GEOLOGINEN TUTKIMUSLAITOS

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N:o 192

ON THE BLACK SCHISTS IN THE OUTOKUMPU REGION IN EASTERN FINLAND

BY

ESKO PELTOLA

With 43 figures and 11 tables in text, 8 plates and 2 maps

HELSINKI 1960

Helsinki 1960. Valtioneuvoston kirjapaino

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ERRATA

p. 38 l. 2 from bottom *for* quartzrich *read* quartz-rich
p. 40 l. 1 from bottom *for* prominent *read* considerable
p. 67 l. 20 *for* unmixing *read* replacement
p. 93 l. 5 from bottom *after* some heavy metal *add* (Goldschmidt, 1954, p. 496)
p. 97 l. 9 *for* central *read* Central
p. 98 l. 15 *for* Southern *read* southern
p. 100 l. 8 *after* lack sulphides, and *add* sporadic
p. 101 l. 13 *after* with amphibole *add* replacing the mica

ABSTRACT

The aim of this study is to elucidate the mode of occurrence, petrography, mineralogy and chemical composition of the black schists in the Outokumpu region of eastern Finland. Among the schists of a sedimentogenic structure and corresponding most nearly to sapropelic sediments in chemical composition — particularly in their content of trace elements —, there can be distinguished originally argillaceous, calcareous and arenaceous varieties. In structure the various black schists of the region are represented by all the different types, ranging from fine-grained phyllitic schists to gneissose schists, which are common in the most highly metamorphozed western part of the region. The regular joint presence of carbon and sulphides is characteristic of black schists, and it is the carbon content of over one per cent (together with the iron sulphides) that causes the black colour of the schist. The occurrence of black schists as interbeds in the phyllites, mica schists, mica gneisses and, in many places, also quartzites of the region as well as their gradual marginal transitions to other rock types indicate that the black schists were originally deposited in the environment where they are now situated. Their occurrence as continuous zones in the middle of the phyllite and mica schist area reflects an exceptional change in the conditions of sedimentation, and the composition of the different black schist varieties depends on the factors connected with the original sedimentation.

PREFACE

This study is based principally on field work done during the years 1955—1958 both on the surface and in the Outokumpu mine, as well as on the laboratory examination of the material collected. In addition to the work of this period, numerous revisions were made during the years 1958—1959, when the final compilation was made.

The impetus for this work was provided by my teacher, Professor Martti Saksela, to whom the project has been of great interest. It gives me great pleasure to acknowledge this, as well as to offer sincere thanks for his valuable advice during the course of the work and for his constructive criticism of the manuscript.

To my chief, Professor Paavo Haapala, I am extremely grateful for the interest he has shown in my work and for his invaluable support at every stage. At the same time I wish to extend my grateful acknowledgment to the Outokumpu Company for the financial assistance that, among many other things, made possible the translation of these pages into English.

Sincere thanks are also due to Dr. Vladi Marmo, Director of the Geological Survey of Finland, for his kindness in arranging the publication of this work as a Bulletin of the Geological Survey.

It also gives me pleasure to be able to express my appreciation to Professor Veikko Okko, Professor Juhani Seitsaari and Dr. Ahti Simonen for their valuable advice given me during the course of many thought-provoking discussions.

In addition to acknowledging the assistance of all my colleagues on the staff of the Outokumpu Company I am bound to mention especially that of Dr. Veikko Vähätalo in making available the laboratory facilities of the Exploration Department of the Company and in giving me permission to use the maps, drill cores and analyses of the Department. Special thanks should be addressed to Dr. O. Kouvo, in charge for the research laboratory of the Exploration Department. Throughout, Mr. Juhani Koskinen and Mr. Pentti Rouhunkoski were always ready to help in every possible way. Mr. Jorma Kinnunen and Mr. Lasse Kosomaa, heads of the Company's laboratories at Pori and Outokumpu, kindly provided all the analyses belonging to this study.

Mr. Erkki Halme took the majority of the photographs included in the study and Mr. Eero Muttonen drew the illustrations and maps.

Mr. Paul Sjöblom translated the original Finnish manuscript into English. Dr. Bernard Evans and Miss Sheila Nolan have been of great help in checking the geological terms. To them as to Mrs. Marjatta Okko, I wish to express appreciation for many fruitful discussions and much good advice before the publishing of this work.

Outokumpu, March 1960.

Esko Peltola

CONTENTS

INTRODUCTION

During the past half century and more, numerous studies have been published on the geology of the Outokumpu ore zone and its surrounding schist area in the Karelian schist belt.

Before the ore deposit was discovered, the descriptions of the Outokumpu region were of a general character and formed part of the systematic geological mapping project started in North Karelia (in eastern Finland) at the end of last century. It was in connection with these mapping operations that Frosterus in 1902 and Frosterus and Wilkmann in 1916 published their descriptive texts for the Joensuu map sheet, which also covers the Outokumpu region.

In those days the degree of metamorphism was generally regarded as a measure of geological age. Accordingly, the highly metamorphozed coarse-grained schists, like the mica schists of the Outokumpu region, were held to be older, so-called Ladogan formations, and the phyllites of the Höytiäinen region to be younger, Kalevian formations. On the other hand, fine-grained schists containing carbon and sulphides were marked down on geological maps in many places as Kalevian formations although the coarse-grained mica schists alternating with them had been considered Ladogan. As Eskola (1927) and Väyrynen (1928) subsequently demonstrated, fine-grained carbonaceous matter makes black schists more resistant to recrystallization and, at the same time, to metamorphism. Thus, in graphite-bearing and graphite-free schists there is a marked correlation between the graphite content and the degree of metamorphism.

The Jatulian, Kalevian and Ladogan formations have thereafter been grouped together in the Karelidic cycle *(cf.* Eskola 1927, 1941). Moreover, the order of age, Jatulium-Kalevium-Ladogium, has been reversed.

Wegmann's (1928) tectonic studies on the structure of the Karelidic mountain chain have brought out the fact that the formations mentioned do not, apparently, represent deposits of different ages but various lithological facies.

Väyrynen's (1928, 1933, 1939) reports from the Kainuu region and the surroundings of Outokumpu have elucidated the stratigraphy and tectonics of the Karelian formations; these studies support Wegmann's conception, just referred to. The Kalevian phyllites, which in many cases occur unconformably on top of either Jatulian quartzites and basal conglomerates or, even more commonly, a gneiss-granite basement, are regarded by Väyrynen as younger than the Jatulian formations. Parts of the Ladogan schists have been included in the Kalevium. In the Kainuu region, Väyrynen divides the Kalevian formations into two series, of which the lower, the so-called Jaurakka facies, consists of conglomerates and quartzites, while the upper, the so-called Kaleva facies, comprises phyllites, graphite-bearing phyllitic schists and mica schists.

The upper, Kaleva facies of the Kalevian formations is quite widely distributed in North Karelia and is accompanied everywhere by the ophiolitic serpentinites characteristic of Kalevian schists, as Haapala (1936) has observed in his study on the serpentinites of North Karelia.

Formations analogous in stratigraphic position and chemical composition to the sulphide- and carbon-bearing schist formations described by Saksela (1933 a) from Karhunsaari, Liperi commune, have been observed to occur elsewhere in North Karelia. As subsequently proved in the region on the western and northwestern flanks of the Sotkuma cupola, they occur in the immediate vicinity of the locally exposed gneissose granite basement.

Mäkinen (1920) was the first to describe the geology of the Outokumpu ore deposit, pointing out that the graphite-bearing schists are closely associated with the other schists of the region and that they pass gradually into mica schists and quartzites.

In his description of the serpentinites of North Karelia, Haapala (1936) mentions their frequent association in various parts of the region with graphite-bearing schists and quartzites, both containing sulphides and chrome-bearing silicates. In the proximity of the serpentinites, the quartzites become richer in amphibole and thus become darker in colour.

In his tectonic study of the region, Väyrynen (1939) regards the Outokumpu complex as a whole as representing a nappe formed by overthrusting from the Pisa area and as belonging to an allochthonous Jatulian formation. As he sees it, the quartzites, dolomites and »carbon-bearing phyllites» of the Outokumpu region indicate a schist complex identical to the Jatulian sequence of Pisa.

According to Disler (1953), the nappes formed by overthrusting in the Karelidic orogeny occur most readily in zones formed by quartzites, black schists and dolomites, where the resistance of the rocks varies.

In his geological study of the Outokumpu ore deposit and the formation associated with it, Vähätalo (1953) has also described the black schists belonging to the formation. According to him, they are closely bound up with the quartzites occurring in the region, the transitions in the contact zones being gradual. In addition to the phyllitic black schists, siliceous varieties

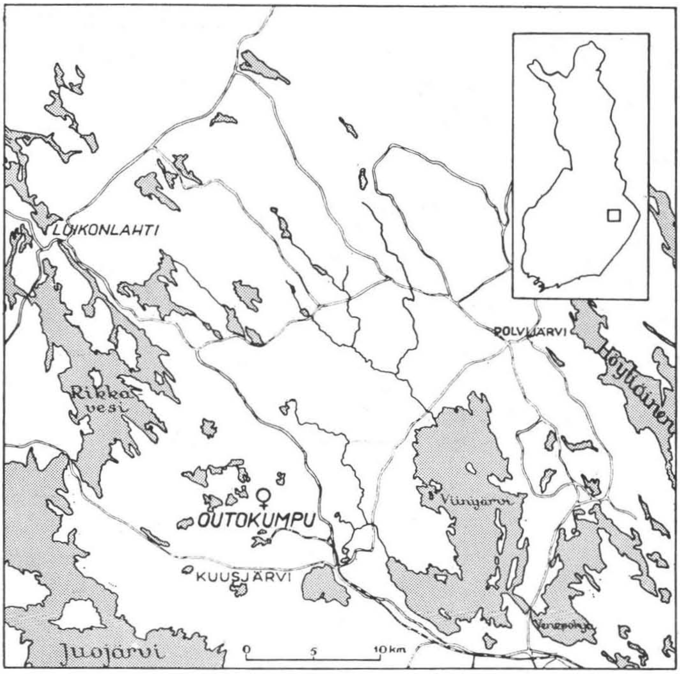

Fig. 1. Location of the Outokumpu region in eastern Finland.

are also met with in places. The layers conform to the schist formation, but in deformed zones the powerful effect of movements can be observed especially in the black schist horizons. The poor iron content of the silicates is reflected by the pale, nearly colourless biotite and amphibole. The sulphides (pyrite and pyrrhotite) occur in many places as fissure fillings, chalcopyrite and sphalerite replacing the primary pyrite.

In considering the genesis of the Outokumpu ore, Saksela (1957) places importance on the selective mobilization of sulphides during metamorphism into tectonically favourable horizons, and is of the opinion that the ore evolved in the same way as the sulphides in the sedimentogenous schists in which two sulphide generations have been distinguished. In the ore only the younger generation would seem to be present in any abundance. The ore material of Outokumpu would appear to have been derived from the black schists and the sulphide-bearing quartzites occurring in the area.

The present study is linked to the researches mentioned above and its aim is to shed light on the geology of the carbon- and sulphide-bearing formations met with in the Outokumpu zone and the schist areas in the vicinity. The area included in this study, extending from Höytiäinen to the Juojärvi —Rikkavesi line, is referred to in the following as the Outokumpu region.

The Outokumpu complex (see Vähätalo, 1953, p. 16) runs diagonally across this region (Fig. 1). With the exception of the easternmost part, the region is poor in outcrops, with esker formations covering it to a great extent, especially on the western side of Viinijärvi. In addition, there is a scarcity of exposed black schists, which become easily weathered. However, mining operations and extensive exploratory drillings throughout the Outokumpu complex from Juojärvi to Polvijärvi have been of tremendous value in the collection of material for this study. The same must be said of the revisory geological mapping carried out by the Exploration Department of the Outokumpu Company here and on the eastern side of Viinijärvi.

