) con-

Fig. 3. An outcrop of soapstone near the Kärenvaara quarry at Nunnanlahti. Photo S. Kilpi.

sisting mainly of talc and carbonate with patches and lenses of green chlorite. As seen in the middle of the photo near the little pool and farther along the same horizon there occur within the soapstone small lenticular bodies made up either of somewhat brecciated massive amphibolite or of schistose hornblende rock. The outer shell of such a lens is composed of biotite which by a rapid transition passes over into the green chlorite zone of the actual contact. To what extent the seemingly gradual passage into the soapstone means a gradual variation in composition, is not known, but in many cases, though the colour becomes fainter and fainter, there is still a discernible sharp contact; in cases where it is missing, the green patches seem to be derived from serpentine of which almost unaltered remains have been occasionally observed in the patches. Sometimes a few grains of colourless amphibole are to be observed near the contact in the soapstone, while on the side of the chlorite-schist grains of a darker amphibole occur. On the right hand side in the photo the darker coloured hanging wall is visible. It is a brecciated antigorite rock.

Fig. 4. Kärenvaara soapstone quarry at Nunnanlahti. Photo S. Kilpi.

Antigorite is the dominant mineral in the serpentine rock. A slice from the schistose part shows a considerable amount of carbonate in a somewhat parallel orientation. The grains of ore exhibit great diversity of size and form and are mainly restricted to the carbonate-bearing portions. Seen under the microscope a specimen from an occurrence near lake Mölönjärvi with the appearance of usual antigorite rock shows equal amounts of blades of chlorite and such of antigorite. The identity of the chlorite is uncertain, its real character ought to be determined by analysing the rock. In addition big, conspicuously well-formed octahedra of magnetite are to be found. Here, too, the antigorite appears to be the latest mineral in the sequence replacing the carbonate. No traces of primary minerals or structure are found. Even the mesh-structure serpentine is entirely lacking.

The peridotitic boulders are of different composition. A slice from one of them shows a large number of short prisms of amphibole enclosing rounded grains of olivine. According to the earlier observations of the writer the olivine has in places disappeared its form only being visible as a brighter spot in the amphibole. This is due to the fact that the abundant magnetite (chromite in part?), though colouring the other parts nearly black, does not enter those parts of the amphibole earlier occupied by olivine. These features indicate that the primary poikilitic texture of olivine and amphibole (pyroxene) has been preserved as a pseudomorph owing to the pigment-like particles of magnetite having separated at a time when the crystals of olivine were in existence, while those of amphibole had not yet been formed. By the partial resorption of olivine the bright spots of amphibole free from ore were formed. The serpentinization is of minor importance. Only a few blades of antigorite may be observed and the magnetite dust in the cracks of olivine shows the commencement of the hydration of olivine.

Thus, notwithstanding the possible slight difference in composition of the original rock and its different mode of occurrence, with accompanying amphibolites, the complete similarity of the serpentine bodies with those described before and the succession and character of changes combine these occurrences intimately with those of the westernmore area.

THE WESTERN ZONE.

Compared with the easterly occurrences the ultrabasic rocks of the western half of the Karelian zone show much less uniformity. A common feature in all of them is the lack of antigorite as a rock-forming mineral. Solitary blades with the properties of antigorite may occur, but never in any remarkable amounts. Everywhere the serpentine mineral is, as far as is recognizable, rather fibrous, being best characterized by the name mesh-structure serpentine, because this structure, though variable, is always easily distinguishable from that of the antigorite.

Two great groups can be distinguished. Within the schist territory serpentinization has been the dominating factor, having led to more or less pure serpentine rocks. In the west, in the territory of micaceous and other gneisses, the abundance of amphiboles is the most remarkable feature. The border between these two types is not sharp. Pure serpentine rocks are to be found among the asbestos-bearing rocks, while, on the other hand, the ultrabasics of the schist formation include many bodies rich in amphibole and, in fact, contain it as a minor constituent, regularly increasing towards the west.

Further, a subdivision of both the types is made. While the ultrabasics of the schist area in every belt show a greater resemblance to each other than to those of the adjacent belt and while areal division of the types can thus be made, the petrographical variations in the westernmost parts show no areal regularity.

THE MIHKALI BELT.

These occurrences, though comparatively little studied themselves, are very suitable to be described first as intermediate members between the easterly and westerly types. Their monotonous uniformity throughout the belt comparable to that of the eastern zone has led to only a few thin sections having been made of them, the microscopical observations being supplemented by a megascopical examination in the field. The results now mentioned are to a great extent dependant on the closer study of the serpentine rocks of Outokumpu discussed later.

The following occurrences belong to this belt: Petronjärvi, Mihkali, Teyrivaara, Reponiemi, Ilveskallio, Soinsärkkä and Sukkulanjoki. In addition, the occurrences of Korhonen and Makumäki are described here. The former is represented by abundant boulders in the vicinity of the farm house of Korhonen (see map I). The actual outcrop was said to have been met with in digging a well, and from the samples shown to the writer the rock is typical of the belt. The Makumäki occurrence is only known as boulders.

Petronjärvi. This occurrence shows the typical properties of the serpentine rocks of the Mihkali belt. The weathered surface is coloured black and brown. In fresh samples the mottled appearance is still more pronounced. The rock is made up of nearly equal amounts of usually scaly talc, forming the grey parts of the rock, and of mesh-structure serpentine. The spatial distribution of the two components seems to be haphazard; the talc areas surrounding the black ones in the same way as do the antigoritic portions in the non-homogeneous rocks of Hovinaho and Kuikkalampi (see p. 18). So far antigorite has not, however, been noticed in the talc fields. Grains of carbonate are sparsely scattered throughout the rock.

Mihkali. In appearance and composition the rock is similar to that of Petronjärvi. Due to the somewhat parallel arrangement of the elongated talc areas and to the bands of coarse magnetite and chlorite, the rock shows in places a slightly pronounced schistosity.

Teyrivaara. The main bulk of the rock is of the usual type. The northernmost end of the outcrop has a considerable content of radiating groups of tremolite (actinolite) the amount of which decreases towards the centre of the body. In the serpentinous parts the amphibole, too, has undergone serpentinization, being now soft and deprived of its original lustre. In thin section it is to be seen in the same relief as the mesh-structure serpentine with varying double refraction. In some loose blocks a porphyritic variety like that described from Kuikkalampi has been observed, with big, sometimes brecciated pseudomorphs after olivine. Some olivine may still be present. The fragments of the pseudomorphs have the same elongated regular form as the original crystals, the brecciation having evidently occurred along certain crystallographic planes, probably 010.

The composition of the pure mesh-structure serpentine is shown by the following analysis. The specimen analysed was microscopically free from impurities. The index of the refraction, measured by immersion, is $\gamma = 1.570$.

Table II. Analysis of mesh-structure serpentine from Teyrivaara by the author.

	Weight per cent.	No. Mol.
SiO_2	43.31	0.7182
Al_2O_3	0.82	0.0080
Fe_2O_3	1.63	0.0102
FeO	5.28	0.0735
MgO	37.08	0.9184
CaO	0.56	0.0100
MnO	0.08	0.0011
H_2O	11.51	0.5834
	100.21	

Soinsärkkä is the only place where the contact is visible. The hanging wall is of grey mica-schist. Next to it there is a layer of biotite and chlorite, from 5 to 6 cms thick. It is followed by a zone of pale, schistose talc, containing needles of green tremolite in the areas adjacent to chlorite. The core of the body is made up mainly of dirty-green mesh-structure serpentine with flakes of talc. A graphite-bearing schist forms the foot-wall.

Sukkulanjoki. The occurrence is situated on the western side of the river Sukkulanjoki, near the road from Polvijärvi to Maarianvaara. It consists of mesh-structure serpentine, talc, chlorite and magnetite. Talc occurs here as big irregular flakes in which nests of chlorite are found. The usually powder-like magnetite colours the whole rock black, occurring in thin sections as narrow crossing strings. The minute crystals have a more haphazard distribution.

Makumäki. The boulders found near Makumäki mostly resemble the porphyritic variety of Teyrivaara, though they are richer in carbonate and still contain a considerable amount of olivine. In the white matrix there are a great number of elongated black crystals of olivine up to 1 cm in length, in places broken up into fragments along parallel planes. Where the border is irregular it is due to the carbonate grains penetrating into the olivine fields. This may finally lead to a complete replacement. In such cases the original structure in thin section is difficult to discern, but in hand specimen, when looked at in a suitable position, the outlines of the ancient crystals may sometimes still be recognized.

Excepting the occurrence of Makumäki olivine has not been observed with certainty. The occurrences of Teyrivaara and Reponiemi, however, may still contain a slight remains of this mineral. Elsewhere, too, the mineralogical composition and the structural features indicate that olivine probably was a chief component of the original rock. Of pyroxenes no trace has been found. At Sukkulanjoki the flakes of talc are similar to the talc pseudomorphs after enstatite and bastite, but in any case the amount of pyroxene, if it ever existed, must have been negligible. The amphibole has existed before the serpentinization, but its mode of occurrence in the outer parts of the serpentine body indicates a transport of material from outside sources and a secondary origin. Talc is subsequent to the mesh-structure serpentine, being accompanied by the usually small amount of carbonate present. The striking similarity in general appearance between the rocks of Hovinaho type and the rock now under consideration strongly suggests correspondence of some kind between the talc fields of the latter and the antigorite fields of the former, as mentioned earlier. No further evidences of this correspondence have, however, been noticed here.

THE SERPENTINE BELT OF OUTOKUMPU—KUUSJÄRVI.

The Outokumpu complex.

The deposit of copper ore at Outokumpu was discovered already in 1910 but, up to the present, no detailed description of its geology has yet been published. The region has been mapped by Mäkinen, who also described its geologic features in a lecture in the year 1919.

In a short account by Eskola in 1933 (18) some special questions are discussed in connection with the occurrence and data of various chrome minerals peculiar to this rock complex.

The prospecting works, especially the diamond drilling, as well as the old and more recent underground workings, present a good opportunity for the study of the complex. In the present work the great majority of observations has been made by a close examination of several kilometres of diamond drilling core, special attention having been paid to the serpentine bodies and their contact zones. After the microscopical study of the serpentine specimens the megascopical examination was repeated. The older drillings were neglected in the repetition, because, owing to the incomplete collections of the cores, they were of no use in the quantitative study of the distribution of the different types distinguished during the microscopical work. The schist series was studied only megascopically.

The complex of Outokumpu constitutes a distinct geologic unit in a vast monotonous territory of mica-schist. It extends in a northeasterly and southwesterly direction towards the Kuusjärvi complex, being separated from it, according to Mäkinen, by a big fault. Another vertical fault plane in a direction of N.15°W., causing a considerable deplacement, divides the formation into two parts, of which the northeasterly half is called Kaasila, the other one Outokumpu. In the mine a number of faults and cracks are additionally visible, but none of them are of any importance. The general strike is parallel to the length direction of the formation; the dip varying from nearly vertical to very low, on an average, and usually having a value of about 30 degrees southeast. The folding axis has a direction of 20°—60° from south to west, with a dip of 10°—20°. Exceptionally axial directions have been noticed dipping a few degrees northeast.

The complex is made up of serpentine rocks, quartzites, dolomites with skarn-rocks, layers of mica-schist, graphite-bearing black-schists and copper ore. Numerous dikes of pegmatite originating from the neighbouring Maarianvaara granite cut the formation. Further more, there is an occurrence of anthophyllite-cordierite-rock in the western part of the ore-field. Towards the southwestern end the number of the separate components becomes smaller. The many thin beds of serpentine common in the northeasterly and middle parts have disappeared. In the latest drilling holes only two massifs of serpentine separated from each other by thick strata of quartzite and mica-schist overlie the ore.

Quartzites and serpentine rocks occur as major components. The mode of occurrence of the serpentine masses and their relations to the enclosing quartzites are the usual ones. In those places where the folding has been intense the lenticular form is more pronounced, as may be seen in the mine on the 165 metres level, where the mining operations have exposed sharp, compressed folds with rapidly varying strike and dip in the proximity of the serpentine bodies. In general, however, the structure of the complex is less disturbed and the serpentines occur in lenticular big masses several kilometres in length, always in conformity with the structural lines of the surrounding schist series.

The Outokumpu quartzite is easy to recognize, due to the content of vividly green chrome minerals, such as tremolite, diopside, fuchsite and uvarovite. Sulphides are nearly always present. Also carbonate is often met with as veins and solitary grains in connection with tremolite and diopside. In places the latter forms strata up to 1—2 metres in thickness.

The number of layers of mica-schist within the strata of quartzite is variable. Near the Central Shaft they are of considerable thickness, but are hardly to be found in the drilling holes between Raivionmäki and Mökkivaara. Farther away, beyond the hill of Mökkivaara, their number and amount again increase.

No actual carbonate rock has been met with independently within the quartzites. As far as known at present these rocks are always connected with serpentine bodies. Their description is given later, together with the skarn-rocks.

The ore is situated in a brecciated zone of quartzite, being overlain and underlain by serpentines. The overlying body is of even and considerable thickness. The body found in the foot-wall is not met with in the older drill-holes and only occasionally on the upper levels of the mine. Downwards, however, the layer of quartzite seems to pinch out and the serpentine is often exposed in the foot-wall. The latest drillings show the ore in direct contact with serpentine. In drill-hole 20 a, farther in the hanging wall, the ore-bearing stratum is absent and the serpentines have joined, forming a single body hundreds of metres in thickness.

The succession of the rocks in the contact zone between serpentine and quartzite is as follows: Next to quartzite there is a layer of coarse diopside rarely exceeding a thickness of one metre. It is followed by a zone of tremolite, which by the gradual addition of carbonate turns into dolomite. A slight content of tremolite is usually visible throughout the carbonate rock. This zone exceptionally measures as much as ten metres, but usually less. Finally, the carbonate material becomes mixed with patches of green or black serpentine, which by growing in size and number change the rock into serpentine. Instead of carbonate talc may occur. This shell-like arrangement in the order mentioned is nearly always to be found at the contacts, though, as a rule, the whole series measures only a few metres in thickness. Some of the members may be lacking, but the order does not vary. — Väyrynen (52) has called the transition type between dolomite and serpentine rock ophicalcite.

THE SERPENTINE ROCKS.

The rock exhibits great variations in its general appearance. The main bulk is made up of pale varieties in all shades of green and yellow. Black and mottled types occur in minor quantites. The rock is mostly massive, more or less granular; only exceptionally are aphanitic, »flintlooking» or schistose varieties to be met with. As a rule, the rock is very resistant against weathering. In some cases, however, it shows quite an opposite behaviour, being, when exposed, rapidly broken up into a fine powder.

The serpentinization is almost complete. Partially unaltered components are not, however, infrequent though the amount of the unchanged minerals is always small. In general, the darker varieties still contain olivine or other anhydrous silicates, whereas in the paler ones hydration is complete.

THE DUNITIC TYPE.

The dunitic variety has been dominant in the premetamorphic rock, though now rarely met with unchanged. Even those portions which are least altered contain at present but a negligible amount of olivine. The colour varies from black to very pale colours, depending upon the stage of alteration.

Owing to the even hydration of olivine, the original structure of the rock is hardly visible in thin section. In hand specimen, however, the granular structure of the original rock is sometimes astonishingly well discernible. The usually equidimensional grains can be directly measured, having a diameter of a few mms. The rock has been nearly monomineralic. In addition to olivine, scattered grains of chromite are met with, and in certain serpentine bodies a slight content of serpentinous pseudomorphs after amphibole may be found. Besides the mesh-structure serpentine, magnetite, chlorite, carbonate and talc occur as secondary minerals.

The alteration of olivine has proceeded along the cracks in and around the margin of the crystal, forming either single bands or systems of bands of serpentine. The interiors of the net are of a different kind, often slightly coloured and almost isotropic. More rarely the bands alone dominate, occupying, close together, the entire serpentine field. As much as is discernible the fibrous individuals are more or less parallel to each other and perpendicular to the elongation of the band.

The serpentinization of olivine was accompanied by precipitation of magnetite. It is mostly powder-like, being evenly distributed throughout the entire serpentine field, or occurring as aggregates and strings along the cracks of olivine. More rarely the magnetite dust directly borders the olivine relics. The zone of magnetite may, then, in part prevent further serpentinization of the grain.

In the completely serpentinized parts the ore dust, in general, is lacking. Instead of it, there occur coarser grains of chrome-bearing magnetite of variable size and form. It may form clouds of minute octahedra or it occurs as groups and chains of coarser grains. Locally they can be present in considerable amounts, whereas some parts are quite free from them. Coarse grains have never been met with on the varieties rich in powder-like magnetite. It is likely that the paler types once had a content of ore dust which was subsequently either removed or recrystallized into bigger individuals. The secondary origin of the magnetite grains and crystals is further supported by their structural properties.

In addition to the disappearance of the magnetite powder some other transformations distinguish the paler serpentines from the black ones. In general, the characteristics due to the special features and composition of the original rock become less distinct and in the extreme products the determination of origin, if possible at all, must be based upon the study of the intermediate types stage by stage. The network of serpentine is less distinct owing to the shorter and discontinuous bands, and the fibrous character of the individuals is far more difficult to recognize. Here and there flakes with the properties of antigorite are to be found, but they have not the distinctly outlined shape of the antigorite of the eastern zone.

The serpentinous pseudomorphs after amphibole deserve special attention. They are met with in the serpentine body underlying the ore. Elsewhere they have been found only in drill-hole 29 a in the serpentine mass overlying the ore. The pseudomorphs are evenly distributed throughout the rock; towards the foot-wall of the body their amount, however, decreases. Simultaneously an increase of elongated flakes of talc is often noticed. Nowhere, so far, has the amphibole of this mode of occurrence been met with unchanged.

Most likely the original mineral has been anthophyllite. The hydration has occurred with complete preservation of the form as visible in fig. (5). Only a few traversing bands of chrysotile show the usual change of amphibole along the cracks across the prism zone.

The pseudomorphs after amphibole may be found both in the dark varieties in which olivine still may be present and in the paler ones, where the original composition is more difficult to decipher. It is to be noticed that just in those parts where the pseudomorphs

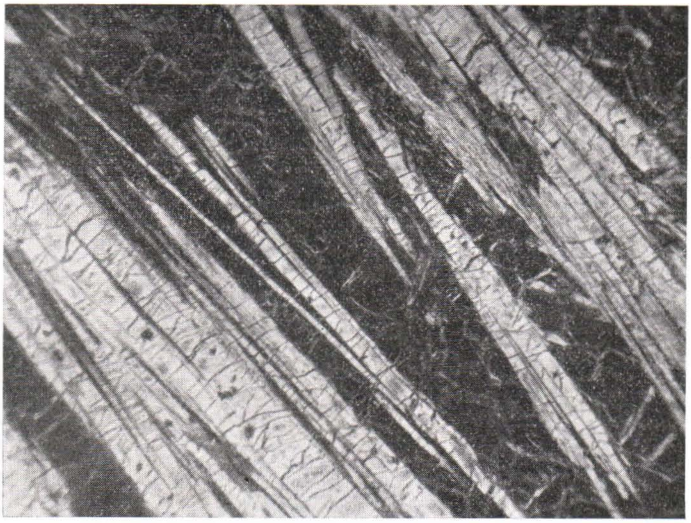


Fig. 5. Serpentinous pseudomorphs after amphibole. Outokumpu. + nic. Magnified 24 x.

after amphibole are most magnificent also the outlines of the grains of serpentinized olivine are visible to the unaided eye. There seems to be no doubt that the serpentinization of olivine and amphibole occurred practically simultaneously. As additional evidence for this there is the fact that no features are available that would indicate the presence of serpentine or magnetite powder during the formation of amphibole.

Thus the position of amphibole in the mineral sequence is determined: it succeeds olivine but precedes serpentine. The other minor components, chromite, talc and carbonate, are better represented in the following types and are discussed there.

A specimen taken from the 130-m's level from the body in the hanging wall was analysed (Table III). It was white-spotted green serpentine with clouds of minute octahedra of magnetite. The white patches seen under the microscope were noticed to be of nearly isotropic serpentinous material. The rock was completely serpentinized.

Table *III*. *Analysis of serpentine rock from Outokumpu by the author.*

	Weight per cent	No. Mol.
SiO_2	37.26	0.6179
Al_2O_3	0.48	0.0047
Fe_2O_3	6.32	0.0396
FeO	2.56	0.0356
MgO	38.11	0.9452
CaO	trace	—
$+H_2O$	12.95	0.7189
$-H_2O$	0.91	—
S	0.63	0.0196
Cr_2O_3	0.28	0.0018
NiO	0.24	0.0032
	99.74	

THE SAXONITIC TYPE.

So far the saxonitic variety has been met with only in the diamond drillings. In hand specimen it is characterized by its mottled appearance which is less pronounced in the more altered parts, where the black magnetite dust of the olivine fields has disappeared and the colourless enstatite has been replaced by green or brownish serpentine. In the more advanced stage of alteration the original features may still be recognizable under the microscope. The darker varieties are less altered. In comparison with the dunitic type the saxonitic variety contains more frequently unaltered anhydrous silicates, though their amounts here, too, are small. The presence of unchanged enstatite is noticeable megascopically and the olivine also can be noticed as tiny glistening dots discernible in the black serpentine when looked at in a suitable position.

The following minerals are met with: olivine, enstatite, anthophyllite, tremolite, chrysotile, bastite, chlorite, kaemmererite, talc, carbonate, chromite, magnetite and pyrrhotite.

Olivine has been the major component in the original rock. Enstatite occur rather sparsely as short irregular prisms often a few cms in length. Exceptionally its amount may become greater. Thus in drill-hole 29 a a layer was met with consisting entirely of bastite, but unaltered pyroxenitic rocks have not been found.

The texture is poikilitic. The small rounded inclusions of olivine are well preserved when protected by enstatite. When enstatite has been replaced by bastite, the forms of the olivine grains are to be seen as windows of mesh-structure serpentine in the bastite flakes. Occasionally greater elongated forms of olivine are noticed with sharp boundaries against the enstatite, but, as a rule, the olivine outside the enstatite plates is so completely serpentinized that its form cannot be determined.

The serpentinization of olivine is similar to that described before. The hydration of enstatite has always occurred with complete preservation of the form of the original crystal proceeding along the borders

Fig. 6. Bastite from Outokumpu.
+ nic. Magnified 24 x.

and cleavages of the crystal. Sometimes strings of fibrous serpentine traverse the prisms. In the most altered rocks the difference between the mesh structure after olivine and the plates of bastite is hardly visible. Faintly outlined forms of the flakes may, however, be discernible in thin sections in the specimens which appear quite homogenous to the unaided eye. In fig. 6. the original, distinct shape of a bastite plate can be seen.

Amphiboles are of minor importance. They are strongly altered into hydrated minerals, though not as much as olivine or enstatite. The serpentine formed is distinguishable from that derived from olivine only by the absence of the magnetite powder. Owing to the serpentinization, the contacts between olivine and amphibole are nowhere visible. Fragments of unchanged tremolite have been noticed in bastite.

Talc is common, occurring in connection with enstatite and still more frequently with bastite. In places a zonal arrangement is noticeable. The core may still consist of enstatite, bordered by bastite which is followed by a zone of talc. Locally talc seems to replace enstatite directly, but usually enstatite is lacking and talc replaces bastite. Sometimes the form of talc suggests amphibole as the original mineral. Here, too, talc my have replaced amphibole directly or after preceding serpentinization. The former case seems more likely, for, as a rule, the serpentinization of amphibole in this and the following type does not occur with preservation of the form. The amount of chrysotilic serpentine replaced by talc seems to be small. It is indicated by certain features peculiar to the mesh-structure serpentine noticed in the talc fields.

Chlorite is present nearly everywhere, but its amount is quite small. It occurs as nests or solitary blades in and around the bastite individuals. In the cracks of the chromite grains the blades of chlorite are often quite numerous.

Chromite is in general of rather rare occurrence in the serpentines. In the saxonitic rocks it is perhaps more frequent than elsewhere. It occurs as solitary grains sparsely studded into serpentine; only in one sample a higher content of chromite was noticed. The biggest grains found in thin sections occur in the serpentine field. The cracks are filled with chrysotilic serpentine, chlorite and carbonate. Smaller, rounded and a little brecciated grains up to 3 mms in diameter have been found as inclusions in bastite. The relations to olivine and enstatite are not known. It seems likely that the crystallization of chromite was at an end before the formation of enstatite.

The mode of occurrence of magnetite is similar described before. The areas occupied by enstatite and bastite are free from the pigment-like magnetite. Instead magnetite may occur as filling material in the cleavages and cracks.

Pyrrhotite occurs as filling material. It seems to be the latest member in the mineral sequence.

A specimen of bastite-bearing serpentine rock was analysed (Table IV). The rock was completely serpentinized and contained bastite, chrysotile, talc, chlorite, carbonate, chromite and magnetite. The first two minerals were the major components. The content of chromite was higher than usual.

Table IV. *Analysis of a bastite-bearing serpentine rock from Outokumpu by the author.*

	Weight per cent.	No. Mol.
SiO_2	35.92	0.5957
Al_2O_3	1.47	0.0144
Fe_2O_3	5.27	0.0330
FeO	2.63	0.0366
MgO	35.77	0.8872
CaO	1.45	0.0259
$+H_2O$	12.20	0.6772
$-H_2O$	1.27	—
S	0.21	0.0065
Cr_2O_3	1.05	0.0069
NiO	0.28	0.0037
CO_2	2.26[1])	0.0514
	99.78	

THE PORPHYRITIC TYPE.

The frequently porphyritic appearance of this type is due to the elongated crystals of olivine or their serpentinous pseudomorphs. In the less hydrated parts especially they are very marked, the black magnetite powder outlining the olivine crystals distinctly against the paler ground-mass of carbonate, amphibole, or talc. Instead of solitary crystals, patches and groups of olivine may occur. Even in the completely serpentinized portions the porphyritic fabric is sometimes fairly discernible to the unaided eye. It is due to a slight difference in colour between the ground-mass — also serpentine — and the serpentinous pseudomorphs. This type is often met with in the diamond drilling cores though its amount is not great. It is likely that in many cases serpentinization has completely destroyed the original texture.

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

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

[1]) The amount of CO_2 is calculated supposing that all lime enters into dolomite.

The olivine of this type is comparatively well preserved, especially when associated with carbonate or amphibole. Its hydration has occurred in the same way as usual along the cracks of the crystals. Occasionally some special features are noticed. Thus, when olivine occur in close connection with amphibole the parts contiguous to the amphibole are preserved, while the more remote portions may have been completely hydrated. Fig. 7. illustrates this. In fig. 8. an olivine

Fig. 7. Photomicrograph showing the protecting effect of amphibole upon olivine. The portions of olivine surrounded by amphibole show only a commencement of hydration, while the more remote parts are almost completely serpentinized. + nic. Magnified 24 x.

grain poikilitically enclosed by amphibole shows a fairly even alteration. Sometimes the olivine individual are surrounded by yellow serpentine. The olivine may, then, show only a commencement of hydration with numerous cracks filled with magnetite dust. The border against the enclosing serpentine is often sharp and regular. The magnetite strings in the cracks are cut at the border and do not continue farther into the serpentine. The serpentine around the olivine core is of a somewhat different kind than usual. Its colour is stronger, dirty yellow, and its birefringence is rather high. The relation, however, are not always equally evident. In places the border between olivine and serpentine is more irregular, with solitary relics of olivine showing uniform extinction within the serpentine area. The strings of magnetite penetrate also into the field of the coloured serpentine, which by and by fades out into the colourless variety.

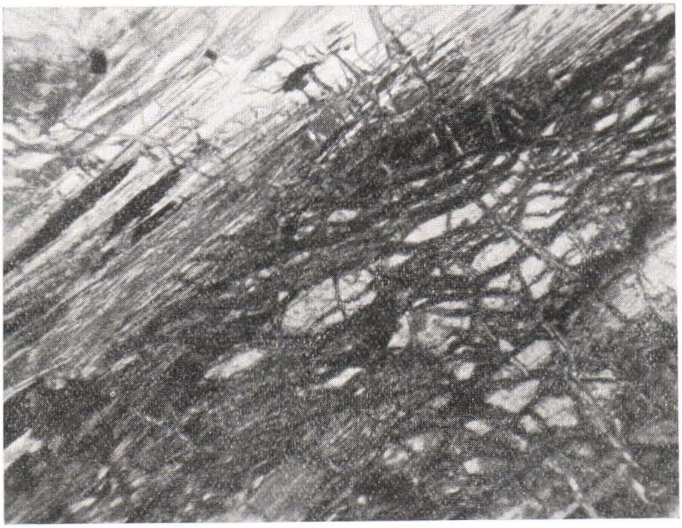


Fig. 8. Crystal of olivine enclosed by anthophyllite. + nic. Magnified 40 x.

Fig. 9. Photomicrograph showing the remains of a partly serpentinized prism of amphibole. The black area as well as the corner to the left below have earlier been occupied by olivine. Outokumpu. Without nicols.

The mode of occurrence of both anthophyllite and tremolite is the same. They occur in elongated crystals of a lath-shaped habit. Fibrous types are also common. The prisms of amphibole penetrate into olivine, dividing the individuals into separate parts; rarely they enclose olivine poikilitically.