The main purpose of the present study is to give a more detailed description of the regional geology and petrology of the carbon- and sulphide-bearing schists on the basis of field observations, microscopic investigations and chemical analyses. The petrographic description is divided into three parts, consisting of different varieties of black schists: 1) argillaceous, 2) calcareous and 3) arenaceous. The structural and stratigraphic relations of the occurrences are dealt with in connection with the geological description of the region. Attention has been given only to such parts of the surrounding schist area as have been deemed to contribute to the study. The intensity of metamorphism, which varies considerably in the region, has made possible comparison of different parts of the region. The black schists, whose carbon content generally protects them from metamorphic influences, have become recrystallized in the area of high-grade metamorphism. This has made possible the study of their mineral composition, which is often difficult on account of the abundant very fine-grained graphite and sulphides. The preservation of the primary structures owing to the carbon content, on the other hand, and the determinations of trace elements have been of importance in elucidating the origin and primary lithological characteristics of the black schists.

The term black schist is applied in this work to such sulphide- and graphite-bearing schists in the Outokumpu region as have a carbon and sulphur content both exceeding one per cent. The colour of the schist, which is blackish gray when the carbon content is close to one per cent, turns black as the percentage of carbon in the rock increases. This holds true of both argillaceous and calcareous black schists. Constituting an exception are a few originally arenaceous schists exceedingly rich in quartz which, despite a carbon content of under one per cent, tend to be darker in colour.

REGIONAL GEOLOGY AND MODE OF OCCURRENCE OF THE BLACK SCHISTS

GENERAL GEOLOGICAL FEATURES OF THE OUTOKUMPU REGION

The basement of the Karelian schist formation between Lakes Höytiäinen and Viinijärvi is the gneissose granite cupola of Sotkuma-Vaivio, which emerges from underneath the schist area at the point of axial culmination occurring there. The basal complex includes arcosic, quartzitic rocks, which according to Frosterus and Wilkman (1916), and Saksela (1933 a) are autochthonous weathering products of gneissose granite situated on the original basement. Near the basement there are, in addition, conglomerates whose uneven distribution and brecciated appearance are attributed by Väyrynen (1939) to the movements of the overlying schist formation, although locally there occur basal conglomerates.

The phyllite formation on top of the gneissose granite cupola varies in character. On the eastern side of the cupola, in the area of Höytiäinen, the rocks are phyllitic and on the whole less metamorphozed than on the western side. In many places they have preserved the varved structure of sedimentogeneous rocks and the distinct lamination characteristic of phyllites. The thickness of the varves ranges from a few millimetres to several decimetres; their coarse-grained, quartz-rich base alternates with the darker, fine-grained, mica-rich top.

In the western part of the phyllite area, on the northern and, particularly, western sides of the Sotkuma cupola, the phyllites gradually become coarser of grain and their banding less distinct (Fig. 2). Here, dark mica-rich phyllites, containing in places small amounts of sulphides and graphite, alternate with coarser-grained parts, often even resembling mica schists; the latter become prevalent on moving westward. It is for this reason that the phyllites and the mica schists cannot be separated from each other by any clear boundary in mapping work. On the western side of the border appearing in the maps of the region previously published *(cf.* Frosterus and Wilkman 1916), phyllites are no longer met with to any noteworthy extent, so it serves as a rough transitional boundary.

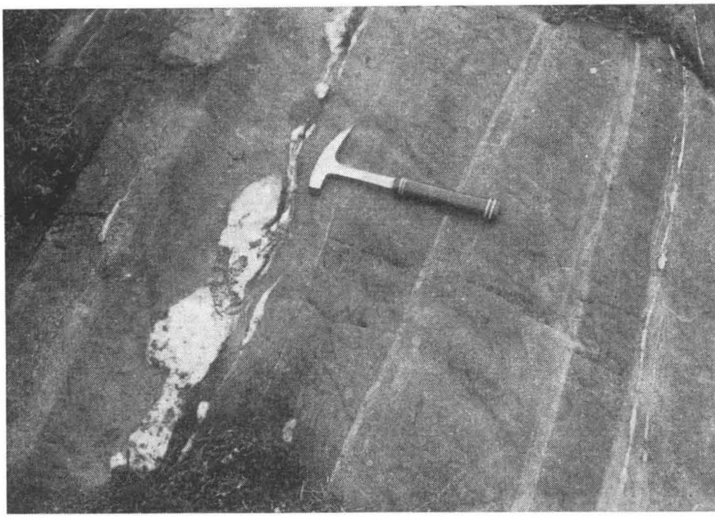

Fig. 2. Graded bedding as relict structure in mica schist with conformable quartz veins. Sola, Polvijärvi. Photo J. Koskinen.

In the environs of Viinijärvi, mica schist becomes the prevailing type of rock, and, as the degree of metamorphism continues to increase westwards, gneissose features begin to appear. As the rock becomes more homogeneous, its varved structure grows less distinct, finally disappearing altogether. In the vicinity of the Maarianvaara granite, pegmatite veins become common and the rock finally grades into veined gneiss.

At the eastern margin of the mica schist area, as well as at its centre (along the northwestern side of Viinijärvi), there occur schist zones composed principally of quartzites and schists containing carbon and sulphides. These conform to the structural features of the mica schist formation in the surroundings and they are penetrated by numerous serpentinite-ophiolites.

The quartzite and black schist formations of the so-called Solansaari—Viitalampi zone, occurring on the western and northwestern sides of the Sotkuma cupola, are discontinuous, with the serpentinite-ophiolites occurring in them as conformable lenses. The zone occurring on the northwestern side of Viinijärvi is more continuous and runs in a southwest-northeasterly direction from Juojärvi to the commune of Polvijärvi. This so-called Outokumpu complex consists mainly of serpentinites and quartzites. Black schists are situated for the most part in the contact zones of the complex and at its northeastern end. The ophiolitic serpentinite lenses thrust in between the quartzite and black schist layers (Haapala 1936) form the main part of the complex in the middle portion of the Outokumpu zone, where the Outokumpu ore is situated (Vähätalo 1953). Also in the mica schist formation in the vicinity of the complex there occur some separate ophiolites together with intervening layers of black schist. The geological features of the two zones, the mode of occurrence of their various members, their contact relations and their tectonics have previously been described by Haapala (1936), Väyrynen (1939), Vähätalo (1953) and Disler (1953).

On the northwestern side of the mica schist formation there occurs the late orogenic granite massif of Maarianvaara. Its pegmatite veins and dykes cut the surrounding gneiss and schist area (part of which is contained within the granite), as well as the nearby Outokumpu complex. Associated with the mica gneiss area inside the granite is the schist zone of Luikonlahti—Kortteinen, which, like the corresponding parts of the mica schist area, consists chiefly of quartzites, serpentinites and black schists.

In the Höytiäinen area the fold axes follow the prevailing Karelidic fold direction, but on the western side of the Sotkuma massif it begins to turn southwestward, and this trend becomes predominant as one proceeds farther west. In the Solansaari—Viitalampi zone the fold axes have a south-southwesterly trend. The axial pitch in the northern part of the zone at Viitalampi is 25° SSW, being steeper in the central and southern parts, or about 40—50° SSW (Appendix I; Vähätalo 1953). Similarly the lineation, which appears as a crenulation or waviness in the plane of schistosity is parallel to the fold axes of the schist area. The dip of the schistosity and of the bedding in the area is very steep, in places quite vertical, generally varying between 75 and 85 degrees WNW-W. Occasionally it is observed to be easterly. In the proximity of the gneissose granite cupola of Sotkuma, on its western and northwestern sides, the dip is everywhere more gentle, and the lowest values on the western flank of the cupola vary between 45° and 55° W.

The trend of the fold axes in the quartzite-serpentinite zone of Outokumpu is for the most part nearly perpendicular to the general Karelidic fold direction. At the northeastern end the trend is approximately N 25° E and at the southwestern end N 60° E. In the middle part of the formation, where the axial pitch is gentle and locally horizontal, the dip of the schistosity varies between 30 and 50° SE, whereas at the northeastern end it is considerably steeper, or approximately 70—80° ESE. The axial pitch is likewise steeper here, being 25—30° SSW (Appendix I; Vähätalo 1953). At the southwestern end the axial pitch is often the reverse (5—10° ENE), which means that the middle parts of the formation at Outokumpu are situated in an axial depression.

Thus the structure of the central part of the schist area consists of an extensive syncline, the Viinijärvi basin (Wegmann 1928). On its eastern flank is situated the Solansaari—Viitalampi zone and on its northwestern flank the Outokumpu zone.

BLACK SCHISTS OF THE PHYLLITE AREA

In the immediate proximity of the Sotkuma cupola, on its western side, dark, mica-rich phyllites, often containing small amounts of graphite and sulphides, are common. This is also shown by the aeromagnetic maps of the region (Appendix I), in which the magnetic anomaly curves around the gneissose granite. The anomalies on the northern and northeastern sides are due in part to amphibolite lenses but, on the western and northwestern sides of the massif, they are largely due to the sulphide- and graphite-bearing phyllite zone, which varies from one to two kilometres in width.

The dark layers of black schist, which vary both in thickness and in their content of sulphides and graphite, conform to the bedding of the mica schists as well as to the general structural features of the area. Occasionally they alternate with dark, quartzitic schists, which frequently contain, in addition, intervening layers rich in amphibole and, in many cases, sulphides and graphite. Other intervening layers very rich in mica and coarse in grain, yet poor in graphite, also occur.

On the western side of the Sotkuma massif the occurrence of deposits rich in sulphides and graphite is common in the immediate proximity of the basal complex. On the cape of Käsämä and on the islands along its southeastern side, the phyllites in many places have intervening layers of black schist, but the presence of Lake Höytiäinen here prevents a detailed study of the contact and transitional zones on the side of the basement.

On the northern side of Rukkajärvi, overlying the basal quartzite, there occurs a conformable black schist layer about fifty metres thick and a few hundred metres long; closer to the granite basement this layer grades into a coarse-grained phyllite. The black schist contains an abundance of coarse-grained amphibole and several thin, phyllitic intervening layers poor in sulphides and graphite. Saksela (1933 a) has described a black schist formation from Karhunsaari, in the commune of Liperi, that is similar in character and stratigraphic position, though considerably larger in size.

In the transitional zone of the phyllite and mica schist areas in the northwestern part of Lake Höytiäinen, the phyllite formation encloses a conformable, lenticular black schist bed about 150 metres thick and with an estimated length of ten times that figure. The strike is N 30° E, and the dip varies from 60° to 75° WNW. The lineation is parallel to the general pitch of the fold axis, which is chiefly 15—20°, S 20° W.