The serpentinization of amphiboles is general, only in the carbonate areas are they better preserved. The solitary prisms within the olivine fields have been attacked by the hydration nearly as strongly

Fig. 10. Photomicrograph from the contact rock between dolomite and serpentine. The railway cutting near Outokumpu station. Magnified 7 x.

as the olivine. The greater groups are less altered. Many of those crystals which occur in the coloured serpentine have entirely escaped hydration. Fig. 9. shows the mode of alteration. The serpentinization occurs along the cleavages and cracks; the change along the cracks across the prism is especially pronounced. The serpentine produced is similar to that derived from olivine but free from ore powder. Bastite-like products are rare.

Fig. 10. illustrates the appearance of an intermediate member between the serpentine rock and the dolomite. It shows the mode of occurrence of carbonate in nearly equidimensional grains penetrating into the serpentinized cracks of the olivine crystals and dividing them

into separate parts. In many places only ghostly relics of olivine and serpentine are discernible within the carbonate. In those portions where carbonate is a minor component it occurs as tiny grains evenly disseminated throughout the serpentine field or forming greater carbonate areas of various form and size of grain. When occurring together with amphiboles it fills the spaces between the needles and penetrates into the cracks and cleavages. Finally the crystals become entirely replaced. This is best visible in the serpentinized parts where fragments of amphibole have been replaced by carbonate material. The carbonate grains have, then, the exact form of fragments, some

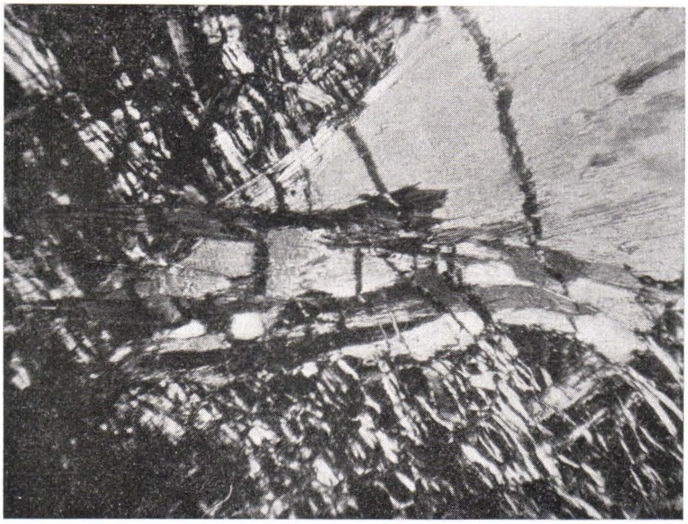


Fig. 11. Bundle of dolomite pseudomorphous after amphibole. Outokumpu. + nic. Magnified 40 x.

of which may still have been left unchanged. They are separated from each other by the serpentine bands corresponding to the serpentinized portions along the transversal cracks of the amphibole. In addition, the arrangement of the carbonate grains often reveals the elongated or fibrous form of the original crystal. Fig. 11. shows a carbonate area pseudomorphous after a bundle of amphibole.

The observations show that the carbonate has replaced both amphibole and serpentine. The process was probably selective to some extent. Occasionally grains of carbonate have been found in intimate contact with olivine, but no certain features are available which would suggest a direct alteration from olivine to carbonate.

As mentioned already the varieties rich in talc occur more separately. Amphibole and carbonate may be present as well, but not in any considerable amounts. As a rule the serpentinization is complete. Fig. 12. shows a specimen of serpentine rock in which the outlines of pseudomorphs after olivine are made visible by the surrounding flakes of talc.

In the completely serpentinized portions free from ore dust the elongated idiomorphic forms of the original crystals are often distinctly outlined. They may measure up to 2 cms and more in length.

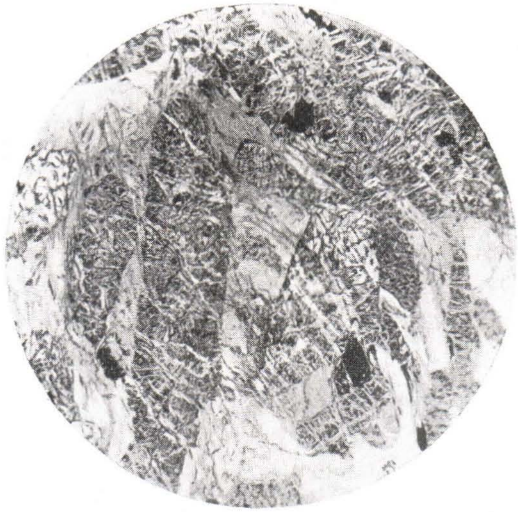


Fig. 12. Serpentinized olivine crystals surrounded by flakes of talc. Outokumpu. Magnified 5 x.

The colour of the ground-mass is a shade different or the border is discernible due to the difference in the structure of the two serpentine varieties. Fig. 13. shows a photomicrograph in which the pseudomorphs are well marked owing to the difference in birefringence. The groundmass is nearly isotropic. Its original mineralogical composition is unknown. Occasionally some flaky forms may still be discernible, but their origin cannot be determined.

The mode of occurrence of the other components, excluding chromite, is similar to those in the types described before. The few grains of chromite found are enclosed in olivine. The grains are more like groups of strongly corroded small crystals packed tightly together. The spaces between the crystals are filled with blades of chlorite, which also border the contact against olivine. Similar groups have been found in the serpentine occurrences farther west. There the corrosion has often been stronger, the relics of the crystals occurring separately.

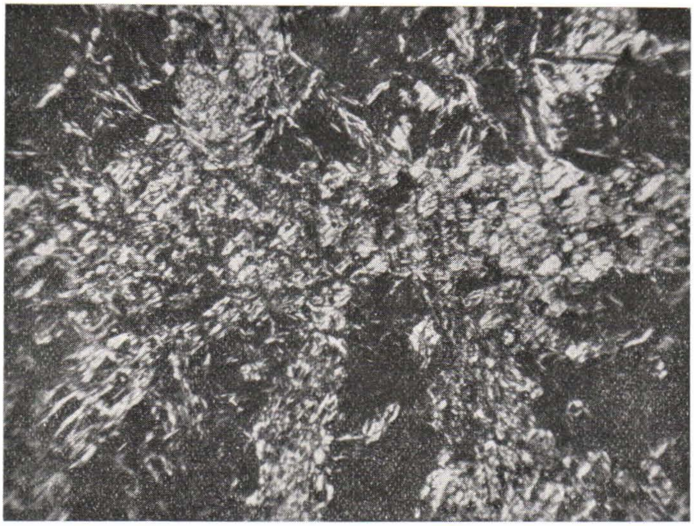


Fig. 13. Photomicrograph showing the serpentinized porphyritic type between crossed nicols. Outokumpu. Magnified 24 x.

THE MINERALOGY.

Olivine. The presence of unaltered olivine in hand specimen is indicated by the somewhat stronger lustre noticeable in the black pseudomorphs which still contain olivine. The outer habit of olivine is mostly granular, the grains measuring up to a few mms in diameter. More rarely olivine occurs in idiomorphic elongated crystals up to several cms in length. The prism zone is mostly well developed, rarely being terminated by pyramidal faces. Cleavage after (010) has occasionally been noticed. The optic axial angle is almost 90°. The indices of refraction show practically no variations in composition. Their values measured by immersion are $\gamma = 1.684 \pm 0.003$ and $\alpha = 1.647 \pm 0.003$ corresponding, according to Winchell, to a content of about 8 per cent. of fayalite in the olivine molecule.

Enstatite. The amount of enstatite is small. It was found unchanged only in a few slices. The serpentinous pseudomorphs show that enstatite has occurred in the form of big irregularly terminated short prisms. Where unchanged relics still are left they can be distinguished from the amphiboles by the distinct prismatic pyroxene cleavages in the basal sections and by the more pronounced traces of the same cleavage planes in the vertical sections. The conversion into serpentine is also different in most cases.

Chrysotile. In the less altered parts the fibrous character of the serpentine forming the bands of the net is often distinct. The colour is faintly green or yellowish, but may often be wholly absent. The

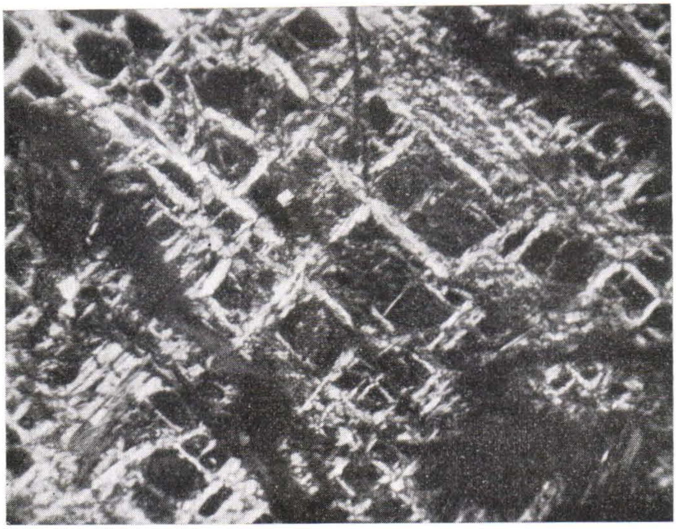


Fig. 14. Photomicrograph showing the basal section of a serpentinized enstatite prism. A few grains of enstatite unchanged. Outokumpu. + nic. Magnified 40 x.

elongation of the fibres is negative and only the occasional blades met with in the interiors of the net have positive elongation. Refringence and birefringence vary. For the former values between $\alpha =$ 1.570—1.560 were obtained by immersion.

Bastite. Bastite occurs in forms similar to those of enstatite. The prismatic cleavages of the latter in the vertical section are hardly any longer visible. In the basal sections the traces of the prismatic cleavages of enstatite are well discernible, due to the different properties of that serpentine which had originated in the cleavage cracks (see fig. 14.). Diagonally to them an indistinct parting is still visible. The optic plane of the bastite is perpendicular to the latter. The colour in thin section varies from dirty green to yellowish. Pseudomorphs are met with where the edges have a distinct pleocroism, from bluish green parallel to the prismatic cleavages to faintly yellow perpendicular to them, whereas in the middle part of the same individual the colour is dirty yellow without any variation in the different positions. The elongation is positive. The birefringence varies greatly. From one specimen an index of refraction was determined by immersion: $\gamma = 1.570$ approximately.

The serpentinous pseudomorphs after amphibole (fig. 5.) greatly resemble bastite. The outer difference are due to the differences of the host minerals. The mineral is colourless. The elongation of the prisms is positive. In one sample the refraction index was determined by immersion: $\gamma = 1.566 \pm 0.003$.

Amphiboles. Tremolite and anthophyllite occur as colourless coarse prisms or in bundles of fibrous needles.

Carbonate. Carbonate occurs with various forms and grain size. The refractive index, determined in several samples by immersion, is on an average $\omega = 1.684 \pm 0.003$, which, according to Winchell, corresponds to a dolomitic composition.

Chlorite. Chlorite has the properties of a clinochlore. It is almost colourless and biaxial, with positive sign and negative elongation. In addition, a few flakes of violet kaemmererite were noticed.

Talc. Talc occurs in coarse flakes, pseudomorphous after enstatite or bastite. Smaller scales may sometimes occupy greater areas.

Chromite. The biggest grains of chromite measure up to 1 cm in diameter. The grains are brecciated, causing a structure which is called by Fisher mitred-structure (21 p. 693). The chromite has a brown streak, it is nonmagnetic and insoluble in hydrochloric acid. The content of chromium was not determined directly, but it seems to be quite high, according to the determination of chromium in a sample which besides the ore minerals contained a considerable amount of serpentine. The amount of Cr_2O_3 was 20.83 per cent. Viewed under the microscope the centres of the grains are seen to be translucent, reddish brown in colour, surrounded by a black opaque zone from which branches penetrate into the grains. According to Phillips (40) and Fisher the content of chromium is higher in the coloured parts.

Magnetite. The various modes of occurrence of magnetite have been dealt with above. The chrome-bearing variety deserves special attention. The grains exhibit great variations in form and size. According to the chemical test the content of chromium is general. A number of small grains were picked up and their content of chromium was determined quantitatively. The colorimetrical determination gave 14.01 per cent. of Cr_2O_3. All the grains are strongly magnetic. When polished and etched by hydrochloric acid, they show a zoned structure (fig. 15.). In continuing the etching the whole grain was affected. Seen under the microscope they are opaque, only in a few cases are the borders of the grains translucent. The fractured grains show that the brecciation is younger than the formation of the translucent rim.

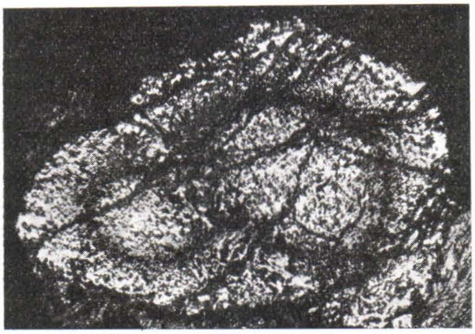


Fig. 15. Chrome-bearing magnetite after etching by hydrochloric acid. Magnified 20 x.

THE MODE OF OCCURRENCE OF THE DIFFERENT TYPES IN THE FIELD.

An attempt has been made to locate the above types in the field. The completely serpentinized rocks are in great majority. As to them it is often impossible to decide which of the three groups is in question. The bastite-bearing portions are most easily recognized, occurring in layers several metres in thickness. Also the porphyritic variety is sometimes well pronounced. It occurs only in thin strata, grading over into serpentine in which the original texture is no longer discernible. The distribution of the types show no spatial regularity. A slight increase of the saxonitic variety towards the southwest is noticeable. The examination of the distribution of those parts which still contain anhydrous minerals, olivine and enstatite, revealed a somewhat astonishing fact. As a rule, the best preserved portions are situated nearest to the contacts, while the most altered parts are to be found in the inner parts of the masses. In the southwestern end of the complex the ultrabasics, in general, are less hydrated and the distribution is more haphazard, the unaltered layers being found also within the bodies.

In most cases the peripheric unhydrated part is of the porphyritic variety but also enstatite-bearing rocks have been met with there. Of course the serpentinization is often complete throughout the body, even near the contacts.

The layer adjacent to the contact sometimes begins with a thin stratum of completely serpentinized rock which rapidly turns to a black olivine-bearing one. As a rule, however, this first zone is absent and the contact rock — which is usually either a carbonate rock or a talc schist — grades over into the black zone. The first crystals and patches in the carbonate may be only partly hydrated. Also in the adjacent, often amphibole-bearing parts, olivine is still to be found in abundance. Towards the centre of the body its amount decreases rapidly. The degree of serpentinization of this outer layer varies in different places, but its intensity always increases towards the centre of the serpentine mass. This exceptional feature is discussed in a later chapter. The thickness of the zone does not exceed a few metres.

DOLOMITES AND SKARN ROCKS.