On the island of Kultakallio, which is situated in the northeastern part of the deposit mentioned above, there is an feldspar-rich arcosic intervening layer 0.4—0.7 metres thick in the folded, phyllitic black schist. This layer is likewise folded. The contact with the carbon-rich schist on the NW side is sharp, but on the SE side a gradual transition is observed. The arcosic layer

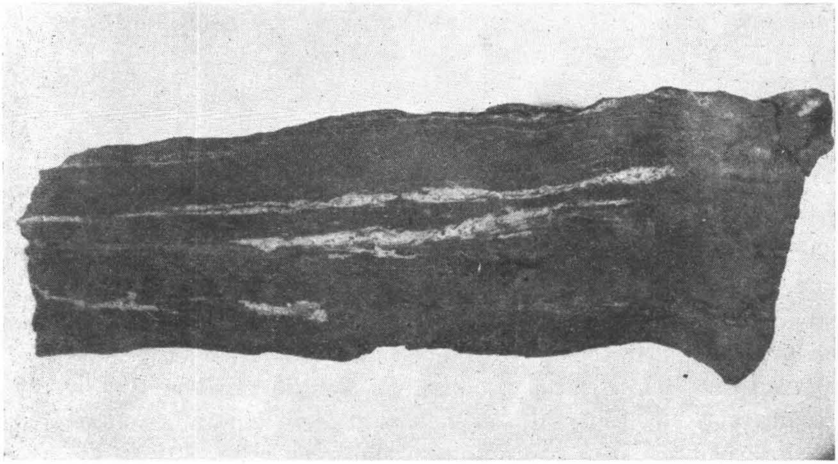

Fig. 3. Phyllitic black schist interbedded with pyritiferous layers. Kultakallio, western part of Lake Höytiäinen, Polvijärvi. Natural size.

is graphite-free and contains pyrrhotite. Its chemical composition is presented in Table IX, No. 21.

The sulphide material of the graphite-bearing deposits of the phyllite area consists of pyrite and pyrrhotite, with the former occurring as conformable layers in the coarse-grained part of the black schist (Fig. 3). In addition, pyrite is met with in the transverse fissures of the black schist.

The fine-grained, phyllitic black schists in many instances contain quartz-rich layers, whose carbon and sulphide content is consistently low. In places, accessory amphibole is met with. The intervening layers rich in amphibole as well as those rich in quartz alternate with micaceous carbon- and sulphide-bearing layers. The quartzitic layers, like those containing amphibole, are dark in colour, owing to their carbon pigment. It should be noted that the sulphide material of the black schists containing amphibole and abundant mica generally consists of pyrrhotite, whereas the varieties rich in quartz contain chiefly pyrite.

BLACK SCHISTS OF THE MICA SCHIST AND MICA GNEISS AREA

SOLANSAARI—VIITALAMPI ZONE

In contrast to the phyllitic formation, several serpentinite lenses occur in the mica schist area. They follow the structural features of the schist formation and occur as conformable lenses. As pointed out by Haapala (1936), graphite-bearing schists and quartzites occur in association with the serpentinites, and they contain sulphides and chrome-bearing silicates, such as tremolite and fuchsite. The tremolite-bearing portions are locally carbonate-bearing.

At Solansaari, one phyllitic lenticular black schist zone several tens of metres thick conforms to the structure of the surrounding mica schist, the dip being nearly vertical and the strike N-S. A few exposures indicate the length of the zone to be approximately 0.5 km. In one exposure it occurs as a thin layer between the mica schist and the quartzite. The zone also contains two serpentinite lenses, but the contacts with the schists are not visible.

Eastwards the mica schist encloses a parallel black schist layer, with a dip varying 80—90° W. It can be followed along its strike for a distance of about. 1.5 km, but according to the aeromagnetic map (Appendix I), it evidently continues southwards underneath Viinijärvi. The thickness of the zone varies between ten and 150 metres, and in a number of exposures it can be observed to be in contact with the mica schist.

The passage of black schists into mica schist and quartzite is usually gradual. In the transition zone, the thickness of which varies up to as much as a few metres, thin black schist varieties rich in mica or quartz appear first as intervening layers, whose thickness increases and content of carbon and sulphides diminishes. Finally the black schist itself occurs as thin intervening layers while the rock grades into pure mica schist and quartzite. Such a gradation into mica schist has been met with at Solansaari on the western side of Saarela farm in the contact zone of black schist (Fig. 4). Locally in the mica schists there occur thin sulphide- and graphite-bearing layers.

In the mica schists there occur quartz veins, several tens of centimetres wide, filling fissures parallel to the schistosity. They are also met with locally in the black schist, though irregular in form (Fig. 4). Intersecting quartz veins are also present. In the middle part of the Solansaari—Viitalampi zone, on the northern side of Suopolvi, there occurs a phyllitic black schist layer a few metres thick in a fine-grained mica schist situated in a transverse ditch. Dark, quartzitic layers and layers containing more mica and with a varying content of carbon and sulphide alternate in the black schist. On the southeastern side of the bed there are some thin serpentinite lenses and skarn-bearing quartzite bands. In the dense phyllitic structure of the black schist one observes folding, which is less evident in the neighbouring quartzite. The dip of the schistosity and the bedding is steep, varying between 75 and 90° WNW. The strike is N 20° E.

At the northern end of the zone at Viitalampi, Haapala and Väyrynen have described serpentinite occurrences that occur there also in conjunction with quartzites, mica schists and phyllitic black schists. In both the last-mentioned rocks and the quartzites there occur amphibole-bearing layers. The strike of the schist formation is nearly N-S, with the dip varying between 80 and 85° W. The fold axis plunges 20—25° S.

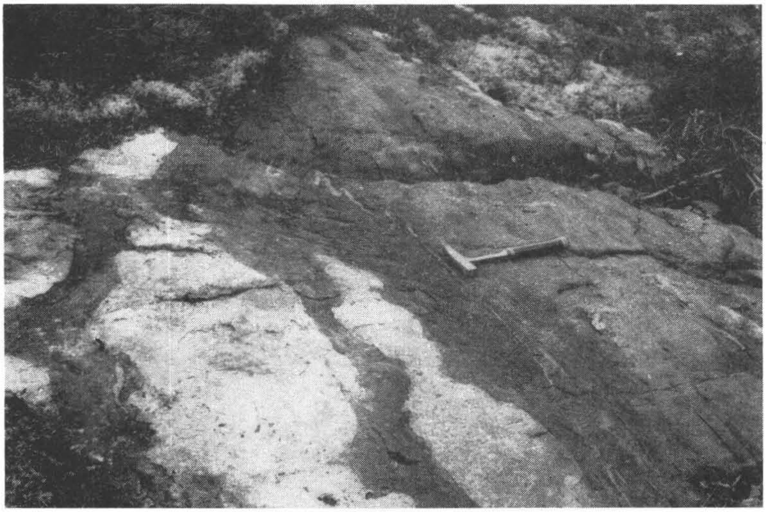

Fig. 4. Black schist with conformable quartz veins grading into mica schist (right). Solansaari, Polvijärvi. Photo J. Koskinen.

In respect of types present and the contact relations, the black schists of Viitalampi are like those of the middle and southern parts of the zone. They are phyllitic schists considerably finer in grain than the mica schist, with micaceous layers alternating with layers rich in quartz and occasionally amphibole. The carbon is chiefly associated with the fine-grained mica-rich layers.

The coarse-grained sulphide material consists mainly of pyrite, which occurs as conformable concentrations parallel to the schistosity, measuring as much as a centimetre in thickness, or as fissure fillings in the coarse-grained, quartz-rich parts of the schist. In the carbon-bearing layers rich in amphibole and mica there occurs pyrrhotite, which in places forms veins intersecting the schistosity.

JUOJÄRVI—HAAPOVAARA (OUTOKUMPU) ZONE

In the central part of the mica schist area there is a long, belt-like zone, which trends in a southwest-northeasterly direction from Juojärvi to Haapovaara, in the commune of Polvijärvi. This so-called Outokumpu complex extends for a distance of about twenty-five kilometres, branching at its southwestern and northeastern parts into several thinner and parallel zones, which conform to the structural features of the surrounding mica schist formation. Its central section is about 1.3 km thick at its broadest known point.

The schist zone contains mainly alternating thin, long quartzite and black schist bands, measuring at most 200 metres in thickness, with the black schist occurring as more continuous layers in the upper and lower parts of the zone. Between the quartzite and black schist belts, ophiolitic serpentinite lenses occur in abundance, constituting in the central part of the Outokumpu complex the main portion of the zone. Also in the mica schist formation some serpentinite ophiolites are met with, and close to the zone there occur isolated bands of black schist.

NORTHEASTERN PART

In the northeastern part of the Juojärvi—Haapovaara zone there are several parallel black schist deposits separated by mica schist layers of varying thicknesses. Closely associated with the black schist horizons are quartzite and skarn-bearing layers as well as conformable lenses of serpentinite ophiolites.

On the northwestern side of Viinijärvi the Exploration Department of the Outokumpu Company has carried out, in addition to geological mapping operations, geophysical measurements and exploratory drillings, which appropriately supplement the geological picture of the area based on the sparse network of outcrops (Appendix II). The tectonic observations presented on the map are also connected with the aforementioned revisory mapping and appear in part in the map of the area published by Dr. V. Vähätalo (1953, Appendix I).

Contrasting with the Solansaari—Viitalampi zone, the black schists appear as long, belt-like horizons, the greatest known thickness being 120 metres while the length is several kilometres. The measurements mentioned are from the upper part of the formation, where the black schist belts are in general more continuous. The black schists occur in the mica schist formation as conformable beds, which follow the structural features of the environment. The gradation into mica schist, with the amount of mica increasing, is in many instances slow. The same must be said of the gradation into quartzite. In this locality, too, the black schist belts are accompanied by layers of quartzite and skarn containing in many places varying amounts of graphite and sulphides.

As a general observation it may be mentioned that in the northeastern part of the Juojärvi—Haapovaara zone the black schists are richer in amphibole and also coarser in grain than on the eastern side of Viinijärvi, although the graphite-rich portions are rather phyllitic. The sulphides, which on the eastern side of Viinijärvi generally occur as conformable concentrations, exhibit in this locality an epigenetic structure. Pyrrhotite occurs in abundance and pyrite, too, is met with not only as conformable concentrations but also in transverse fissures with silicatic vein material (Fig. a, Plate V).

When comparing the upper and lower parts of the zone with each other, it will be noted that the intervening layers rich in amphibole closely associated with the black schists are more common nearer the footwall complex. The thickness of the amphibole-bearing layers varies from a few millimetres to several tens of metres, and they often contain both graphite and pyrrhotite as impregnations. The black schist deposits of the central and lower parts of the zone are smaller in size, being divided into several parallel, lenticular belts. The occurrence of pyrrhotite is common here, whereas pyrite is met with only locally.

In the upper part the black schist layers occur in belt-like zones several kilometres long and closely following one another; their combined thickness, with included layers, varies between 250 and 300 metres. Mica- and quartz-rich black schist types prevail here, and in the transitional zones against mica schist they are often only graphite-bearing phyllitic mica schist. It should be noted that the mica-schist, which normally is homogeneous and fine- or medium-grained, consistently becomes folded, coarse-grained, and even gneissose when in the proximity of contacts with the black schist zones. In addition to the quartz layers, there also occur in the upper part intersecting quartz veins, often in conjunction with coarse pyrite. The quantity of sulphides seems here to be in general less than in the footwall complex, while pyrite is met with more than pyrrhotite. The graphite-bearing interbanded skarn layers in the upper part are also dominated by pyrrhotite, with the pyrite occurring only as an accessory constituent and is lacking in the purer skarn zones.