As mentioned earlier, the layers of carbonate are closely connected with serpentines. So far no actual carbonate rock has been met with indepedently within quartzites. The outcrops are rare. In a prospecting pit and drift at Raivionmäki a dolomite rock is exposed. It is probable that this rock is connected with the northernmost body of serpentine belonging to the Outokumpu complex, though the serpentine mass itself is not exposed. In the wall of the trench there occur lenticular areas of grey carbonate separated from each other by a network of light green tremolite and diopside. The inner parts of the rock between the carbonate portions consist of diopside, the parts next to dolomite being composed of tremolite. A chromite-bearing dolomite described by Eskola (18) can be found as boulders in the vicinity of the pit.

The railway cut near Outokumpu station shows a thin layer of carbonate overlain by a slab of quartzite. A contact wall against the hanging wall is made up of coarse diopside, a few dms in thickness. On the side of the foot-wall the carbonate layer passes gradually over into serpentine.

In several parts of the Outokumpu mine thin beds of carbonate are visible at the borders of the serpentine bodies. The examination of the diamond drilling cores further strengthens this assumption as to a close relationship between serpentines and dolomites.

The hand specimens of dolomites show an even-grained rock of varying colour. The purest varieties are white or grey. Seen under the microscope the pure types are fairly uniform, being composed of carbonate grains of nearly equidimensional shape. Occasionally the grains exhibit greater variation in form and size. The bigger irregular grains may in such instances enclose smaller rounded ones. The values of the index of refraction ω, measured by immersion, vary to some extent. The following values were obtained:

Raivionmäki,	chromite-bearing dolomite	$\omega = 1.691$
»	pure dolomite from the prospecting pit	$\omega = 1.685$
Railway cut,	from the dolomite layer	$\omega = 1.682$
» »	from the transition zone	$\omega = 1.682$

According to Winchell's tables all these values indicate a dolomitic composition.

Prisms of tremolite can nearly always be found among the grains of carbonate and some ore minerals are invariably present.

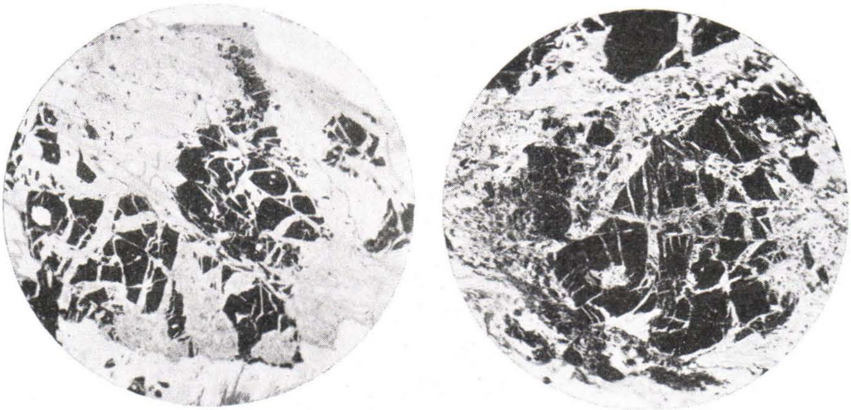


Fig. 16. Chromite in dolomite. Chromite in serpentine.
Magnification 5 ×.

Tremolite occurs mostly as slender prisms of varying shade from colourless to intense green. The colourless and the green varieties have been met with together. In a sample from drill-hole 26 a the green amphibole is arranged around and among the aggregates of fractured grains of chromite, the amphibole between the groups of chromite being colourless. The coloured variety shows a pleochroism γ bluish green, β yellowish green and α faintly yellow.

Some of the ore minerals are of special interest. Besides at Raivionmäki, chromite in dolomite has been found in several drill-holes, though not in abundance. The bigger grains are usually fractured in the same manner as in serpentines (see fig. 16.). Under the microscope the grains of chromite are seen to be translucent in their central portions, while the borders and some traversing strings are opaque. The picture is exactly the same as that of the chromite in serpentines. In pure tremolite layers chromite of similar properties has been met with.

In some thin sections the ore is seen to occur as irregular clouds separated from each other by areas of carbonate and amphibole. When examined between crossed nicols the portions covered by ore are seen to be composed of material similar to that in the space between them. The ore shows no relation whatever to the structural properties of the carbonate or amphibole. The clouds may be made up of a very fine powder (fig. 17) or of minute grains. Occasionally similar clouds have been met with in serpentines. Most likely the mineral is magnetite. In addition, magnetite occurs as material filling the cleavage cracks of amphiboles and around the carbonate grains.

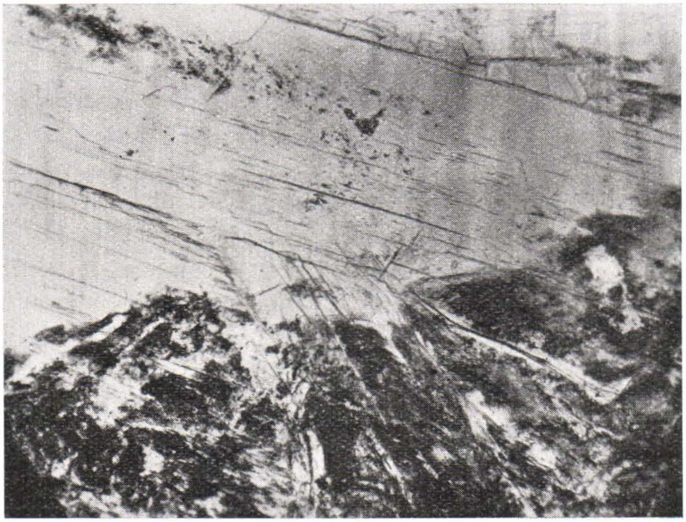


Fig. 17. A cloud of the o.e dust in dolomite rich in tremolite. Outokumpu. Magnified 40 x.

In the proximity of chromite some flakes of pale coloured mica were noticed. The colour is brown with a reddish tint along the cleavage. Perpendicular to the latter the colour becomes fainter. Occasionally, when in contact with the ore grains, the outer edges show a strong variation in colour, from green to colourless. The small optic axial angle shows a negative sign. Birefringence is high. The properties correspond to those of the chrome-bearing mica from Kuusjärvi.

In addition to these minerals serpentine, chlorite, talc and sulphides are noticed. Diopside has not been met with in the slices of dolomite. On a few occasions patches of serpentine were found far away from the contact within the carbonate.

Outcrops consisting of chrome-green diopside and tremolite can be met with in many places around the Outokumpu mine. The outcrops and the examination of the diamond drilling cores show that these diopside and tremolite layers most likely are replacement products of carbonates, i. e. they are to be considered as skarn rocks.

The bands of diopside form the outer zones of the contacts against quartzite, being separated from the dolomite or serpentine by a layer of tremolite. This arrangement can be seen practically at every contact zone in the diamond drilling cores. The passage from the tremolite rock into dolomite is gradual and the following carbonate rock is often interrupted by bands rich in amphibole or entirely composed of it.

The thickness of the skarn layers is rarely more than a few metres and is usually too small to allow them to be marked separately. On map II they are included among the dolomites.

The skarn minerals in quartzites occur more evenly distributed. They form thin layers and streaks on the schist planes. Only diopside may occur in thicker bands, up to a few dms in thickness.

Diopside forms coarse prisms up to 10 cms and more in length. Its colour is chrome-green, only exceptionally has a greyish white variety been met with. The content of Cr_2O_3, according to the determination of E. S. Tomula (24) is 0.44 per cent.

The diopside layer seldom contains any remarkable amounts of other minerals. In places a chrome-green tremolite occurs abundantly. Sulphides are nearly always present in small amounts. Pyrrhotite in special is common, sometimes occurring in fairly well developed crystals. Grains of coarse carbonate — probably calcite — often fill the space between the pyroxene crystals.

The properties of tremolite show greater variations. In the quartzites and in connection with diopside the tremolite is of a vivid green colour, indicating a content of chromium. The determination by E. S. Tomula shows 0.64 per cent of Cr_2O_3. According to the determination of Eskola (18) a brownish green tremolite from a uvarowite-tremolite-tawmawite-vein contains 1.61 per cent. of Cr_2O_3. In dolomites the colour of the amphibole varies greatly. Chrome-green, dirty green, nearly black, white and colourless varieties have been met with. — A dark, dirty green type shows a distinct pleochroism as described earlier (see p. 48). Its mode of occurrence in connection with chromite indicates that it also has a content of chromium.

The borders of the tremolite layers are less sharp than those of diopside bands. Also the mineralogical composition varies more. In the tremolitic rocks within the dolomite all the minerals mentioned in connection with dolomites may be found.

The Kuusjärvi complex.

The occurrences of ultrabasics near Lake Suuri Kuusjärvi, about 5 kms to the southwest from the Outokumpu mine, form a direct continuation of the Outokumpu complex. The form and the bounda-

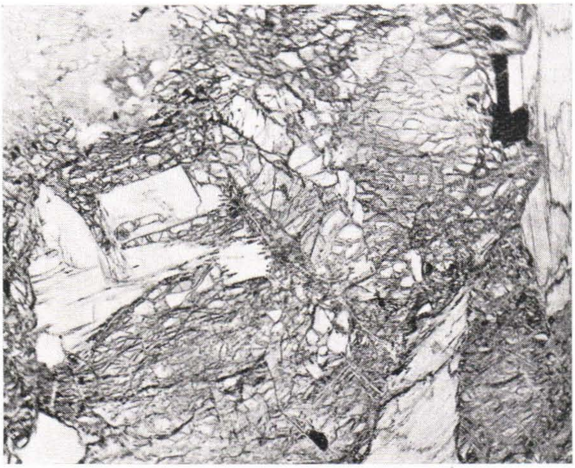


Fig. 18. Photomicrograph showing olivine, serpentine and flakes of the chrome-bearing mica. Kuusjärvi. 10 x.

ries of the Kuusjärvi complex are, however, less definite, the different constituents of the complex occurring more separately in the surrounding mica-schists. The relations to the country-rock are not exposed. Besides mica-schist also the Maarianvaara granite outcrops in the neighbourhood.

Most of the outcrops consist of serpentines. The layers of quartzite are small. Occurrences of ores have been searched for through diamond drilling, without result, however. The writer has had no opportunity of studying the cores of the drill-holes, but from the observations in the field a few differences from the rocks of Outokumpu may be noticed. Dolomites with their skarn minerals are absent, and the amount of carbonates in the serpentines is quite small. Talc often occurs in abundance. In some outcrops big flakes of ice-green talc may form the main constituent of the rock.

In general, the ultrabasics are better preserved than at Outokumpu. By the side of the road to Viuruniemi village there is an outcrop of intensely black serpentine with flakes of white talc and brown mica. Also the amount of pyrrhotite is considerable. Olivine is visible to the unaided eye. The reflecting cleavage planes show individuals up to 2—3 cms in diameter. Seen under the microscope the crystals of olivine are found to have undergone an even serpentinization along a network of cracks (fig. 18.). Roughly estimated, one third of the olivine has been decomposed. Cleavage along (010) could be noticed. The index of refraction measured by immersion was $\beta = 1.668$, corresponding, according to Winchell, to a content of about 8 mol. per cent. of $FeSiO_3$.

The mica is distinctly pleochroic, being pale brown along the cleavage and colourless perpendicular to it. Locally greenish tints are visible. (—) $2E = 18°$ approximately, $\gamma = 1.585 \pm 0.003$. Birefringence, measured by Berek's compensator, has a value of 0.035. The content of Cr_2O_3 determined colorimetrically was 1.28 per cent. The appearance and properties are those of a mica of the biotite series.

In addition to the minerals mentioned above, anthophyllite, carbonate, chromite and magnetite have been met with.

Anthophyllite occurs as slender prisms or fine fibres. A growth of the latter, parallel with the (010) cleavage of olivine, was noticed in a slice.

Talc and carbonate occur in the cracks and in the interstices of the olivine grains. Carbonate is rare.

Chromite has been found as small rounded grains which are met with in the serpentinized cracks as well as in the olivine itself.

Pyrrhotite occurs mostly in connection with the blades of mica and talc.

The following analysis (Table V) was made from a specimen corresponding to the above description, only carbonate and anthophyllite being absent.

Table V. Analysis of a serpentine rock from Kuusjärvi by the author.

	Weight per cent.	No. Mol.
SiO_2	37.44	0.6209
Al_2O_3	0.53	0.0052
Fe_2O_3	2.97	0.0186
FeO	4.71	0.0655
MgO	43.70	1.0839
CaO	0.12	0.0021
$K_2O + Na_2O$	0.55	0.0089
$+H_2O$	7.86	0.4363
$-H_2O$	0.50	—
S	1.47	0.0458
Cr_2O_3	0.18	0.0012
NiO	0.28	0.0037
	100.31	

Near Lake Suuri Kuusjärvi close to the Outokumpu railway an occurrence of enstatite-bearing serpentine is exposed. Enstatite occurs as big elongated prisms evenly studded into the black serpentine. In thin section the olivine is seen to have undergone complete serpentinization. Enstatite is better preserved. The centre of the prism may still be unchanged, the borders being converted into bastite or talc. The alteration into talc, especially, is pronounced and seems to have strongly attacked the unaltered enstatite. This can be seen megascopically, due to the flaky talc covering the enstatite prisms and cleavage planes.

The indices of refraction of enstatite, measured by immersion, are $\alpha = 1.658 \pm 0.003$, $\gamma = 1.670 \pm 0.003$. These values correspond (Winchell) to a member of the enstenite series containing about 7 mol. per cent. of $FeSiO_3$.

In addition, anthophyllite, brown mica, and carbonate were noticed.

THE ULTRABASIC ROCKS OF MALJASALMI.

Towards the west from Lake Suuri Kuusjärvi in Maljasalmi village there are some occurrences of ultrabasics near a little lake named Hilipanlampi. Also here the environment is made up of coarse mica-schist, but the relations to the country rock are not visible, nor are the ultrabasics themselves well exposed. Black serpentines rich in olivine have been noticed as well as pale coloured, completely hydrated rocks. An asbestos-bearing variety has been met with as boulders. In connection with the olivine-bearing body there is an outcrop of a nearly pure pyroxenitic rock, with big crystals of enstatite of random orientation. Some black glistening dots indicate the presence of olivine. In the interstices of the enstatite prisms packs of violet kaemmererite and brownish mica are visible. Crystals of pyrite are common.

Fig. 19. presents a photomicrograph of a slice made from the pyroxenite. It shows clearly the prismatic pyroxene cleavages. The indices of refraction of enstatite, determined by immersion, are $\alpha = 1.659 \pm 0.003$, $\gamma = 1.671 \pm 0.003$, corresponding to 7 mol. per cent. $FeSiO_3$.

The mica-like blades of kaemmererite are flexible inelastic. In thin section they are colourless, often showing a polysynthetic twinning. Birefringence is moderate. The optic sign is positive. The optic axial angle has an approximate value $2E = 43°$. The index of refraction, measured by immersion, is $\alpha = 1.582$. The content of Cr_2O_3, determined colorimetrically, is 2.22 per cent.

Anthophyllite occurs as long acicular prisms piercing through the enstatite. It is also found in parallel growth with pyroxene, occurring then in the cleavages as very fine fibres.

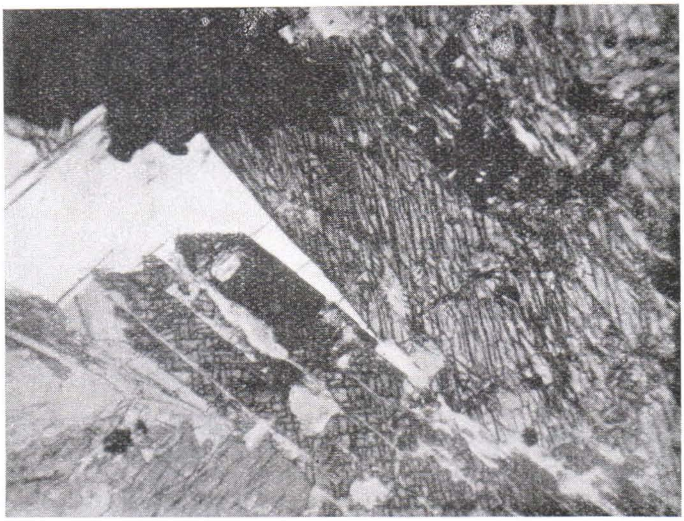


Fig. 19. Enstatite from Maljasalmi. White: kaemmererite. + nic. Magnified 25 x.

Serpentinization has hardly touched the rock. The few inclusions of olivine with their magnetite dust show the commencement of hydration.

THE SERPENTINES OF ONKISALMI, PETRUMAJÄRVI AND VARISTAIPALE.

The Onkisalmi occurrence is situated in the parish of Liperi, about 2 kms to the southwest of the Onkisalmi ferry. The neighbouring outcrops consist of coarse mica-schist. About 5 kms farther southwest there is another outcrop of ultrabasic, but the author did not visit this. In the continuation of the same belt near Lake Petäjäjärvi, about 10 kms from Onkisalmi, there occurs a zone of quartzite surrounded by mica-schists. The quartzite greatly resembles that of Outokumpu, containing chrome-green tremolite. In a boulder in the vicinity also uvarovite was noticed as small green dots in the quartzite. The presence of abundant serpentine boulders indicates that also ultrabasics occur in the neighbourhood though no outcrops were found.

The serpentines of Petrumajärvi occur in an environment of micaceous gneisses richly traversed by intrusions of granite. The relations of serpentine and granite have been discussed on page 13.

The occurrences of Varistaipale are situated in the gneiss territory. Some special features connected with them have been described earlier (see p. 13).

These occurrences are all thoroughly hydrated rocks with a local content of olivine which seems to have been the only constituent of the premetamorphic rock. The Varistaipale serpentines resemble the dunitic rocks of the Kuusjärvi complex. At Petrumajärvi and Onkisalmi the formation of amphibole has been considerable. Subsequently amphiboles have, to a great extent, been converted into talc. The boulders at Petäjäjärvi are mostly made up of pale, pure serpentine of the Outokumpu type.

THE SERPENTINE BELT OF NIINIVAARA-SÄYNEINEN.

This belt of serpentines occurs in a somewhat isolated position in the northwest corner of the area of map I in connection with quartzites surrounded by gneisseous mica-schists and richly traversed by intrusions of the Maarianvaara granite. The relations to the country-rock are not exposed. Megascopically and microscopically these serpentines correspond to those at Outokumpu being, however, completely hydrated. So far no certain instances of pyroxenes have been met with, the olivine, apparently, having been the dominant component before hydration.

Niinivaara. The outcrops of Niinivaara form abrupt rocky hills. The areas contiguous to the outcrops are covered by soil. The rock is dark green in colour and consists of serpentine, with a few groups of serpentinized amphibole. Olivine is absent, but locally its elongated form can be seen in pseudomorphous groups.

In the bodies towards the north (Polvikoski, Kiukoonkoski, Mäntyjärvi) up to Lake Aittojärvi the serpentine is of similar character. Serpentinized amphiboles are common in these bodies. Especially the occurrence of Mäntyjärvi is of interest in this respect. The pseudomorphs after amphibole occur on the surface of the outcrop as big stellate groups. The individuals of such a group may have a length of up to 5 cms and more. The granular serpentine between the groups and pseudomorphs contains grains of dolomite and magnetite.

Aittojärvi. The big bodies in the neighbourhood of Lake Aittojärvi are made up of pale green serpentine of the Outokumpu type. They occur in close connection with carbonate rocks with transitional forms from one rock into another. The carbonate-bearing portions contain chrome green tremolite in abundance. In a slice some grains of faintly translucent ore of a reddish tint were noticed. They were probably chromite.

Poskijärvi. The Poskijärvi complex contains the same members as that of Outokumpu, with the exception of ore. Quartzites do not occur as abundantly, however. Also the layers of carbonate seem to be smaller. Layers of bright green, chrome-bearing tremolite are common, but diopside is of rarer occurrence. The ultrabasics have undergone complete hydration. In some parts a slight content of olivine may still be found.

Säyneinen. The occurrence of Säyneinen forms a small brecciated outcrop of black serpentine with a number of radiating groups of amphibole. Locally the rock has a mottled appearance, due to areas rich in talc in which irregular patches of black serpentine can be seen. These talc-bearing portions show no relation to the borders of the mass.

Vehkalahti and Luikonlahti. The occurrences of Vehkalahti and Luikonlahti do not geographically belong to the zone under discussion, but are nevertheless described here, as they are more similar to the occurrences of Outokumpu.

The Vehkalahti serpentines occur in the gneiss territory near the western border of the mica-schist area which encloses the serpentines of the actual Niinivaara-Säyneinen belt. In the neighbourhood there occur a number of outcrops of tremolite-schists but the contacts of the ultrabasics are not exposed. The samples show a black serpentine in which olivine may still be found. In a boulder a transition from pure carbonate rock into serpentine was noticed, but outcrops of carbonate rocks are not known.

The Luikonlahti complex is made up of quartzites and serpentines surrounded by metamorphosed gneisses and schists. Also a small deposit of copper ore belongs to this complex. All these rocks are traversed by numerous veins of the Maarianvaara granite. The structure is very disturbed. The axial directions, dip and strike show considerable variations.

The contacts of the serpentine bodies against their country-rock are not exposed. At one place a vein of quartz was met with in serpentine with zones of coarse mica on both sides against the enclosing rock. The zone of weathering is in places very thick, as mentioned earlier (p. 14). The black varieties are better preserved. Some boulders composed of carbonate rich in inclusions of serpentine suggest that aureoles of carbonate surround the serpentine bodies. The inclusions of serpentine are rounded and even-sized. This structure is sometimes, however, traversed by coarser inclusions of serpentine in a vein-like arrangement. Zones of chrome-green tremolite and diopside have also been met with at the contacts.

Types of serpentine similar to those at Outokumpu can be found. Even the porphyritic variety with big elongated pseudomorphs after olivine was met with. In the black varieties olivine may still be present, but, as a rule, hydration seems to be more complete than in the serpentines of the Outokumpu complex. In a thin section from the collections of the Geological Survey, labelled as having been made from a specimen from Luikonlahti, elongated crystals of olivine were embedded in a matrix of coarse diopside.

Farther north near a little lake, Petronjärvi, there is an ultrabasic outcrop of a kind different to those described above. It is discussed later (see p. 63.).

THE ULTRABASIC BODIES OF THE GNEISS TERRITORY.

The westerly gneiss territory forms a direct continuation of the big schist complex in the east, though the numerous intrusions of granite as veins and bigger masses have greatly disturbed the earlier structure and the intense migmatitization and granitization have caused thorough changes in the original composition.

These special conditions have left a great impression also upon the ultrabasic bodies occurring within the region. These are characterized by their haphazard distribution, by their small size and lenticular shape and especially by their general and abundant content of amphiboles. Further, it is to be noticed that serpentinization, as a rule, is of less importance, though even pure serpentines may be found. Carbonatization is practically absent. Relatively to the last two phenomena the formation of talc has been intense and general. No actual talc deposits are known, however.

Due to the random distribution of the different varieties no systematic areal description is given, especially as the writer could only spend a short time at many of the occurrences and from some of them only hand specimens were studied.

Among the varieties observed three groups of ultrabasic bodies can be distinguished, excluding pure serpentine rocks, which are of the Outokumpu type.

The distinctions of the groups are as follows: the first group is characterized by a moderate content of partly hydrated olivine and by abundant bundles of more or less parallel fibres of anthophyllite. The asbestos-quarry of Paakkilanniemi is a well-known representative of this group.

The second variety is represented by the occurrence of Tiilikainen. It is composed almost entirely of stellate groups of anthophyllite.

The third group, which is very little known so far, comprises a few occurrences of tremolite rock.

Paakkilanniemi etc.

The asbestos-bearing occurrences of Paakkilanniemi (Paakkila) are situated in the parish of Tuusniemi, about two kilometres to the west of the Ohtaansalmi ferry. The abandoned quarries and the one at present under work occur in a straight line in the enclosing gneiss. According to information received from the foreman of the quarry a new lens has been discovered on the northwestern side outside this line. The surrounding gneiss shows a weakly developed parallel structure traversed by veins of granite. The actual contact is marked by a layer of mica which is followed by chlorite. In places also tremolite has been noticed in the outer shells of the ultrabasic.

The asbestos-bearing rock has a mottled appearance, due to the intensely black patches of serpentinized olivine and the greyish white lumps and bundles of fibrous anthophyllite. In the quarry now under work some differences can be noticed between the different portions of the cross section which can be studied at the southwesterly end of the lens. In the centre the black patches are irregular in shape, filling up the spaces between the amphibole bundles, or intergrown by the amphibole fibres in poikiloblastic manner. The tiny glistening dots in the serpentine indicate the presence of nonhydrated olivine. The bundles of amphibole may have a length of several centimetres, the other dimensions having somewhat lower values. Though the bundles themselves have a random orientation, the fibres in them are often fairly strictly parallel to each other.

In the parts next to the foot-wall the amount of the serpentine patches is smaller. They are often elongated with sharp borders. The colour is dirty brown and the patches are deprived of their lustre as a result of the complete hydration of olivine. The matrix is made up of short fibres of amphibole of random orientation. Also rosette-like groups of fibres are common. Locally, green chlorite occurs in abundance. It is further met with as veins. The hanging wall is not yet exposed and thus the relations there are unknown.

Seen under the microscope the perfect fibrous structure of anthophyllite can be seen distinctly. The different parts of a single bundle are often separated by areas of talc (fig. 20.) having, however, simultaneous extinction. Besides the fibrous variety a few cleavage fragments of coarser anthophyllite have been met with. The analyses (Table VI and VII) show the composition of the anthophyllite.

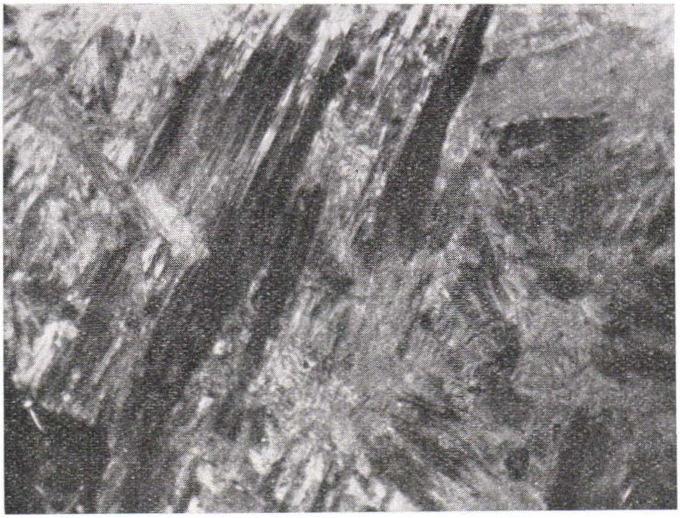


Fig. 20. Anthophyllite asbestos from Paakkilanniemi.
+ nic.

Table VI. Analysis of anthophyllite from Paakkilanniemi (hand picked) by R. Kalajoki.

	Weight per cent.	No. Mol.	No. (O,OH).	No. of metal atoms.
SiO_2	59.12	0.9804	1.9608	7.96
Al_2O_3	0.91	0.0089	0.0267	0.14
Fe_2O_3	1.01	0.0063	0.0189	0.10
FeO	6.89	0.0959	0.0959	0.78
MgO	29.67	0.7359	0.7359	5.98
CaO	0.06	0.0011	0.0011	0.00
MnO	0.23	0.0032	0.0032	0.03
$K_2O + Na_2O$	0.30	0.0048	0.0048	0.08
H_2O	1.97	0.1094	0.1094	1.78
	100.16		2.9567	

The last column in table VI contains the number of metal atoms calculated on the basis of 24 (O, OH) per anthophyllite molecule. Grouping these numbers together there are 8.1 (Si, Al)-atoms, 6.97 (Mg, Fe etc)-atoms and 1.78 (OH)-atoms corresponding closely to the formula $H_2(Mg, Fe)_8(SiO_3)_8$ (see Warren 45).

Table VII Analysis of anthophyllite from Paakkilanniemi (best technical asbestos) by R. Kalajoki.

	Weight per cent.	No. Mol.
SiO_2	59.27	0.9829
Al_2O_3	1.25	0.0121
Fe_2O_3	0.96	0.0060
FeO	6.40	0.0891
MgO	28.72	0.7123
CaO	0.18	0.0032
MnO	0.23	0.0032
K_2O+Na_2O	1.41	0.0227
H_2O	1.22	0.0677
	99.64	

The values of table VII show directly that the calculation of the different metal atoms on the same basis as in table VI should give a greater excess of (Si, Al)-atoms, a deficit of (Mg, Fe etc)-atoms and a still greater deficiency in the amount of water.

Olivine occurs as inclusions in the anthophyllite bundles or fills up the spaces between them and is traversed by the fibres in a poikiloblastic manner. It is greatly hydrated, producing the ordinary mesh-structure serpentine rich in ore powder.

Biotite is sparingly met with, mostly showing the strong birefringence of biotite, but having the colour and pleochroism of chlorite.

Chlorite often shows a polysynthetic twinning, moderate birefringence and a rather large optic axial angle. The optic sign is positive. It is believed to be clinochlore. Kaemmererite has not been noticed at Paakkilanniemi.

Talc replaces anthophyllite, occurring in fair pseudomorphs after this mineral. The formation of talc seems to have taken place without a preceding serpentinization. This can be concluded from the fact that amphiboles here, in general, are not much serpentinized and when this is the case the product is a mesh-structure serpentine. Occasionally talc forms big irregular flakes. Their origin is not known, but they greatly resemble talc flakes pseudomorphous after enstatite or bastite.