MIDDLE AND SOUTHWESTERN PARTS

As mentioned earlier, the middle part of the Outokumpu zone is situated in an axial depression between Suuri Kuusjärvi and Vuonosjoki. As in the northeastern part, the Outokumpu complex is also divided in its southwestern part into several separate, parallel zones, which conform to the structural features of the surrounding mica schist formation. The scarcity of exposures in the southwestern part of the region makes it impossible to determine whether the separate serpentinite and black schist occurrences near Juojärvi belong to the zone, as the geophysical measurements seem to indicate. However, the 1.5 km long serpentinite lens conformably penetrating the mica schist on the southeastern side of Suuri Kuusjärvi evidently represents a separate occurrence. The same ought perhaps to be said of the parallel quartzite-black schist belt running southwest from Kaita-Kuusjärvi and which is closely associated with a serpentinite body. Separate parallel

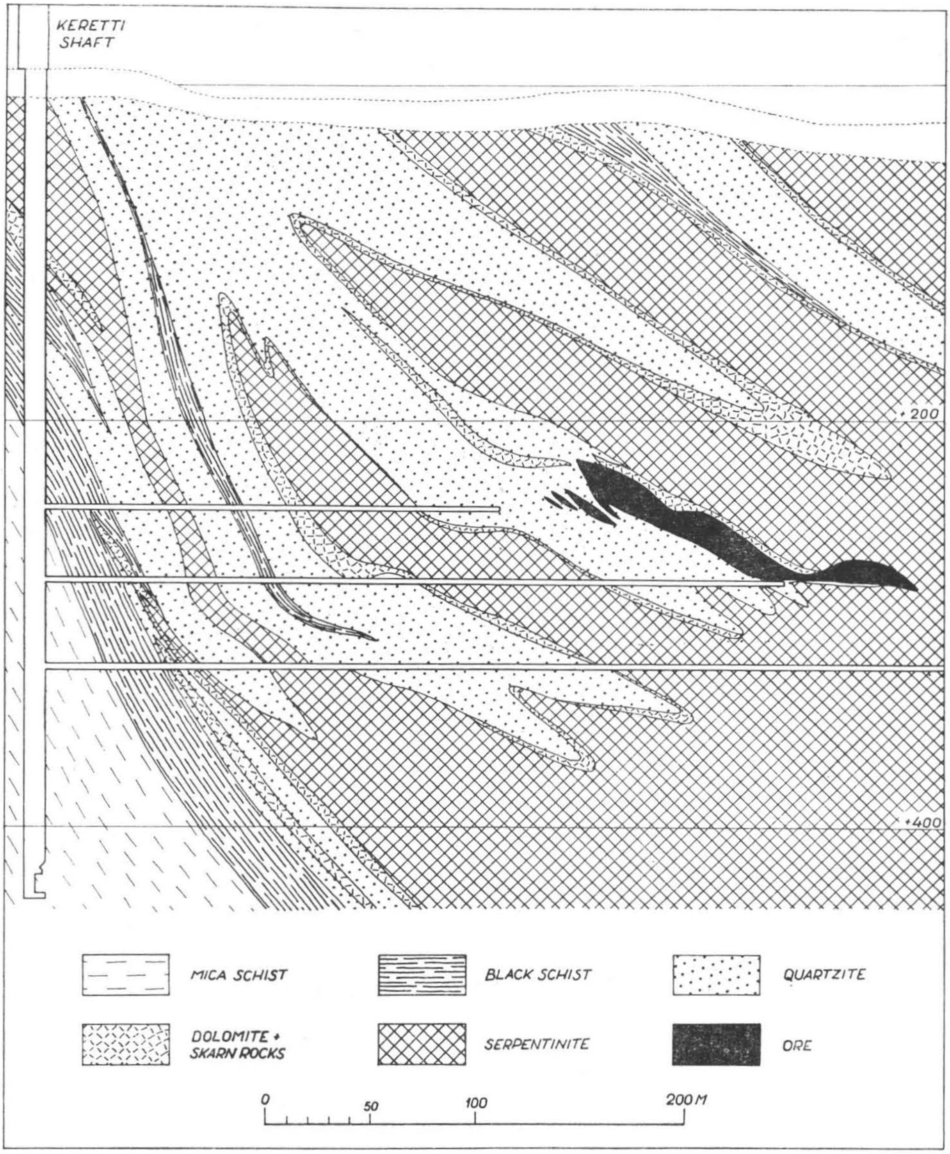

Fig. 5. Cross-section of the Outokumpu complex by Keretti shaft.

serpentinite lenses are known to occur elsewhere in the mica schist area, as, for instance, at Maljasalmi and at Varislahti in the western part of the commune of Kuusjärvi.

The thickness of the more homogeneous middle part of the Outokumpu

Fig. 6. Deformed layer of black schist in serpentinite. The transition series from black schist to serpentinite is as follows: black schist rich in biotite — chlorite — tremolite and talc-bearing serpentinite. Outokumpu mine, Keretti shaft, +320 level. Photo H. Konkola.

zone varies between 0.7 and 1.3 km (Appendix I; Vähätalo 1953). It contains mainly serpentinites, quartzites and different kinds of black schists. Although the share of serpentinite and quartzite is considerably greater than in the northeastern and southwestern parts of the zone, one can perceive in the mode of occurrence of the black schist, as well as in its gradation into other schists, numerous features that are characteristic of it, as noted above. The black schists occur here also in intimate association with mica schists, which are locally met with as layers within the formation; in many places they are also associated with quartzites. The black schists occur in the contact zones of the serpentinite-quartzite complex against the mica schist, as layers within the complex and locally as separate layers in the mica schist outside the zone.

The thickness of the black schist layers varies from a few metres to as much as 200 metres while the length is generally several hundred metres and, in the thicker layers, some kilometres.

At the contact of the lower part of the complex there occurs against the mica schist a more continuous black schist horizon, observations having been made by means of diamond drilling over a distance extending about five kilometres. This horizon is to be seen in the cross-section of the Keretti shaft in the southwestern part of the ore deposit (Fig. 5), where its thickness varies between 25 and 40 metres. The same horizon has been drilled through in the middle part of the ore deposit as well as at the northeastern end at Kaasila, where the thickness of the black schist layer has proved to be the maximum 200 metres. Furthermore, the electrical and magnetic anomalies of the north-

Fig. 7. Quartzose black schist layer (dark) below the footwall of the ore. The veinlets of carbonate are parallel to the tectonic *ac*-plane. (Black schist layer with tension cracks filled with carbonate.) Outokumpu mine, Keretti shaft, upper edge of the Lietukka ore body.

eastern extension of the ore deposit as well as the aeromagnetic anomalies of the region (Appendix I) are situated in the same area as practically a continuous belt trending in about the same direction.

In this black schist deposit there occur thinner interbedded layers containing quartzite, mica schist and skarn minerals and in which sulphides and some graphite are met with locally. Moreover, the horizon has been penetrated by thin, conformable serpentinite lenses, which are in many instances talc-bearing. The zone is almost always sheared in the vicinity of the serpentinite ophiolites, and it is intersected by faults with varying trends. The black schist belt consists in detail of many lenticular bodies, which together give the impression of one larger continuous layer, the dimensions of which have been given above.

Inside the complex the black schist occurs as bands in the quartzite and in the contact zones of quartzite and serpentinite. Black schist has frequently been met with in the extension of the lower edge of the Lietukka ore body of the Outokumpu ore (see p. 49, Vähätalo 1953), occurring chiefly at the contact of the serpentinite as well as, locally, within the serpentinite. Inside the complex the black schist layers are smaller in size than those described from the footwall contact of the complex, appearing more as scattered, conformable lenses.

In type they are the same as in the lower part of complex, but in the contact zones of the serpentinites as well as within them, sheared, intensely folded black schist horizons become dominant (Fig. 6).

The black schist layers often exhibit beautiful miniature folding, for in regard to tectonic movements these horizons are incompetent. In carbon-rich horizons the folding has increased in intensity even farther and the rock finally breaks up. Graphite-rich planes appear abundantly and the structure becomes mylonitic. Deformation is often to be observed exclusively in the black schist layers (Figs. b and c, Plate V).

In the immediate vicinity of the Outokumpu ore, black schist occurs locally at the upper edge of the ore (Fig. 7). It has been met with below the footwall of the upper edge of the Lietukka ore body as layers in the quartzite and in the footwall contact of the ore between the serpentinite and ore. Black schist does not occur as the host rock of the ore with the exception of local mineralized layers against the footwall contact. On the other hand, in certain thin black schist layers situated below the upper edge of the ore there occurs a weak chalcopyrite impregnation in addition to the pyrite typical of this part of the ore deposit.

On the extension of the lower edge of the ore, or in its proximity, the black schist occurs locally as layers in the serpentinite or at the contact zone of the serpentinite and quartzite, usually on the hanging-wall of the ore. On the extension of the lower edge of the ore in the western part of the Lietukka ore body, exploratory drilling has proved the black schist to occur as separate layers in the serpentinite. Quartzites are not found here in association with black schist. The black schists of this part of the formation do not appreciably differ in character from those described above. At the extension of the lower edge of the ore the black schists are associated with an abundance of graphite-free skarn lenses, which are often present in the dolomite-bearing contact horizon of the serpentinite.

In the upper part of the complex few observations have been made of the black schists, as in the case also of those situated at the southwestern end of the Juojärvi—Haapovaara zone. Only a few drill holes provide data here to supplement the paucity of exposures. On the basis of the geophysical measurements carried out in the area, black schists may be assumed to occur here, too, in great abundance. Against the mica schist of the hanging-wall, however, there is apparently no distinct contact comparable to that occurring in the lower part of the complex (Fig. 8). Moreover, in a hole drilled at Matovaara the upper part of the complex proved to have layers of mica schist considerably thicker than in the lower part.

On account of the deficient research material available, it is not possible to make accurate observations in regard to the southwestern end of the zone. However, it should be noted that, here, the black schists differ structurally

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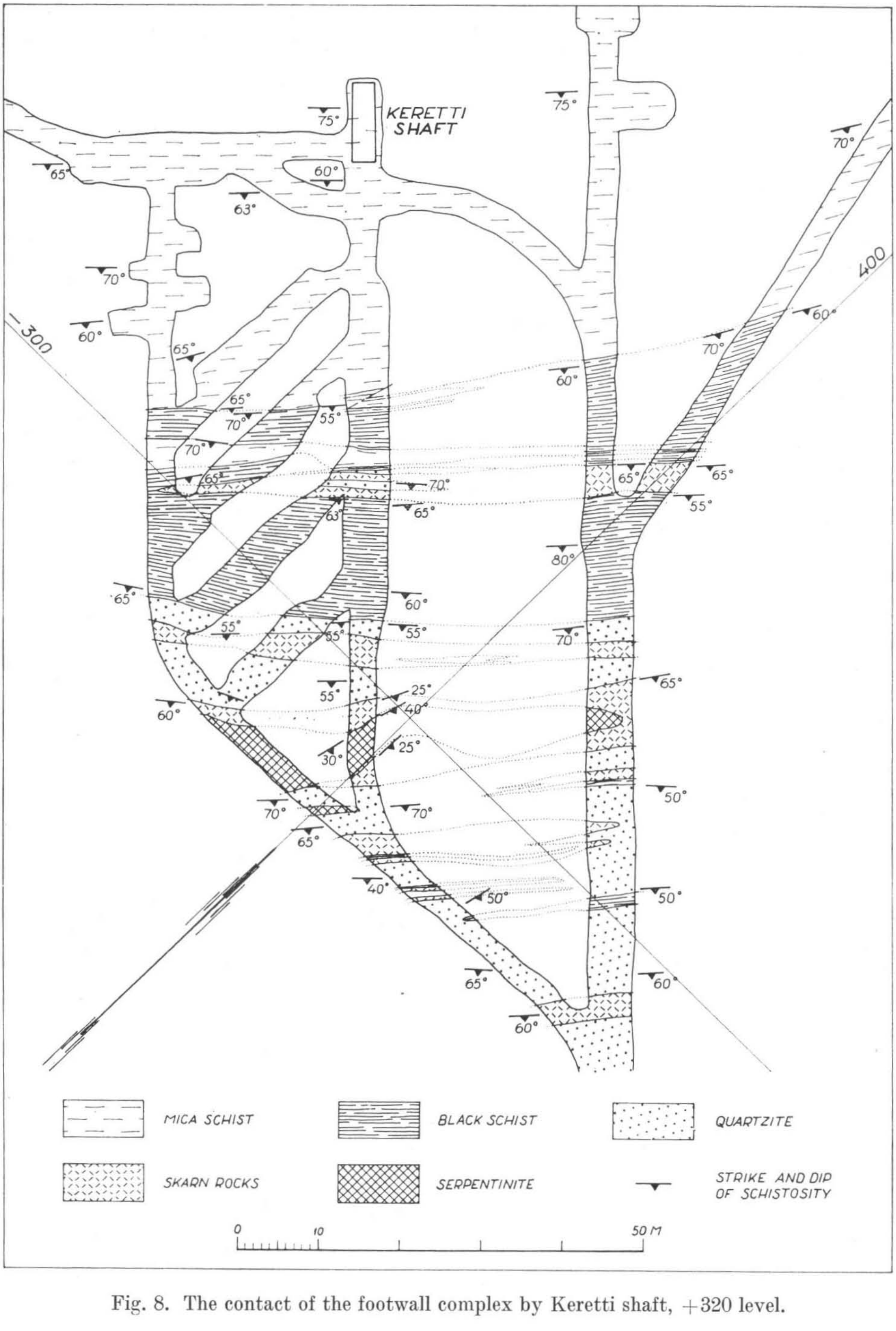