Serpentine is of the common type, with the properties described in connection with the Outokumpu serpentines. The brown dots near the foot-wall are, however, somewhat remarkable for their exceptional character. In thin section their colour is dirty yellow. Birefringence is high, refringence as usual in serpentine. Olivine as well as magnetite dust is absent. The yellow centre is bordered by a narrow zone of colourless serpentine of a flaky habit and with the properties of antigorite. The border against talc or asbestos is marked by a string of minute grains of magnetite strictly following the margin of the patch. This magnetite was probably precipitated in connection with the recrystallization of the colourless serpentine from the yellow variety.

Pyrrhotite is present in abundance. Small grains of chromite were noticed.

The composition of the rock is shown by an analysis made by the writer (Table VIII). The analysed sample was taken from the central part of the quarry and ought to correspond to the average composition of the asbestos-bearing rock.

Table VIII. Analysis of the asbestos-bearing rock from Paakkilanniemi, by the author.

	Weight per cent.	No. Mol.
SiO_2	53.96	0.8949
Al_2O_3	0.86	0.0084
Fe_2O_3	1.83	0.0115
FeO	4.59	0.0639
MgO	31.32	0.7768
CaO	0.15	0.0027
H_2O	5.14	0.2853
S	1.08	0.0337
Cr_2O_3	0.24	0.0016
NiO	0.25	0.0033
	99.42	

The occurrences of Pirkonmäki and Perhemäki at Rikkaranta in the parish of Kuusjärvi belong to the same group as the Paakkilanniemi occurrence. The content of amphibole is smaller and the formation of talc is richer. Occasionally the somewhat radiating groups of anthophyllite have been completely converted into talc. The amount of residual olivine varies. In places elongated forms of olivine can be noticed, though the outlines of the crystals are often indistinct, due to the needles of amphibole or talc penetrating into olivine. (Fig. 21.)

In one slice groups of corroded ore grains were noticed. They were translucent, of a reddish brown colour with properties of chromite similar to that described on page 42.

At Perhemäki the contact against the enclosing gneiss is exposed. The parts next to the country-rock are rich in black mica, which is followed by a zone of chlorite. A layer of talc forms the passage into the ultrabasic.

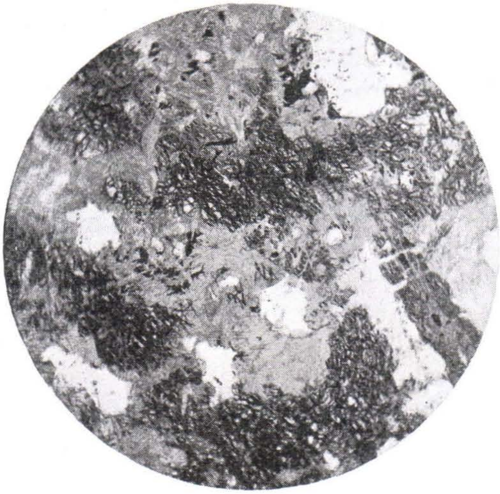


Fig. 21. Photomicrograph of an ultrabasic rock rich in olivine and talc. Pirkonmäki.

A sample from Pirkonmäki was analysed by Mr. E. Savolainen. (Table IX.) The analyst mentions that the analysed rock was composed chiefly of serpentine, talc and magnetite.

Table IX. Analysis of a serpentine rock from Pirkonmäki, Rikkaranta, by E. Savolainen.

	Weight per cent.	No. Mol.
SiO_2	51.80	0.8590
Al_2O_3	2.33	0.0228
Fe_2O_2	0.20	0.0013
FeO	4.70	0.0654
MgO	32.89	0.8157
CaO	1.11	0.0198
MnO	0.09	0.0013
$+H_2O$	5.58	0.3097
$-H_2O$	0.63	—
S	1.13	0.0352
	100.46	

About three kilometres to the north from the Luikonlahti occurrence near Lake Petronlampi in Kaavi Parish there is a small ultrabasic body exposed in a couple of prospecting pits. In one of these the contact against the enclosing gneiss is exposed. The border is marked by a layer of dark mica which is gradually replaced by a green chlorite. It is followed by a zone of talc. Another trench in the more central part of the body shows the main bulk of the rock made up of bundles of fibrous amphibole and patches of black serpentine. Olivine is still to be found. The formation of talc has been considerable. Especially towards the periphery of the body the amount of the big flakes of talc increases. The fibres of anthophyllite are too coarse and brittle for industrial purposes.

At present the occurrences of Paakkilanniemi are the only ones that produce good fibre. A new dressing mill has been built quite recently in the vicinity of the quarries. Attempts have been made to separate talc and ore minerals from the tailings. The ore minerals contain considerable amounts of nickel and chromium. Also platinum is present.

The boulders found at Rikkaranta and on both sides of the northwestern end of Lake Juojärvi indicate bodies of similar composition also elsewhere.

The occurrence of Tiilikainen.

The quarry of Tiilikainen is situated about 5 kms to the southeast from Paakkilanniemi, quite near Lake Juojärvi (Kapustalahti.)

The country-rock is not exposed. The portions of the outcrop next to the contact are composed of dark brown mica. The zone of mica passes gradually to a layer of pale chlorite. This is, in turn, succeeded by stellate groups of white fibrous anthophyllite. As far as is visible to the unaided eye the whole rock is made up of these groups. The size of the groups is rather even, up to 5 cms in diameter. A vein 40 cms in width, made up of coarse fibres of anthophyllite arranged transversally to the vein, traverses the body.

The anthophyllite of this vein was analysed by Mr. E. Savolainen (Table X). He determined also the index of refraction γ, giving a value $\gamma = 1.634$.

Table X. Analysis of anthophyllite from a vein from Tiilikainen, by E. Savolainen.

	Weight per cent.	No. Mol.
SiO_2	59.56	0.9877
Al_2O_3	0.66	0.0065
Fe_2O_3	0.76	0.0048
FeO	7.49	0.1043
MgO	28.97	0.7185
MnO	0.17	0.0024
$+H_2O$	2.38	0.1321
$-H_2O$	0.31	
	100.30	

The calculation of the metal atoms from the analysis X shows greater deviations from the formula $H_2(Mg, Fe)_7 (SiO_3)_8$ than in the case of the Paakkilanniemi anthophyllite, namely 8.25 (Si,Al)-atoms, 6.42 (Mg, Fe etc)-atoms and 2.19 (OH)-atoms. This may be due to impurities of the analysed material.

In thin sections from the main rock anthophyllite is seen to be the dominant component. The index of refraction γ, was measured by Miss A. Hietanen. The value observed, 1.635, indicates a composition similar to that of the analysed anthophyllite of the vein (Table X).

A small amount of talc, chlorite and grains of ore were noticed. In a slice from the collections of the University of Helsinki made from a specimen of a similar rock a trifling amount of residual olivine was noticed. The grains of olivine were separated by bundles of amphibole, but showed a uniform optic orientation. A commencement of hydration was shown by the magnetite powder occurring in connection with them.

The biotite of the contact zone is much altered. The first stage seems to be the losing of elasticity, followed by a discolouring, which is stronger farther from the contact, advancing from the periphery of the packs of mica towards the centre. The resultant mineral is dirty yellow in colour with a greasy lustre. The fresh-looking mica shows a distinct pleochroism from brown to colourless. The optic axial angle, measured in a sample, gave a value of approximately $2 E = 28°$, the index of refraction of the same blade of mica is $\gamma =$ 1.591.

Serpentinization is practically absent.

The bulk composition of the rock is shown by an analysis made by Mr. E. Savolainen (Table XI).

Table XI. Analysis of the anthophyllite rock from Tiilikainen, by E. Savolainen.

	Weight per cent.	No. Mol.
SiO_2	57.56	0.9546
Al_2O_3	3.34	0.0327
Fe_2O_3	3.22	0.0202
FeO	2.20	0.0306
MgO	28.01	0.6947
CaO	0.71	0.0127
MnO	0.40	0.0056
K_2O	0.10	0.0011
Na_2O	0.58	0.0094
$+H_2O$	2.88	0.1599
$-H_2O$	0.68	—
S	0.24	0.0075
	99.92	

The tremolite rocks.

This group is rather enigmatic. A few kilometres to the east from the Ohtaansalmi ferry, quite close to the high-road, there is small outcrop of a rock composed of needles of greenish tremolite of random orientation. It is possible that the outcrop presents only the outer shell of an occurrence belonging to one of the other types, as occasionally the ultrabasics are surrounded by aureoles of a similar kind, such as, for instance, at Varistaipale.

Tremolite has been met with in the outer layers also at Paakkilanniemi. Read (41) has described zoned ultrabasic bodies from Unst, Shetland Islands, in which actinolite occurs as a zone around the masses, but may, in some cases, become the dominant component of the whole body.

These rocks were not examined in detail. An analysis of the tremolite (Table XII) has been made by Mr. R. Kalajoki. Also the determinations of the indices of refraction and the specific gravity are made by him. Unfortunately, the exact place from which the analysed specimen has been taken is not known. The analysed tremolite is from somewhere near Lake Kaavinjärvi, north of the Ohtaansalmi ferry.

Table XII. Analysis of tremolite from Kaavinjärvi, by R. Kalajoki.

	Weight per cent.	No. Mol.	No. (O, OH)	No. of metal atoms
SiO_2	57.79	0.9614	1.9228	8.11
Al_2O_3	1.23	0.0120	0.0360	0.20
Fe_2O_3	0.69	0.0043	0.0129	0.07
FeO	3.87	0.0539	0.0539	0.45
MgO	22.70	0.5630	0.5630	4.75
CaO	12.30	0.2193	0.2193	1.85
MnO	0.25	0.0035	0.0035	0.03
Na_2O+K_2O	0.36	0.0058	0.0058	0.10
H_2O	0.47	0.0261	0.0261	0.44
	99.66		2.8433	

$\alpha = 1.614$, $\beta = 1.625$, $\gamma = 1.636$.

Sp. gr. = 3.02.

Supposing the formula of tremolite to be $H_2Ca_2 (Mg, Fe)_5 (SiO_3)_8$ and grouping the metal atoms as made by Warren (44) the following numbers are obtained per molecule, when calculated upon the basis of 24 (O, OH): 8.31 (Si, Al); 1.95 (Ca, Na); 5.30 (Mg, Fe etc) and 0.44 (OH). With the exception of the group (Ca, Na) the deviations are great.

III. THE ORIGIN OF THE ULTRABASICS.

The investigation described above decidedly show that before serpentinization these rocks were made up of olivine with a local content of pyroxene (enstatite) and chromite. In the western and middle parts the content of amphibole is general and their serpentinization witnesses that they, too, belong to the earlier components.

The origin of these minerals seems obvious enough, at any rate as far as the dunitic and saxonitic types of the Outokumpu complex are concerned. Olivine, enstatite and chromite are the oldest minerals everywhere. No evidences of any pre-existing minerals or textures can be found. The primary nature of these minerals is further supported by the granular texture of the pure olivine rocks — visible also as pseudomorphs in the pure serpentines — characteristic of the dunites and by the poikilitical fabric of the enstatite-bearing variety.

As to the porphyritic type, the observations lead to more contradictory conclusions and a final answer is far more difficult to reach. If one accepts the olivine and enstatite of the aforementioned types as primary, any more complicated history can hardly be supposed for the porphyritic variety within the masses. Their mode of occurrence is similar and no observations are available which would suggest any older host rock than the porphyritic one. Thus the question is restricted to the origin of the olivine of the contact zones.

Väyrynen (52) has expressed the opinion that olivine of these occurrences, in general, is secondary, supporting this view by the mutual relations of amphibole and olivine. The exceptional mode of occurrence of the olivine-bearing rocks which form shells around the serpentine bodies, might be explained by assuming them to be of different origin. Some other features favour the idea of the secondary origin of this olivine. Namely, if it is accepted that the dolomites are replacement products of the ultrabasic rocks (see p. 74) it may be supposed that the outer layers of the original bodies have been completely, or, at any rate, to a great extent serpentinized before they were replaced by carbonate, as the microscopical examination shows that olivine is rarely, serpentine most easily carbonitized. In fact, a thin band of pale serpentine has occasionally been found separating the olivine-bearing zone from the actual contact against the quartzite. Has this been the case, it is strange how the primary olivine crystals of the present contact between dolomite and serpentine have preserved a comparatively good shape and state, while the material between them — which cannot have been so widely different in chemical or mineralogical composition — has suffered such thorough changes.

It is to be noticed, however, that many difficulties arise in assuming a part of the olivine to be of a different origin. In places the serpentine layers contiguous to the contact are completely made up of pale serpentine not distinguishable from the general type, but its original texture, still visible due to the slight differences in colour, shows all the distinctions of the contact zone of the olivine-bearing parts. Further, it is to be taken into consideration that in many places within the masses the ancient texture bears a striking resemblance to that of the nonhydrated borders. In additions to these neither mineral relics nor structural features have been found which would with certainty indicate any constituent older than the olivine.

The result is that it is not possible to draw any border between the supposed secondary olivine and the primary one. In the present state of knowledge no final conclusion can be drawn. However, the weight of evidence so far seems to favour the idea of the primary origin of the olivine.

Elsewhere within the area the observations are less numerous, but all of them support a similar explanation of the original composition. In the eastern zone olivine seems to have been the sole component in the premetamorphic rock. In the belts of Mihkali and Niinivaara-Säyneinen residual olivine has been sparsely found, representing the only primary mineral in these occurrences. From Outokumpu, towards the south and southwest a slight change in composition can be noticed. Enstatite, also met with at Outokumpu, has been found in some occurrences, and in exceptional cases it is the major constituent of the rock. In the gneiss territory pure olivine rocks have given rise to serpentines. In the asbestos-bearing rocks enstatite may locally have formed a considerable portion of the premetamorphic minerals.

Even amphiboles have undergone serpentinization. In such cases the amphiboles apparently have previously occurred together with olivine. The relations of amphiboles and olivine are often difficult to decipher, both of them being usually hydrated, but the frequent occurrence of amphiboles in the peripheric parts of the masses indicates a secondary origin. This is further supported by observations in the Tiilikainen type, where residual olivine occurs in practically pure anthophyllite rock, and by the conversion of enstatite into anthophyllite noticed in the slices from the ultrabasics of Maljasalmi.

Summing up these results, it can be stated shortly that the vast majority of the ultrabasics of the investigated area have originally been dunites. Only in the southwestern corner are there some occurrences of saxonitic and even pyroxenitic character.

Their general mode of occurrence as lenses and lenticular masses in conformity with the enclosing rock indicates intrusion during orogenic movements. In Benson's (7) classification of basic igneous rocks the ultrabasics of these distinctions form the fourth group, the members of which may belong either to Cordilleran or Alpine types (see p. 10).

IV. THE METAMORPHIC HISTORY.

From the observations made it can be determined that amphiboles, both anthophyllite and tremolite, have undergone serpentinization. Especially in the occurrences of the western parts of the schist complex, as for instance at Outokumpu and Mäntyjärvi, the intensity of hydration of these minerals is quite comparable to that of olivine and enstatite. In the gneiss territory they have been preserved but serpentinization, in general, is much less pronounced there. Carbonatization has occurred at the expense of serpentine and amphiboles. As to the formation of talc it is apparent that serpentinization is earlier; talc replaces both chrysotile and bastite. The mutual relations of talc and carbonates are uncertain. As a rule, they occur together, as for instance in the bodies of the eastern zone, or separately but in corresponding positions, as in the Outokumpu serpentines.

The succession of events is the following: amphibolization as a first step during the metamorphism, followed by serpentinization, carbonatization and formation of talc. This is the order of a single cycle under continuously changing conditions in one direction. In reality the transformations have been more complicated. In the following description these changes will be dealt with more closely.

AMPHIBOLIZATION.

The content of amphiboles is common in the western zone, being an essential feature of the ultrabasic bodies of the gneiss territory. The amphiboles in the Outokumpu bodies which may be taken as an example from the schist complex occur in two different ways. In the serpentine masses adjacent to the ore amphibole has been evenly distributed throughout, the rock, being now represented only by the perfect pseudomorphs after amphibole. The other type occurs in the peripheric parts near the contacts. It is also serpentinized, though only partly and in a different way, forming mesh-structure serpentine. In some cases it is younger than serpentine, synchronizing, then, most likely with the amphiboles of the skarn rocks. This younger generation of amphibole is separated from the other by the great gap of time during which serpentinization and carbonatization have occurred.

The origin of the amphiboles within the masses is uncertain. As to the amphiboles of the outer layers, their position indicates transport of material, namely, silica and lime from outside sources. It is possible that a part of the tremolite is derived from diopside, but its amount cannot be great, as only in one slice from Luikonlahti has diopside been noticed with certainty in an olivine-bearing rock.

The areal distribution of the ultrabasics rich in amphiboles in those parts which are abundantly traversed by the younger granite makes it probable that these two phenomena, i. e. amphibolization and intrusion of granites, are related. In many cases the original composition seems to have been dunitic, and solutions carrying silica and originating from granites must have penetrated from the outside to produce anthophyllite. The few grains of olivine in the Tiilikainen type appear, in fact, to be relics of an intense amphibolization. Anderson (1) has arrived at the conclusion that in the Kamiah anthophyllite deposits in Idaho anthophyllite has formed at the expense of olivine. From his description the rock is similar to that at Tiilikainen. Phillips (40) has supposed that certain anthophyllite schists on the Shetland Islands have derived from peridotites by transport of silica from outside sources. Harker (31) does not, however, agree with him but believes that the original rock has been of a pyroxenitic character. According to Du Rietz (16) silica produced by pegmatites has caused the formation of actinolite or tremolite in certain peridotites of Northern Sweden.

In some occurrences a content of enstatite has been noticed. Locally, as at Maljasalmi, the composition is pyroxenitic. It can be assumed that in certain cases this rock has given rise to bodies rich in anthophyllite; in fact, the conversion of enstatite into anthophyllite has actually been observed in the slices from Maljasalmi. In the Paakkila type the arrangement of the anthophyllite bundles, their relations to olivine, and their form and structure strongly suggest that anthophyllite, to a great extent, has been derived from enstatite.

Within the gneiss territory the different generations of amphibole, if existing, are not distinguishable, probably due to the fact that serpentinization and carbonatization which have occurred in the meantime are of minor importance. The layers of tremolite and the tremolite rocks belong perhaps to a later phase, being contemporaneous with the skarn rocks of the eastern occurrences, and as to their origin maybe even being replacement products of carbonate, though any actual carbonate rock within this area is not known.

In recent literature the formation of amphiboles in the serpentines has often been stated to have occurred during serpentinization or subsequent to it. According to Martiny and Angel (3) the tremolite in certain serpentines of Gleinalpe is formed by reaction with limestones during serpentinization, and regarding the serpentines of Ganoz the latter writes: »— die schönen Stubachitserpentine zweiter Tiefenzone erleiden ebenfalls eine zweite, diaphtoritische Kristallisation unter Neubildung von Feinantigorit, Pennin und Tremolit». Du Rietz (16) states that chrysotile is younger than tremolite only in a few cases. On the other hand, Väyrynen (51) has pointed out that in the serpentines of Kainuu also tremolite has undergone serpentinization.

According to Zavaritsky (53) tremolite in the Rai-Iz peridotite massif in the arctic Ural is formed during a later metamorphic process, but — as he writes — »it is doubtless that the formation of tremolite and probably of chlorite proceded serpentinization of the rock. These minerals are met with in peridotites which are either utterly exempt of, or nearly untouched by serpentinization. In partially serpentinized rocks tremolite is replaced by serpentine to a similar grade as olivine».

SERPENTINIZATION.

The process of serpentinization, assuming the original material to be forsterite — an assumption which closely corresponds to the facts — is, when set out chemically, as follows:

1. $3\ Mg_2SiO_4 + 4\ H_2O + SiO_2 \rightarrow 2\ H_4Mg_3Si_2O_9$
   forsterite — serpentine

Serpentine may partly originate from metasilicate according to the equation:

2. $3\ MgSiO_3 + 2\ H_2O \rightarrow H_4Mg_3Si_2O_9 + SiO_2$

The amount of metasilicates in the present case can be neglected. It is obvious, then, that two components are essential to the process, namely, water and silica. The latter may in part be replaced by carbon dioxide with a simultaneous formation of carbonate.

Frosterus believed serpentinization of the investigated rocks to be due to superficial solutions which under the conditions of weathering acted upon the anhydrous rocks. The effects of superficial agencies in the Mooihoek Mine, Bushveld Igneous Complex have been described by Hall (30): »— the weathered silicified opal-bearing serpentine passes downwards into normal serpentine, serpentinized dunite, partially altered dunite and finally into fresh olivine dunite, the last change occurring at ground water level».

It is to be expected that alterations due to weathering should, here also, be of similar distribution. The spatial distribution of serpentinization shows, however, that the degree of hydration is quite indepedent of the present surface, nor does it show any difference between the foot-wall and hanging wall of the bodies. The more serpentinized parts in the foot-wall of the asbestos-bearing body of Paakkila and similar local phenomena at Outokumpu represent only a trifling amount of the serpentinized mass. They have apparently nothing to do with the main act of serpentinization.

The conception of atmospheric weathering as a cause of serpentinization cannot, therefore, be accepted.

As pointed out in the historical part, several workers are of the opinion that serpentinizing solutions in certain cases originate from granites (Dresser, Graham etc.). With regard to the Canadian asbestos-bearing serpentine near Quebeck Graham (28 p. 178) writes: »The acidic, i. e., highly siliceous, magmatic 'extract' not required for the formation of granite and which contained all the water and other volatile constituents of the original magma may well be supposed to have found its way along the joints and crevices in the surrounding peridotite and to have exerted a very intense action on the rock from which it differed so widely in chemical composition». Dresser (15), in discussing the origin of the chrysotile veins of the same occurrences, points out that the veins are surrounded by zones of completely serpentinized peridotite roughly proportional to the thickness of the veins. According to him the serpentinizing solutions penetrated into peridotite along the fissures, the positions of which are now marked by the chrysotile veins. Similar veins, though only a few mms in thickness, occur locally in the pale serpentine at Outokumpu. In a slice a number of them were met with in a rock which still contains grains of olivine. The distribution of olivine is quite independent of the vicinity of the veins. Olivine was found to be as abundant in the isles formed by the branching veins as farther away from them. Keep (see Read 42) lays stress upon the action of the pegmatitic phase of the granite intrusions as a factor in the serpentinization process which has taken place with some serpentines of Belingwe District, Southern Rhodesia. Also Du Rietz shares the opinion that hydrothermal solutions from granites have caused hydration.

It is, therefore, of interest to try to follow the relations of the younger granite to serpentinization within the area studied by the results obtained during this work. Assuming the action of the granite to be favourable for the process, an increasing stage of hydration ought to be expected in those parts where the granite intrusions are more numerous.

In the schist complex, among phyllites and mica-schist, where the intrusions of granite are absent, serpentinization is practically complete. Near the western border of the complex olivine is common in the occurrences of Outokumpu, Kuusjärvi and Maljasalmi. The outcrops of granite in the neighbourhood are rather rare. Farther north in the Niinivaara-Säyneinen belt occurrences of granite are numerous, especially in the middle parts. Serpentinization of the ultrabasics there is complete. Within the gneiss territory the number of granitic intrusions increases. The ultrabasics connected with them have frequently a content of olivine, though its amount is not great.

Evidently the areal distribution of the intensity of serpentinization is in no way related to the proximity or the abundance of granite.

The effect of the traversing granitic veins upon the ultrabasics can be directly studied in some places in the Outokumpu mine. The phenomena at the contacts are as follows. The actual contact is made up of brown mica on the side of granite and of green chlorite on the side of ultrabasic. The zone next to it is composed of white talc with rare prisms of nearly colourless tremolite. The parts adjacent to talc are of a greyish white colour and contain fine-grained talc and carbonate. A few flakes of kaemmererite were also noticed. The rock passes gradually into black serpentine in which elongated pseudomorphs after olivine can be discerned. Outlines of these pseudomorphs are distinctly visible also in the greyish talc-carbonate zone. In the actual serpentine, outside the discoloured zone, no variations can be traced with regard to the proximity of the granite.

The action of the granite upon the enclosing ultrabasic seems thus to be restricted to the formation of the layers of mica, chlorite, talc and carbonate. The relations are of such a kind that one cannot avoid the impression that the ultrabasic rock was in its present state already during the time of the intrusion of the granite.

The result of these observations is that no connection can be supposed to exist between serpentinization and the effects of granite. This fact was pointed out also by Väyrynen (51) as regards the serpentines of Kainuu. Benson (6) has arrived at the same conclusion in his study of the great serpentine belt of New South Wales.

Serpentinization is, thus, closely connected with the ultrabasic bodies themselves. Not only the lack of evidence about the action of agencies from outside sources indicates the autometamorphic character of the process. It is further supported by the distribution of the hydrated and nonhydrated parts within the masses. In most cases a detailed picture cannot be given, but the observations show that hydration has attacked the bodies fairly evenly. With regard to the Outokumpu serpentines the spatial distribution of the olivine-bearing portions is well-known and shows quite remarkable features. As a rule, the zone next to the contact is made up of black serpentine with grains of olivine, the amount of which gradually increases towards the periphery. The thickness of the black zone varies greatly, while the layers containing olivine seldom exceed a few metres, the inside part of the (black) zone being completely hydrated. The transition to the pale-coloured serpentine is rapid, though gradual. On the side of the contact the passage into the enclosing rock is also gradual, due to the rapidly increasing amount of talc and carbonate penetrating into the serpentinized parts of the olivine crystals.

This remarkable feature, that the degree of serpentinization increases towards the centre of the body is hardly explicable unless by the assumption that the serpentinizing solutions were derived from the masses themselves. Supposing the olivine to be secondary, the water required for the subsequent serpentinization may have originated from the serpentines, as analyses (up to 15 per cent of water) show that there is an excess of water in the serpentine bodies over the theoretical value indicated by the formula $H_4Mg_3Si_2O_9$. In many cases, however, the amount of the zonal layers when compared with the whole mass is very great. It does not seem probable that the earlier serpentinized parts could have stored all the water needed.

In the southwestern end of the Outokumpu complex the layers containing olivine are more numerous within the masses alternating with the paler completely serpentinized parts. Here, too, the zones containing anhydrous silicates are quite small, when compared with the thickness of the whole black layer.

The line of thought accepted here as an explanation for serpentinization has been discussed earlier in the historical part. Further reference may be made to the papers of Hess (32) concerning serpentinization in general. According to him the process of serpentinization forms a direct continuation of the crystallization of olivine and pyroxene. The residual liquid, termed hypohydrous, contains more silica and less water than the hydrothermal solutions. Serpentine is formed either by reactions with the olivine or directly from the residual liquid. As to the origin of the water, Hess considers it likely that it has been absorbed by the magma from the rocks with which it came in contact during its intrusion.

CARBONATIZATION.

Making exception of the gneiss territory, it can be stated that evidences are everywhere available indicating a more or less intense replacement of the ultrabasics by carbonates. With regard to the bodies of the eastern zone this phenomenon has been dealt with in the work of Frosterus discussed earlier, and the eastern occurrences are, therefore, only briefly mentioned here.

The carbonate of the eastern occurrences is magnesite. The microscopical features are not easy to decipher. Due to the lack of any special characteristics in the host rock, the replacement origin of carbonate is difficult to determine, especially when the subsequent recrystallization of serpentine resulting in the formation of antigorite seems in part to have occurred at the expense of magnesite, thus complicating the mutual relations in the mineral sequence. The mode of occurrence of talc-magnesite-rocks around the serpentine bodies with transition forms to the latter, however, strongly suggests that these rocks are to be considered as replacement products of the ultrabasics.

The presence of dolomite in the ultrabasic bodies of the western zone is quite common. Mention may be made of the occurrences of carbonate rocks or carbonate-bearing serpentines at Aittojärvi, Poskijärvi, Mäntyjärvi, Luikonlahti and Outokumpu. The microscopical examination and the observations in the field witness that the mode of occurrence of carbonate in connection with the serpentine bodies is so similar everywhere that the general application of the results obtained by investigations in one place seems to be justified.

The origin of the Outokumpu dolomites has lately been discussed by Eskola (18). The questions requiring answers as well as the results obtained by the earlier investigations be set forth by citing him: »— the serpentine is largely dolomite-bearing in such manner that the carbonate would appear to replace silicates. In many areas of the same Karelian zone there occur talc-carbonate rocks, or soapstone, in connection with serpentine rock. In the case of soapstone an assumption of a partial replacement of the silicate minerals by the carbonate is hardly dispensable. Could not, then, the process in places have gone a step farther, so as to give rise to a pure dolomite. — An alternative explanation, however, is the one following the ordinary lines of reasoning i. e. taking the dolomite to be an ordinary sedimentary rock and the skarn to be an ordinary skarn. Were this the case, then the partial carbonatization of the serpentine, and the origin of talc-carbonate rocks would be simply due to a transfer of the carbonate from the adjacent layers to the body of serpentine. In the present state of knowledge this explanation would seem the more probable one. But I am not taking any stand as to this question, which remains for future investigators to solve. I only wish to emphasize that this is one of the cardinal points not only in the geology of the Outokumpu region but also in the great general problems of serpentine rocks associated with carbonate rocks in many ancient mountain chains».

In order to decide if the evidence at present is sufficient for the solution of the question, the new and old data supporting the metasomatic origin of the dolomite may here be summed up:

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

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

3. The microscopical examination of serpentines shows that a carbonatization of the silicate minerals has occurred, the alteration,

consequently having occurred in the direction ultrabasic rock → carbonate rock.