Fig. 8. The contact of the footwall complex by Keretti shaft, +320 level.

from those in other parts of the zone. The graphite- and sulphide-bearing occurrences met with at Itkonsalo close to Juojärvi are strongly folded, coarse-grained, gneissose schists, which contain both concordant and discordant quartz and potash feldspar veins. In places there are sulphide- and graphite-bearing mica gneisses, in which more or less skarn-bearing layers occur. The sulphide material is principally composed of pyrrhotite. Pyrite is found as coarse crystals in association with massive sulphide concentrations in the plane of schistosity as well as in fissures intersecting it.

In the black schists of the middle and southwestern parts of the Juojärvi—Haapovaara zone, amphibole-bearing layers occur in all the horizons. In this respect this part of the zone differs from the northeastern part. Black schists rich in mica and quartz are common throughout the zone, like the parts with skarn minerals. Sulphides usually consist of pyrrhotite. Pyrite is more likely to be present in the interbanded quartz-rich layers, while the micaceous parts contain both iron sulphides in varying amounts.

Like the mica schist formation, the black schists reveal an increase in the degree of metamorphism toward the west. The fine-grained phyllitic black schists, which are common in the northeastern part of the Outokumpu zone, gradually increase in grain-size towards the middle part of the zone. Only the graphite-rich varieties of black schist preserve their pelitic structure, but in places even these can be observed to become more mylonitic as a result of shearing. At the southwestern end of the zone, where the mica schist grades over into arteritic vein-gneiss, gneissose features occur also in the black schist formation. The carbon-poor schists here have in many cases changed to sulphide- and graphite-bearing mica gneisses, in which skarn mineral-bearing layers occur. It is noteworthy, in addition, that pyrrhotite predominates in the middle and, particularly, the southwestern parts of the zone.

LUIKONLAHTI—KORTTEINEN ZONE

In the northeastern part of the gneiss and schist area remaining within the late-orogenic granite of Maarianvaara, there occurs a bow-shaped schist zone, which includes, besides the ordinary gray mica gneiss, quartzites, black carbonaceous schists and carbonate rocks. Along the eastern margin of this zone, there occur numerous serpentinite ophiolites, various skarn rocks and intersecting granite, aplite and pegmatite veins.

Väyrynen (1939) has published a general description of the geological and structural features. Here, consideration will be restricted to the carbon- and sulphide-bearing schists occurring in the Luikonlahti area and their mode of occurrence, in order to achieve a basis for a comparison between the black schist formations described earlier.

In form and mode of occurrence the black schists resemble those previously described and they are present mainly in the mica gneiss formation. Locally they include quartzitic, skarn mineral-bearing and micaceous layers, and, together with the mica gneisses, they are frequently cut by granite and pegmatite veins.

The influence of regional metamorphism as well as that of the younger granite of the surroundings can be clearly detected. The black schists are coarse-grained and their schistosity, especially close to the granite, becomes indistinct. The rock undergoes a structural change, becoming disorientated and then massive, when the contact with granite and pegmatite dykes is approached. For this reason the coarse-grained, massive black schist is quite common in those parts of the area where dykes of granite and pegmatite are abundant. The contacts of the aplitic granite and pegmatite dykes are sharp, and often the black schist contains large pyrite crystals in addition to the massive pyrrhotite; in places there are thin veins in the schist wholly composed of pyrite. Sphalerite can occasionally be detected with the naked eye in the pyrrhotite.

In addition to the massive granoblastic black schist there are in the area amphibole-bearing schists containing graphite and sulphide. They are coarse-grained and the distinct schistosity is expressed by parallel amphibole prisms. There are interbanded layers of skarn, poor in sulphides and graphite; other skarns lacking these minerals are also met with.

As mentioned earlier, the black schists of the formation occur in conjunction with layers of quartzites. In structure, the quartzites are still schistose and fine in grain, and they have a low content of graphite and sulphide. The same may be said of the portions rich in mica, but close to the granite the rock becomes coarser in grain and less orientated.

According to a personal communication of Mr. Erkki Heiskanen, chief geologist of the Ruskealan Marmori Company, exploratory drillings carried out in the ore deposit of Luikonlahti have shown the black schists to occur in the mica gneiss area at the margins of the serpentinite-quartzite complex in the same way as they occur in the Juojärvi—Haapovaara zone of the Outokumpu area. In places thinner black schist layers are met with also in the inner portions of the complex in association with the quartzites and the concordant serpentinite lenses. The thickness of the black schist belts situated in the upper and lower parts of the complex is the same, averaging about 100 metres, while the length is at least ten times that figure.

GENERAL PETROGRAPHY AND MINERALOGY

PHYLLITES, MICA SCHISTS AND MICA GNEISSES

Weathering sediments rich in argillaceous material are quite common in the Karelian supracrustal formations. Phyllites, mica schists and mica gneisses in the Höytiäinen and Outokumpu regions represent different types of micaceous schists.

Characteristic of the fine-grained phyllites is a well-developed lamination and a varved structure. The thickness of the varves generally ranges from a few millimetres to several decimetres and the grain size from 0.005 to 0.05 mm. The main minerals are mica and quartz as well as plagioclase, which varies in amount. The mica is principally biotite, but muscovite is also met with. The parallel structure indicated by the mica flakes is exceedingly well developed, and in many places there occurs miniature folding (Fig. 9). Iron ore is always present and epidote occurs inside the plagioclase.

The base of the varves is quartzitic and often contains iron ore. The plagioclase, which varies in quantity, corresponds most nearly to oligoclase in its optical properties. The coarse-grained base, where the grains are likely to measure as much as one mm, gradually becomes finer in grain in the upper part of the layer and at the same time richer in mica. The boundary between the varves is sharp.

In the northern part of the Höytiäinen phyllite area, there occur fine- and medium-grained schists, grey in colour, in which the graded bedding has been destroyed in many cases by metamorphic recrystallization, and the rock is coarser in grain. The amount of mica is smaller and there is an abundance of plagioclase. The anorthite content of the plagioclase varies according to the optical properties within the range An_{20-35}. The mica is biotite that has undergone local chloritization. Muscovite is also to be seen. The mica crystals occur parallel to the schistosity, often as porphyroblasts. The quartz grains sometimes exhibit an undulose extinction. In addition to the accessory apatite, epidote is occasionally present. Locally, certain grey phyllites contain small quantities of sulphides as well as fine-grained graphite (Table I, No. 2). The sulphide material is pyrrhotite, and the graphite pigment

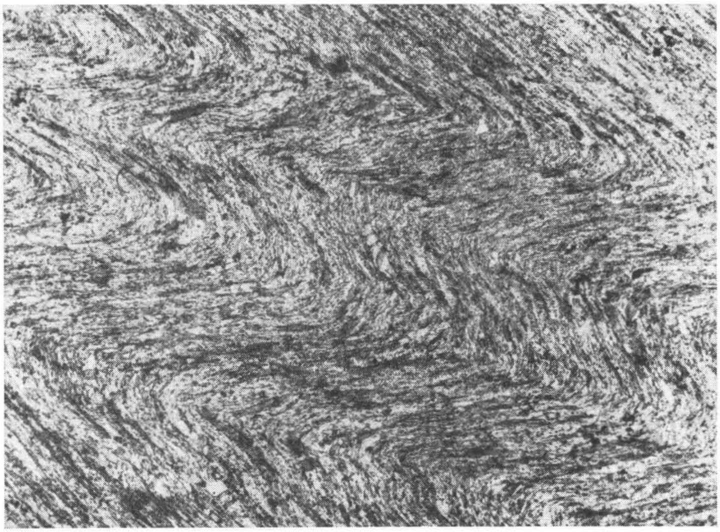

Fig. 9. Pelitic phyllite. The main schistosity is crossed by a later strain-slip cleavage resulting from microfolding. Kinahmo, Polvijärvi. One Nicol. 16 x.

occurs mainly in the plagioclase. Such phyllites occur in the cape of Kinahmo in the northern part of Höytiäinen.

Dark, micaceous phyllites are common in the proximity of the basement of gneissose granite. They are stratified, medium-grained and micaceous schists, in which a varved structure is not often observed. According to Väyrynen (1939), the amount of biotite in the dark phyllites rises to 50—60 %, while feldspar is in such cases almost totally absent. In the paler layers, however, it occurs in abundance. The dark micaceous phyllites are often sulphide- and graphite-bearing, as is to be observed in many places along the western side of the Sotkuma massif (Table I, No. 1). The mineral composition has been calculated from the analysis with the exception of the mica, the quantity of which has been determined by means of the integration stage. The lepidoblastic iron-rich biotite flakes and accessory pyrrhotite and ilmenite grains have become parallel to the schistosity. In addition to quartz, interstitial plagioclase (An_{35-40}) occurs in the analysed specimen. The grain-size of the graphite pigment occurring in the plagioclase varies from 0.001 to 0.05 mm. In addition to the aforementioned accessory minerals, the schist contains apatite while the biotite is locally chloritized. Locally, shearing has taken place in the phyllites.