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

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

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

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

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

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

The writer is of the opinion that all these evidences lead to the conclusion that the carbonate rocks have formed as a result of a strong carbon dioxide metasomatism. The solutions causing carbonatization probably absorbed the material required, viz. lime and carbon dioxide, from the rocks with which they came in contact. The time of carbonatization is, however, not known with sufficient accuracy to be of any use in tracing the sources of the solutions.

Carbonatization is a common phenomenon in serpentines and it is mentioned in nearly all of the works dealing with the ultrabasics. The process is, in general, regarded as a hydrothermal one, taking place subsequent to serpentinization. Thus Graeber and Honess (27) describe a strong carbonatization in a peridotite dyke at Dicksonville occurring immediately after serpentinization and, according to these authors, caused by hydrothermal solutions. Creveling (12) mentions that in the peridotites of Presque Isle dolomite replaces olivine and pyroxene. According to Wilcockson and Tyler (48) the carbonation process in certain serpentines in Anglo-Egyptian Sudan was caused by hydrothermal solutions derived from granites. The carbonate material penetrated into the cracks of olivine, replacing antigorite. In the Kalgoorlie District in Australia talc-magnesite-rock has been formed at the expense of ultrabasics (Thomson 43).

It may be pointed out here that the conception of the metasomatic origin of the dolomites does not alter the picture as far as the real character of the skarn rocks is concerned. This explanation leads to the one that the formation of the skarn minerals belongs to a late period of metamorphic history, a fact which is in harmony with the circumstance that these minerals have not been affected by the changes which have attacked the minerals of the earlier phases.

Väyrynen (52) has connected skarn rocks with the influence of the contact action of the Maarianvaara granite, supporting this view by the distribution of the diopside occurrences. The results obtained now do not give with any certainty additional evidences to this effect.

THE FORMATION OF TALC.

The development of talc is not restricted to any particular area, but it is a common phenomenon almost in every occurrence studied. Some slight differences can be noticed between the different parts of the region.

In the serpentines of the eastern zone talc occurs, as a rule, in the peripheric parts together with magnesite, as for instance at Solansaari and Haaralanniemi. In the bodies of Sola and Solansaari the central portions are quite free from it, whereas at Louhiinsalo and Revonkangas talc is found as extremely coarse flakes, forming nests and veins in pure antigorite. In the Mihkali belt the parts rich in small scaly talc are unrelated to the borders of the masses, with the exception of the occurrence of Soinsärkkä. The arrangement of the different layers (see p. 27) around the serpentine body at Soinsärkkä is strictly the same as met with at Outokumpu and in several places within the gneiss territory. The zone of talc follows the layer of chlorite and grades over into the serpentinous core. Towards the core the talc becomes coarser. At Outokumpu the thickness of the talc layers varies, but is, as a rule, less than one metre. No regularity as to preference of the foot-wall or hanging wall is noticeable. In many bodies the flakes of talc can be met with in abundance, evenly disseminated through the rock both in the black and pale coloured varieties, but, in general, in those types where olivine is absent. The bastite-bearing serpentines regularly contain talc.

In the above cases talc has chiefly formed at the expense of serpentine. In the Kuusjärvi complex, as well as in the occurrences of Onkisalmi and in the bodies of the gneiss territory, the conversion of anhydrous silicates into talc is pronounced. Fairly developed pseudomorphs after enstatite and anthophyllite are common. So far as observed, the amount of talc formed directly from olivine is quite subordinate.

In the westernmost bodies the formation of talc is comparatively strong. A zone of coarse talc surrounds the masses, as for instance at Luikonlahti and Petronlampi, and also within the bodies the content of talc is considerable (Paakkila).

It is believed that the development of talc was caused by hydrothermal solutions originating from the granite. This hypothesis is chiefly based upon the slight increase of the amount of talc towards the west. The difference is not very great but quite noticeable.

Frosterus has emphasized that stress was an essential factor in the formation of talc in the westerly occurrences. The present author does not agree with him. The random orientation of coarse flakes of talc proves that stress was not necessary for the process. This is in agreement with the results obtained by Gillson (25) regarding the talc deposits of Vermont and by Burfoot (10) with regard to the occurrences of talc in Virginia. Hess (32), in his study of the talc deposits at Schuyler, Virginia, points out that the controlling factor during the changes from anhydrous ultrabasic body to talc rock was temperature. According to him with falling temperature the following facies will successively be formed from the ultrabasic rock: actinolite amphibolite facies, chlorite greenstone facies and steatite facies. The term facies is used in the sense defined by Eskola (19). This corresponds in the present case to the order: amphibolization, serpentinization and formation of talc. In his paper dealing with the basic rocks in Karelian formations, Eskola (20) holds it probable that talc-carbonate-rocks have been formed under the conditions of the albite-epidote-chlorite facies.

V. SUMMARY.

In the middle and westerly parts of the ancient Karelian mountain zone in eastern Finland a number of ultrabasic bodies occur. Characteristic of all of them is their mode of occurrence as discontinuous belts following the structural lines of the enclosing schists and gneisses. The easternmore belts, occurring in gently folded phyllites and micaschists, are often of considerable length and regularity, while the westerly occurrences, which are surrounded by disturbed schists and gneisses, are of more random distribution. The masses themselves are, as a rule, lenticular in shape, strictly following the structure of

the country-rock. The size of the bodies varies considerably. Within the area of mica-schists and phyllites the masses are several hundreds of metres in length, while in the westerly gneisses the dimensions are much smaller. With the exception of the easternmost occurrence the ultrabasics do not associate with differentiates of more acid character. In the westerly parts there occur numerous outcrops of younger granite intrusions which traverse also the ultrabasics.

The majority of the ultrabasic rocks belong to the serpentines. The bodies of the eastern occurrences are made up almost completely of antigorite. Olivine is met with in small amounts. In addition to these minerals the rock contains chrysotile, magnesite, talc and magnetite. The order in the mineral sequence is believed to be: olivine → chrysotile (magnetite) → magnesite (talc) → antigorite. Talc and magnesite occur in abundance in the peripheric layers of the bodies forming soapstones with transition forms to the serpentinous core.

The westerly zone shows more heterogeniety. Within the schist complex the bodies are practically pure serpentine rocks differing from the easterly occurrences by the fact that they are solely composed of mesh-structure serpentine. Olivine is rather rare. Enstatite and chromite have been met with in the bodies of the southwesterly part of the area. Anthophyllite, tremolite, chlorite, bastite, dolomite, talc, magnesite and sulphides occur as secondary minerals. In close connection with the serpentine rocks there are dolomites, together with skarn rocks containing chrome diopside and chrome tremolite.

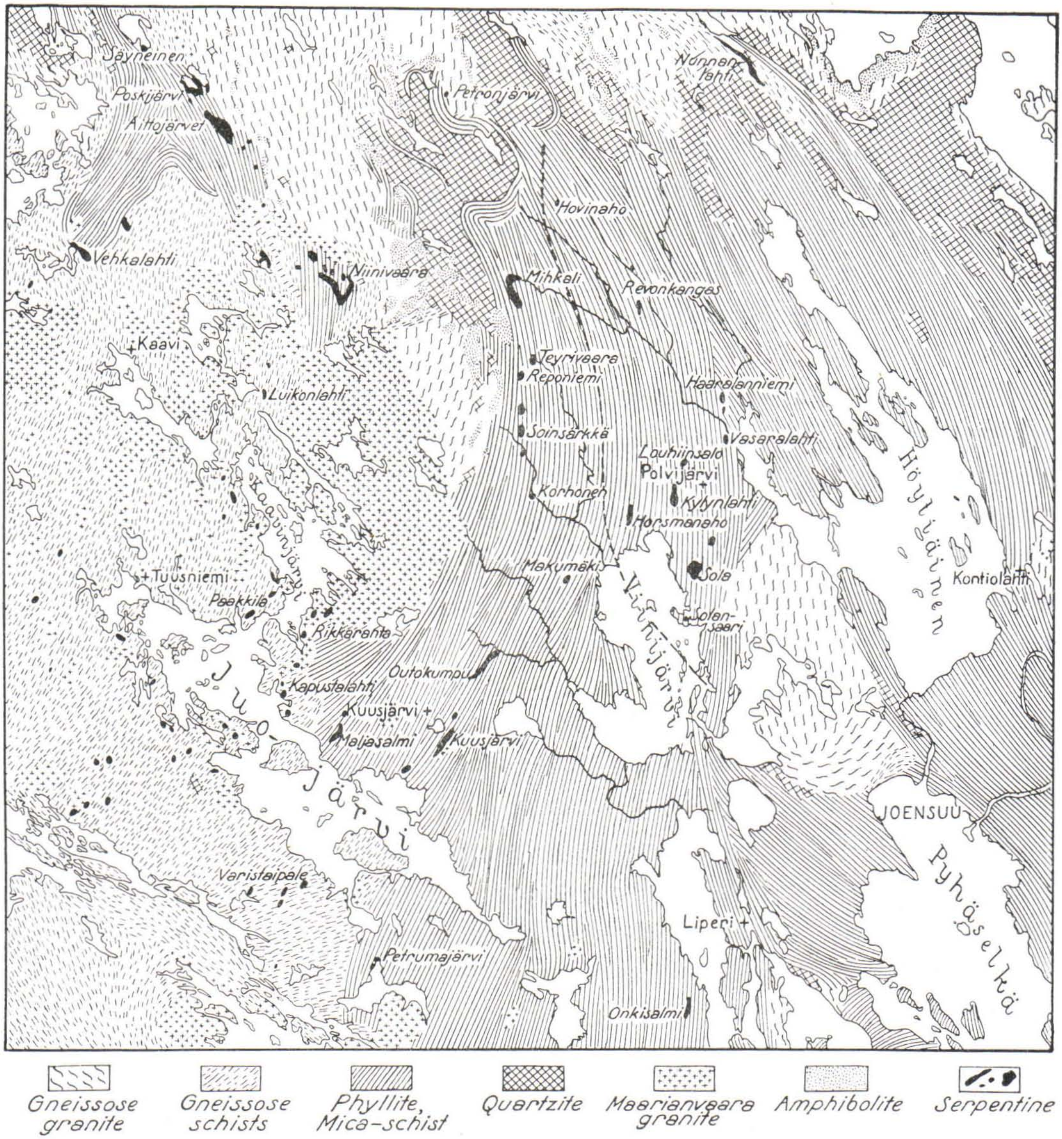
In the ultrabasic bodies of the westerly gneisses the content of amphibole is an essential feature In places the fibrous anthophyllite has gained commercial importance Olivine is more common than within the other parts of the investigated area, but it is, also here, greatly serpentinized.

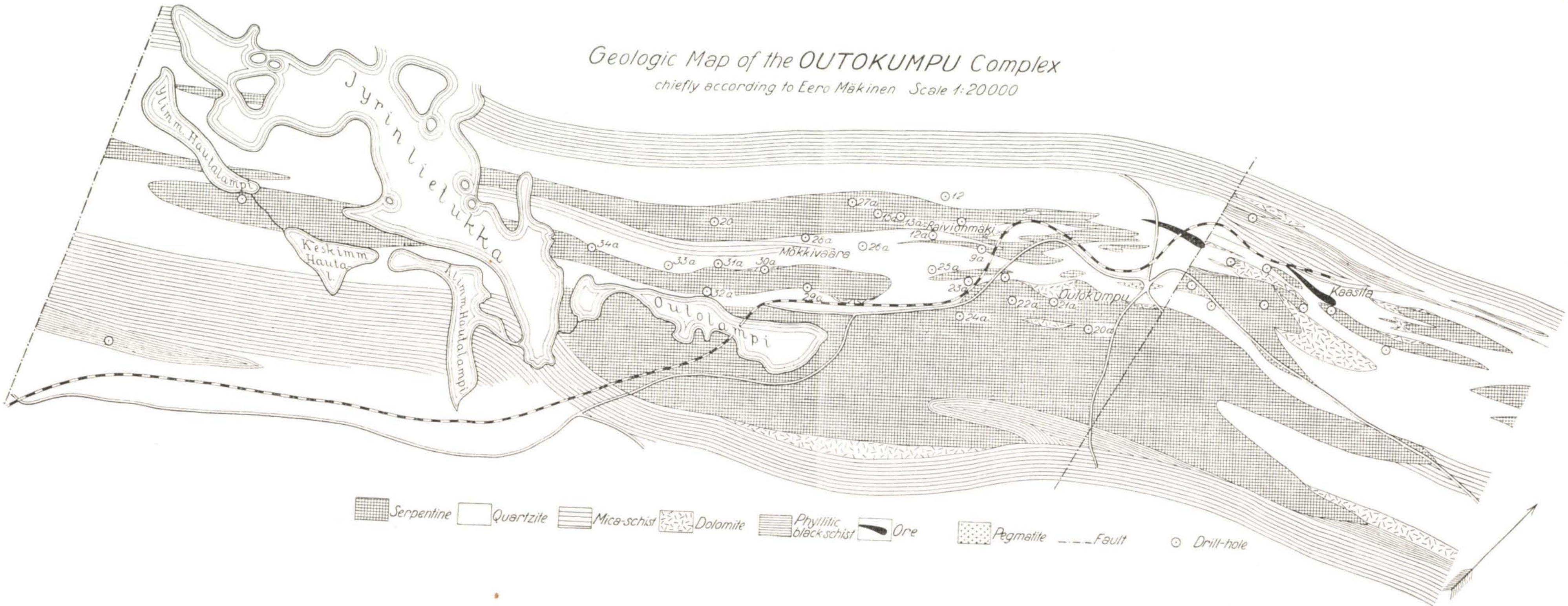
The investigations show that the original composition of the ultrabasics has been dunitic, only in a few cases has the original rock been enstatite-bearing peridotite.

The original rock has undergone several successive changes, viz., amphibolization, serpentinization, carbonatization and the development of talc in the order mentioned. Serpentinization is believed to be an autometamorphic change. The development of amphibole is supposed to be due partly to the conversion of pyroxene and partly to the accession of silica from outside sources. Carbonatization and the formation of talc were caused by hydrothermal solutions. The former process has resulted in the formation of actual dolomites.

Subsequent to carbonatization a new silicification occurred during which the skarn rocks were formed. Also in the ultrabasics themselves amphiboles of the second generation were developed. It is not known if this second amphibolization was followed by the subsequent changes of the cycle. That this were the case is indicated by the recrystallization of chrysotile to antigorite in the eastern occurrences.

Geologic Map of Northern Karelia
according to B. Frosterus and W.W. Wilkman. Scale 1:600000




Geologic Map of the OUTOKUMPU Complex
chiefly according to Eero Mäkinen Scale 1:20000
Jyrinlietukka
Ylimm. Hautalampi
Keskimm. Hauta l.
Alimm. Hautalampi
Outolampi
Mökkivaara
Raivionmäki
Outokumpu
Kaasila
Serpentine
Quartzite
Mica-schist
Dolomite
Phyllitic black schist
Ore
Pegmatite
Fault
Drill-hole

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