As the degree of metamorphism increases (proceeding westwards), the phyllites gradually pass into coarse-grained mica schists, while the varved structure becomes steadily less distinct. In the better preserved parts of the

Table I. Analyses of the micaceous rocks of the Outokumpu region (Analysed in the Central Laboratory of Outokumpu Co)

	1		2		3		4	
	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.
SiO_2	55.58	9 263	67.07	11 178	67.42	11 237	68.59	11 432
TiO_2	0.87	109	0.80	100	0.71	89	0.56	70
Al_2O_3	18.56	1 820	13.70	1 343	13.08	1 282	13.44	1 318
Fe_2O_3	1.30	81	0.87	54	0.40	25	1.55	97
FeO	7.01	974	4.54	631	4.41	613	5.26	731
MnO	0.03	4	0.07	10	0.03	4	0.07	10
MgO	3.79	948	2.55	638	2.26	565	2.33	583
CaO	2.53	452	1.84	329	2.31	413	1.30	232
Na_2O	2.25	363	2.39	385	2.67	431	1.86	300
K_2O	3.06	326	2.70	287	1.72	183	3.04	323
H_2O+	1.78				1.28			
H_2O-	0.16		1.23		0.06		1.77	
P_2O_5	0.01	1	0.08	6	0.01	1	0.17	12
C	0.91		0.44		0.66		0.07	
CO_2	0.13	30	0.14	32	0.10	23		
F	0.12	32	0.04	11	0.06	16		
S	1.00		0.71		1.10		0.24	
Fe(S)	1.55	277	1.08	193	1.70	304		
V_2O_5	0.04	2	0.05	3	0.04	2		
	100.68		100.30		100.02		100.37 (BaO = 0.12)	
Niggli numbers								
si	183		300		318		310	
ti	2.2		2.7		2.5		1.9	
al	36.1		35.9		36.3		35.8	
fm	41.2		37.0		34.8		41.2	
c	9.0		8.8		11.7		6.2	
alk	13.7		18.2		17.2		16.8	
k	0.48		0.43		0.30		0.52	
mg	0.46		0.46		0.46		0.38	
c/fm	0.22		0.24		0.34		0.15	
qz	+28		+127		+131		+143	
Mineral composition Volume percentage								
Quartz		26.8		38.3		34.7		
Plagioclase	An_{38}	33.2	An_{30}	30.5	An_{34}	34.0		
Potash-feldspar						1.0		
Biotite / Chlorite		36.0		22.9		25.2		
Muscovite				5.8				
Iron sulphides		1.6		1.1		1.9		
Graphite		1.2		0.5		0.8		
Ilmenite		1.0		0.9		0.9		
Accessories		0.2				1.5		
		100.0		100.0		100.0		

1. Phyllite, dark. Käsämä, Polvijärvi.
2. Phyllite, grey. Kihnamo, Sivinlampi, Polvijärvi. (The mineral composition is calculated from the analysis.)
3. Mica schist. Keretti shaft, Outokumpu.
4. Average chemical composition of mica schist, Southwestern Finland. Simonen (1953).

mica schist one nevertheless meets with a relict varved structure (Fig. 2), indicating the connection between the phyllites and mica schists and their similar depositional conditions.

The mica schists are rich in quartz and feldspar, while the amount of biotite is lower and that of plagioclase higher than in the phyllite formations. The mica schists consistently contain small amounts of almandine porphyroblasts, which indicates an Al_2O_3-excess in the original sediment. In texture they are grano-lepido-blastic, usually varved, medium-grained rocks, in which coarse-grained biotite occurs as flakes parallel to the schistosity. In the middle part of the Outokumpu zone, the schist becomes more homogeneous, and the varved structure becomes more difficult to detect.

The main minerals are quartz, plagioclase and biotite, which is in places chloritized. Sericitization can be observed in the plagioclase and its composition varies, according to the optical properties, from oligoclase to andesine. In the samples taken from Sola, on the eastern side of Viinijärvi, the anorthite content varies An_{20-30}, whereas in the specimen taken from the Keretti shaft of the Outokumpu mine it is An_{35} (Table I, No. 3). In addition to accessory almandine porphyroblasts, the schist contains some potash feldspar, ilmenite, apatite, sporadic sulphide grains (pyrrhotite) and magnetite. The graphite, which is to be seen occasionally in addition to the elongate ilmenite grains, occurs as inclusions in the cleavages of the mica or as scattered grains parallel to the schistosity.

The quartz veins, which are rather common in the mica schists of the area, occur as fissure fillings both parallel to the schistosity (Fig. 2) and transverse to it. Westwards, across the Outokumpu area, the quantity and dimensions of the veins, and the grain-size of the schist increase, so that the mica schist has become mica gneiss in the western and northwestern parts of the area. In addition, in the vicinity of Maarianvaara granite, the pegmatite veins become more common and the rock changes here into arteritic vein-gneiss.

In mineral composition the mica gneisses are similar to the mica schists. A reduction in the quantity of biotite is to be observed, while the feldspar correspondingly increases. The biotite also occurs in directions deviating from the plane of schistosity and around the zircon inclusions there are broad metamictic haloes. Although graphite occurs in only quite small quantities, it can be observed to occur consistently in mica gneisses as coarse, scattered flakes. In the phyllite area the grain size of the graphite ranges from 0.001 to 0.05 mm, whereas in the mica gneisses it varies between 0.02 and 0.1 mm. The accessory graphite and ilmenite grains are often orientated parallel to the schistosity unless replaced by the mica or other porphyroblasts. The same is to be said of the pyrrhotite, which is sometimes present.

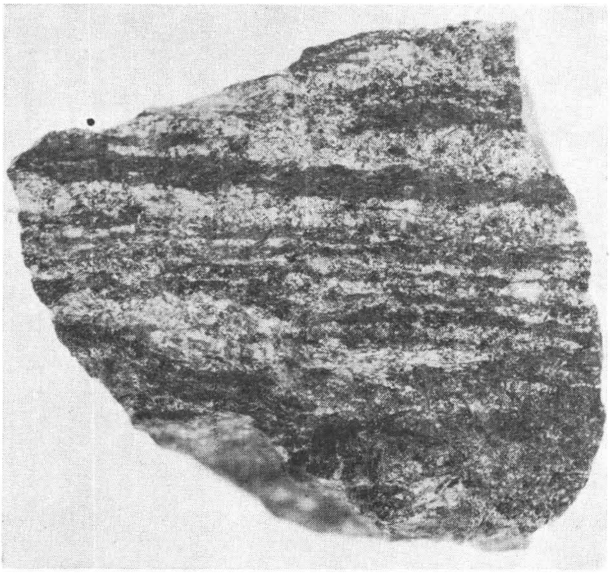

Fig. 10. Banded black schist composed of carbonaceous layers alternating with layers consisting chiefly of quartz and iron sulphides. Mulo, Pyhäselkä. 3 x.

The gradual change from phyllite first into mica schist and then into mica gneiss indicates that the mica schists and gneisses present highly metamorphozed varieties of the phyllitic schists. This is to be observed in the growth of the size of the grains as well as in the local preservation of sedimentogenic structures and textures. The chemical composition of the phyllites and mica schists varies within the same limits and indicates that they have been assembled from similar material. Further, the chemistry (excluding the carbon and sulphur contents) of the phyllites and mica schists compares fairly closely with the average composition of the Svecofennian mica schists (Table I, No. 4).

BLACK SCHISTS

The most characteristic feature common to all the black schists of the phyllite and mica schist area is their consistent content of graphite and sulphides. It is the feature that first strikes one in megascopic examination of the rock. As the name suggests, they are black in colour (in any fresh section) or greyish black, but on account of their sulphide content weathered surfaces tend to be rusty. Furthermore, they are stratified, with dark graphite-bearing layers alternating with coarse-grained, pale, often sulphide-bearing layers (Figs. 3, 10, 11, d Pl. V, a Pl. VI and b Pl. VIII). This is

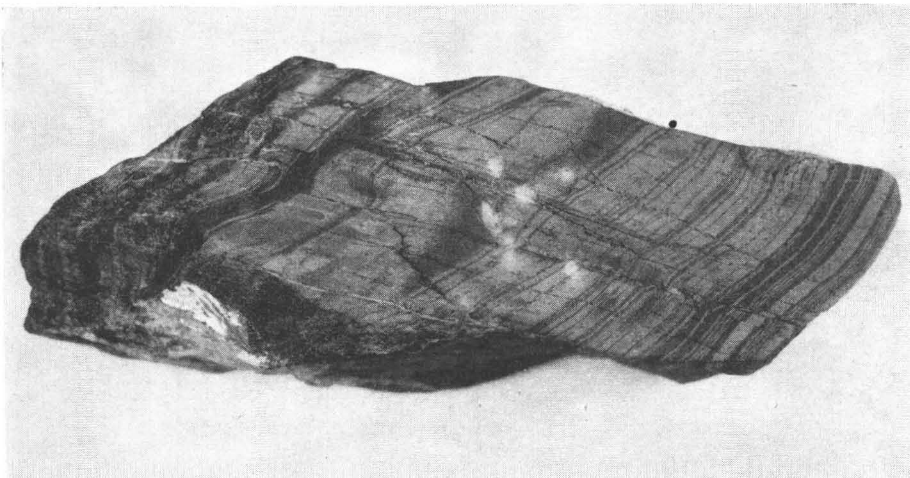

Fig. 11. Quartzitic carbon-bearing schist. The banding is caused by layers rich in pigmental carbon. Mulo, Pyhäselkä. Natural size.

more clearly visible in the less highly metamorphozed parts of the area, especially the phyllite area, and here the layers are observed to be consistently much thinner than those of the normal phyllites.

In regard to composition the graphite- and sulphide-bearing occurrences are mainly argillaceous schists, and in the better preserved parts there are observable structural features characteristic of pelitic sediments. In many places, amphibole-bearing black schists occur in association with black schist or as separate layers in phyllite, and these rocks are usually coarser in grain than the other graphite-bearing layers. In these, too, stratification occurs between the graphite-rich, fine-grained and the pale graphite-poor, coarse-grained layers (Fig. d, Pl. V). As mentioned previously there also occur in the schist area skarn mineral-bearing layers free from graphite. They considerably exceed in quantity the amphibole-bearing black schists and they are found interbanded with the phyllites, mica schists and quartzites. Coarse graphite- and sulphide-bearing amphibole-rich schists are generally called sheaf schists because of the mode of occurrence of the amphibole crystals. The passage from argillaceous black schists into varieties richer in quartz is gradual, being generally due to an increase of quartz in the coarser-grained parts of the schists. Locally certain dark quartzites contain some graphite, but frequently they are lacking in graphite and their colour is caused by a very fine sulphide or oxide pigment. Quartz-rich black schists occur as thin layers in the other schists of the area, especially in the quartzites and in the transition zones of these and the black schists.

The micaceous black schists, closely resembling clayey sediment in composition, will hereafter be called argillaceous, the amphibole-rich black schists calcareous, and the quartz-rich black schists arenaceous.

In connection with the petrographic descriptions, several of the most common minerals contained in black schists will also be described. Since the fine grain of the black schists as well as their abundant graphite pigment hamper the separation and identification of the minerals, the investigation has been confined principally to optical determinations of the silicate minerals mainly in the coarse-grained part of the schist and ore-microscopic examination of the opaque minerals.

Mr. Y. Vuorelainen of the research laboratory of the Exploration Department of the Outokumpu Company has carried out the separation of a number of minerals by means of Clerici solution and clarified certain fractions under a binocular microscope as well as determining the X-ray data for a number of minerals and the different modifications of the same mineral.

ARGILLACEOUS BLACK SCHISTS

Argillaceous black schists occur as thin layers or as thicker deposits in the phyllites or in their more highly metamorphic derivatives, mica schists and mica gneisses. They are in many places associated with thin quartzitic schists, which are often dark of colour and in places mica-bearing and impure. In the middle of the Outokumpu zone, where the amount of quartzites is greater, black schists are encountered in many places as bands in the quartzites. In these cases the marginal parts of the thicker black schist bands and all the thinner bands show gradations into varieties rich in quartz, which are often dark, mica-poor quartzitic schists containing sporadic graphite.

The passage into mica schists and quartzites is gradual, with the transitional zone ranging from a few centimetres to several metres. As the mica schist is approached, the most fundamental change is the gradual reduction of the graphite and sulphide contents, while the rest of the mineral constituents remain unchanged. As the black schist grades over into quartzite, the quartz content correspondingly increases. The gradation does not, however, take place evenly and many kinds of intermediate forms are met with in the transitional zone.

The thickness of the banding of the argillaceous black schists is considerably less than that of the carbon-free schists. This is most clearly evident in the less metamorphozed phyllite area. The thickness ranges from a few millimetres to several centimetres and in very carbon-rich parts only 1—3 mm.

The argillaceous black schists of the phyllite area with primary structures and textures represent the lowest grade metamorphism in the region. The banded structure consists of two kinds of layers, which differ both in grain size and mineral composition.

The mineral composition of the fine-grained layers is the same as in the phyllites. In addition to mica and quartz, they contain fine-grained graphite, whose grain size is about 0.001 mm. Its content varies in the analysed specimens from 2.0 to 7.5 % and occasionally it includes carbonaceous matter representing a lower degree of graphitization, as revealed by its optical properties and certain X-ray determinations. The mica is pale biotite and muscovite, and its grain size, like that of the quartz, ranges from 0.005 to 0.05 mm. Sphene is regularly met with as coarser grains parallel to the schistosity, their length being 0.05—0.3 mm; they are poor in graphite but do contain sulphide inclusions (pyrrhotite). The sphene is leucoxenic in character, for within it rutile or ilmenite is often met with as an inclusion. »Thucholite» grains are met with as accessory minerals in the form of spheroids whose diameter varies from 0.08 to 0.2 mm. Further comment on this topic will be made later in dealing with the opaque minerals. They often contain uraninite inclusions (Figs. c and d, Pl. I). Fine-grained sulphides are usually associated with the carbonaceous layers.

The minerals ordinarily contained in the coarse-grained layers are pyrite, potash feldspar, quartz and iron-poor biotite. Coarse-grained pyrite occurs in places as concordant concentrations (Fig. 3), whose thickness varies from 1 to 5 mm. Potash feldspar occurs as irregular bands of grains parallel to the bedding. The quartz without undulose extinction is accompanied locally by recrystallized plagioclase. The pale-coloured biotite flakes vary in length from 0.05 to 0.3 mm. They occur parallel to the schistosity like the pale amphibole, which is sometimes conspicuous in certain layers. Sphene is an accessory mineral enclosing microscopic pyrrhotite inclusions.

A fine-grained phyllitic black schist from the island of Kultakallio, in Lake Höytiäinen, has been analysed (Table VII, No. 7, p. 78); containing abundant pyrite, pale tremolite occurs locally in the coarser-grained layers. The sample represents the carbon-rich some amphibole-bearing part of the black schist and therefore differs from a typical clay in its chemical composition. Its Na_2O-content indicates that the schist contains a considerable quantity of plagioclase, which evidently is more common in the carbon-rich layers of the argillaceous black schists, but which cannot be identified on account of its fine grain. The sample was obtained from a black schist layer about 150 metres thick at the western margin of the phyllite area, from among layers poor in graphite and rich in quartz or amphibole.

In the argillaceous black schists occur gradual transitions into quartz-rich varieties. As the quartz content increases, the amount of graphite and

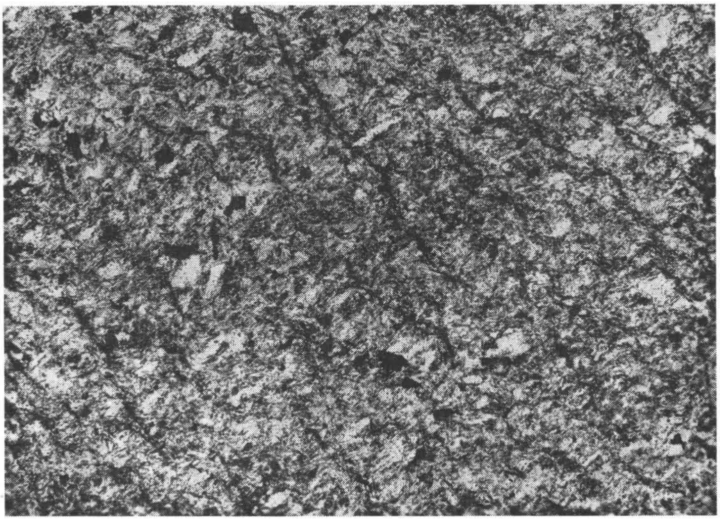

Fig. 12. Quartzose black schist including disseminated carbon. The schistosity shown by the mica flakes deviates from the bedding plane. Kultakallio, Polvijärvi. One Nicol. 16 x.

sulphides decreases more rapidly than the other constituents, as will be perceived from the chemical composition of the samples analysed (Tables VII and IX) and the al- (c + alk) diagram (Fig 41 p. 83). At the same time they alter into coarse-grained schists, which have been observed to be quite common in the graphite-poor schists elsewhere.

A quartz-rich portion of the carbon-bearing deposit of Kultakallio, with a graphite content of 2.0 % (Table VII, No. 13), has been analysed. On account of its lower content of carbon its bedding is not so well defined as in the varieties richer in carbon, which are distinctly finer in grain. However, it appears in thin section as a relict structure, the graphite pigment occurring parallel to the original bedding (Fig. 12). The thickness of the layers varies from 0.5 to 1.0 mm. The mica flakes, 0.02—0.2 mm in length, have crystallized parallel to the transversal cleavage.

In addition to quartz and mica, the rock contains an abundance of plagioclase, the anorthite content of which, calculated from the analysis, is about An_{50}. The grain size of the matrix formed by the plagioclase and the quartz varies from 0.02 to 0.4 mm. The mica is a pale biotite, whose $2V\alpha$ value and refractive indices indicate its phlogopitic composition (Table II, No. 5). The potash feldspar occurs as irregular grains and as fissure fillings. They exhibit grid twinning, and they are pigment-free, as is the quartz. Sphene (as leucoxene) occurs in the usual amount in the carbonaceous schists, the grain-size varying from 0.03 to 0.3 mm. It encloses fine-grained

Table II. Optical properties of biotite in different black schist modifications

	1	2	3	4	5	6	Measuring precision
$n\gamma$ Na	1.598	1.598	1.5985	1.597	1.5985	1.602	} ±0.001
$n\beta$ Na	1.597	1.597	1.597	1.596	1.597	1.602	
$n\alpha$ Na	1.565	1.566	1.566	1.564	1.565	1.559	±0.003
$n\gamma - n\alpha$	0.033	0.032	0.032	0.033	0.033	0.043	
$\gamma = \beta$	brownish yellow	pale br. yellow	———	yellowish	———	pale br. yellow	
α	colourless	colourless	colourless	colourless	colourless	colourless	
2 Vα	12°	13°	13°	11°	13°	5°	±1.5°

1. Quartz-rich argillaceous, phyllitic, black schist (Table VII, No. 14).
2. Gneissose calcareous black schist (Table VIII, No. 18).
3. Massive, argillaceous, graphite- and sulphide-bearing rock (Table VII, No .8).
4. Phyllitic argillaceous black schist (Table VII, No. 11).
5. Quartz-rich argillaceous black schist (Table VII, No. 13).
6. Argillaceous black schist (Table VII, No. 10).

pyrrhotite. Graphite pigment (about 0.001 mm) occurs in the rock in even quantities incorporating, however, mainly the plagioclase. Accessory minerals are apatite, muscovite, magnetite and sporadic corroded pyrite grains. Chalcopyrite occurs as microscopic inclusions in the pyrrhotite. The mineral composition calculated in the analysis is shown in Table VII, No. 13, p. 79.

The refractive indices are determined by the immersion method and the figures for 2 V α and $\gamma \Lambda c$ with the U-stage by Mr. H. Papunen.

According to Winchell (1956 p. 374), the micas investigated are rich in magnesium between phlogopite and eastonite in composition, being closer to the former.

The argillaceous graphite- and sulphide-bearing occurrences of the Solansaari—Viitalampi zone resemble in many respects the black schists of the phyllite area described above. Here too the coarse pyrite grains occur in places as conformable concentrations, while potash feldspar occurs alongside the quartz as irregular grains parallel to the bedding and as fissure fillings in the coarser parts of the schist. The layers richer in carbon have preserved their fine grain, but the paler layers are nearly as coarse- grained as the mica schists of the zone.

In addition to the quartz, pale biotite and graphite pigment (0.001—0.05 mm), limited amounts of pigment-free sphene, fine-grained sulphides and fairly large ilmenite grains occur in the fine-grained layers. The mica flakes and the sphene grains are parallel to the bedding, but the coarser (0.02—1.0 mm) ilmenite grains have a random orientation and are apparently detrital grains of the original sediment. Locally one can notice plagioclase in the quartzrich graphite-bearing layers as nebulous grains, indicating recrystallization, but in the carbon-rich parts this does not appear.

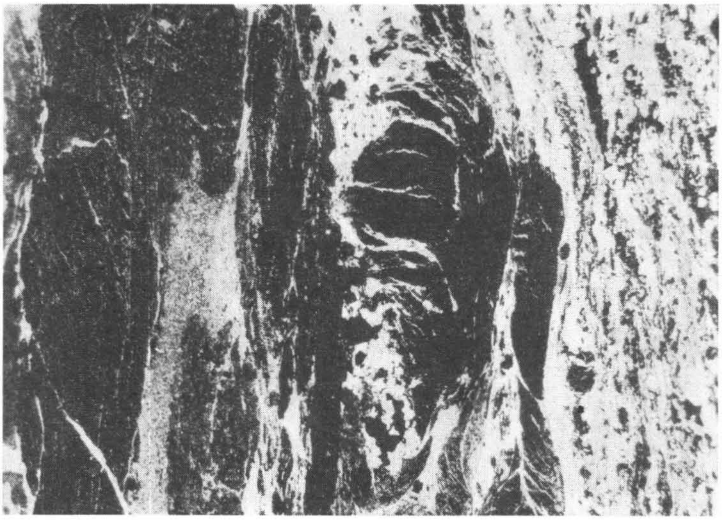

Fig. 13. Sheared contact between fine-grained and coarse-grained layers in phyllitic black schist. Suopolvi, Polvijärvi. One Nicol. 16 x.

Quartz and biotite comprise the main part of the coarse-grained, graphite-poor layers, in which the coarse sulphide material consists of pyrite; recrystallized plagioclase and, locally, potash feldspar occur as fissure fillings. The quartz occurs as irregular grains, which in places form lenticular aggregates. These, like the Fe-poor, long, coherent biotite seams or smaller flakes run parallel to the schistosity. The grain-size of the quartz and the mica varies from 0.1 to 1.0 mm. The biotite porphyroblasts are observed in places to contain pelitic parts of the schist as inclusions.

The composition of the plagioclase is, according to its optical properties, An_{30-45} and the Fe-poor biotite is a phlogopitic, magnesium-rich mica (Table II, No. 1).

The sample from the middle part of the Solansaari—Viitalampi zone on the north side of Lahnajärvi (Table VII, No. 12, p. 79) is a fine-grained schist rich in carbon and sulphides, and in structure it resembles the argillaceous black schists of the phyllite area. The coarse pyrite grains, which occur here, too, parallel to the bedding, often begin to be replaced by pyrrhotite, and in many places miniature folding or shearing occurs in the schist, especially between the fine- and coarse-grained layers (Fig. 13).

The samples analysed from the southern part of the zone, at Solansaari, and from the northern part, in the vicinity of Viitalampi, (Table VII, Nos. 11 and 14, p. 79) represent carbon- and sulphide-poor varieties of argillaceous black schists. Moreover, they are coarser in grain, thus again illustrating

Fig. 14. Fine-grained layers rich in graphite (including a pale-coloured biotite porphyroblast) alternating with layers consisting of chloritized biotite, quartz and sulphides. Drill hole KT 11, 210 m, Outokumpu. One Nicol. 16 x.

the marked relationship between the carbon content and degree of coarseness of black schists.

Both samples are coarser in grain and poorer in carbon than usual, the quartz grains varying from 0.01 to 0.5 mm and mica from 0.05 to 0.1 mm. Also the grain-size of the graphite has increased, being here about 0.01 mm. An appreciable part of the mica, the sulphides and the elongated quartz grains are orientated parallel to the graphite-rich layers. The plagioclase is clouded by pigment, but the carbonaceous matter has either been thrust aside by the pale biotite or has been left within the crystal inclusions. According to the U-stage and refractive index determinations, the mica is iron-poor, phlogopitic (Table II, Nos. 1 and 4). In the Solansaari occurrence the pale biotite occurs as porphyroblasts, in which graphite pigment, fine sulphide grains, quartz, and occasional sphene and potash feldspar occur as inclusions. The porphyroblasts are not always parallel to the schistosity.

In the coarse-grained parts of the schist there occur recrystallized, clear plagioclase porphyroblasts, whose anorthite content, according to the optical properties, varies An_{25-35}. Potash feldspar is met with as fissure fillings. Sulphides do not occur as coherent elongated concentrations parallel to the bedding, as in carbon-rich schists, but are evenly distributed. Pyrrhotite comprises a prominent part of the sulphides. Pyrite forms scattered cubes.

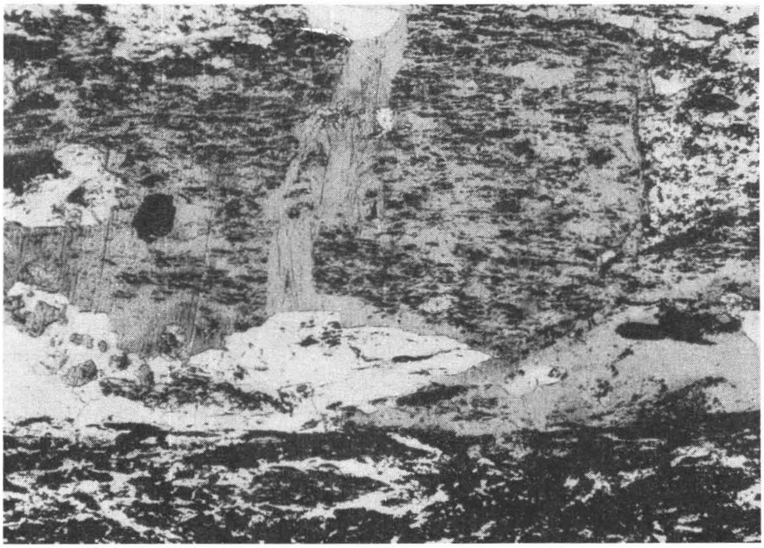

Fig. 15. Graphite as helicite texture in a large porphyroblast of biotite belonging to the coarse- grained layer of the black schist. Drill hole Oku 129, 48 m, Sukkulansalo, Kuusjärvi. One Nicol. 50 x.

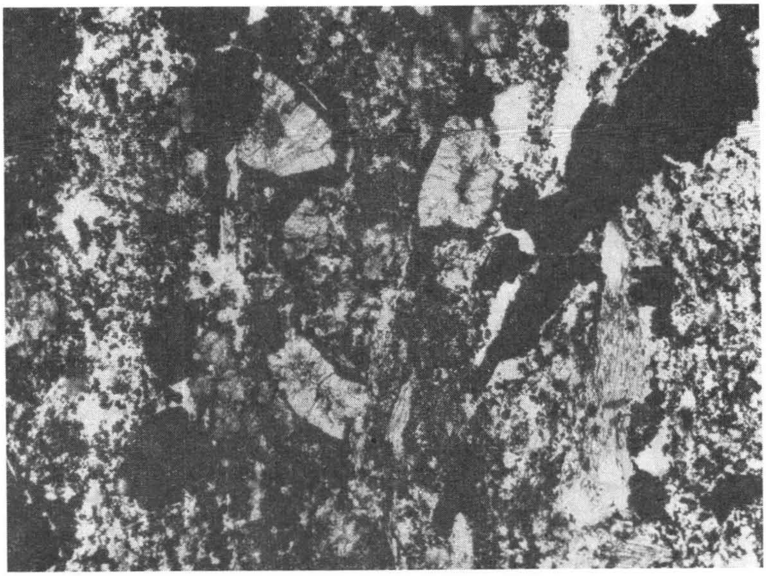

Fig. 16. Porphyroblast of andalusite with carbon pigment (chiastolite) in argillaceous black schist. Drill hole K 323, 12 m, Outokumpu mine. One Nicol. 30 x.

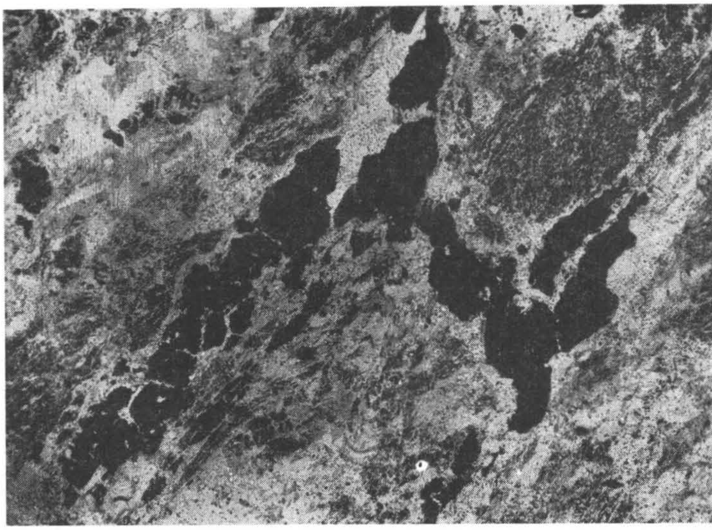

Fig. 17. Veinlets of pyrrhotite in argillaceous black schist rich in mica. Drill hole Oku 129, 48 m, Sukkulansalo, Kuusjärvi. One Nicol. 16 x.

In regard to mineral composition, the mica-rich argillaceous black schists of the Outokumpu zone resemble those described above, but differ from them in texture. The strong recrystallization and deformation, which have destroyed the varved structure and, in the western parts, also the bedded structure of the mica schist formation, can be seen also in the carbon- and sulphide-bearing schists of the zone. The argillaceous black schists of the northeastern and middle parts of the zone are still in many places bedded; this is particularly true of the carbon-rich varieties, which most commonly have best escaped the metamorphic effects (Fig. 14); however in the southwestern parts of the zone the black schists grade into highly metamorphozed, gneissose schists. All that remains of the bedded structure here are parallel, deformed rows of graphite grains, which have been preserved in the plagioclase and biotite porphyroblasts as a helicitic texture (Fig. 15).

In the graphite-rich layers of the argillaceous black schists, one often sees plagioclase porphyroblasts in which the other components of the originally fine-grained layer, fine-grained graphite (0.001—0.01 mm), quartz, mica, sulphides and the accessory minerals, sphene and apatite, are present as inclusions. Chalcopyrite, sphalerite as well as »thucholite» are often observed under the microscope. The sphene often contains inclusions of ilmenite, and sometimes rutile (Fig. a, Pl. I). In the fine-grained layers of the highly metamorphozed carbon- and sulphide-bearing schists and para-

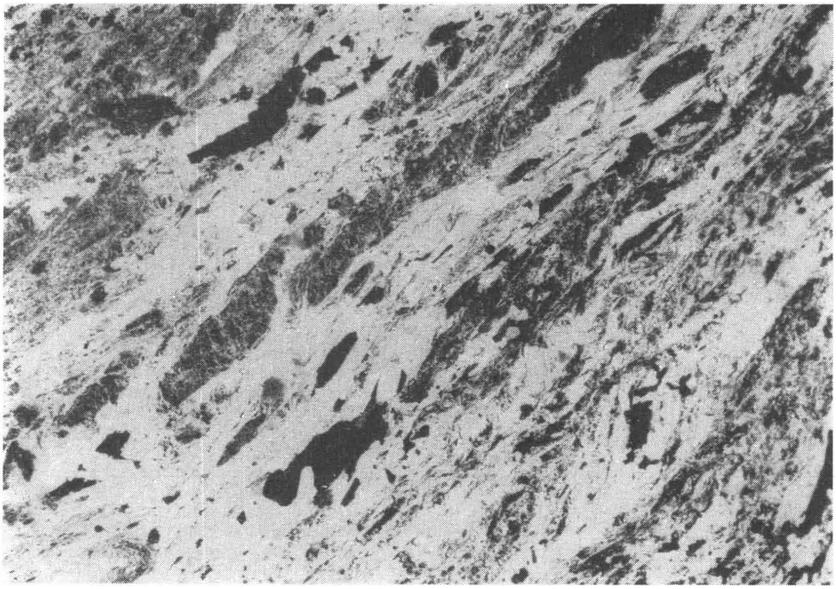

Fig. 18. Recrystallized argillaceous black schist with coarse-grained, micaceous layers alternating with brecciated, fine-grained layers rich in carbon. Suopolvi, Polvijärvi. One Nicol. 21 x.

gneisses one also finds andalusite as porphyroblasts (Fig. 16), revealing an Al_2O_3-excess in the original clayey composition. The andalusite is often poorer in pigment than the environment, and Vähätalo (1953) has mentioned andalusite as occurring in the Outokumpu area in exactly this type of black schist.

In the coarse-grained, pale layer of the black schists the main minerals are quartz, mica, plagioclase and potash feldspar. This part includes the bulk of the sulphides of the black schists. In the more highly metamorphozed argillaceous varieties the obliteration of the bedded structure, due to the mobilisation and recrystallization of the sulphide followed by the mica, is quite common; it begins in the carbon-poor, coarse-grained layers and extends into the carbon-rich layers (Figs. 17 and a, Pl. VII).

As recrystallization advances, mica is met with as well as plagioclase, often as two separate generations, of which the older contains abundant pigment. Of these, the older biotite, which is usually richer in iron than the younger, generally occurs parallel to the original bedding, shown by the helicitic texture of the graphite pigment contained in it (Fig. 15). The younger mica and the plagioclase are clear and have grown in random orientation with the phlogopitic, pale biotite replacing the older, pleochroic mica and the plagioclase. The younger plagioclase, potash feldspar and

Table III. Phlogopite (Table VII, No. 10)

	1	1 a				Theor.
	%	%	Mol. prop.	Atomic prop. (O = 24)		
SiO_2	42.00	42.93	7 155	Si 6.1	} 8.0	8
TiO_2	2.00	—	—	Al 1.9		
Al_2O_3	19.92	21.09	2 068			
V_2O_5	0.35	0.37	20			
Fe_2O_3	—	—	—	Fe^{3+}		
FeO	2.57	2.72	378	Fe^{2+} 0.3	} 6.1	6
MnO	0.10	0.11	16	Al 1.6		
MgO	18.77	19.88	4 970	Mg 4.2		
CaO	1.56	0.21	38			
BaO	—	—	—			
Na_2O	1.33	1.41	227	Na 0.4	} 2.1	
K_2O	8.82	9.34	994	K 1.7		2
F	0.09	0.10	53			
Cl	—	—	—			
H_2O+	1.74	1.84	1 022	H 1.7		4
	99.25	100.00				

1. Chemical composition, 1 a. Recalculated composition (excluding sphene).

sulphides occur as fissure fillings. The composition of the plagioclase varies according to the optical properties An_{40-50} and the paler biotite is phlogopitic (Table II, No. 6).

Locally certain argillaceous black schists contain carbonate-bearing bands, in which amphibole porphyroblasts occur. These likewise replace the other minerals of the schist, destroying the primary structure. It is the recrystallization of the amphibole and the mica, together with the mobilisation of the abundant sulphidic matter, that destroys the original sedimentogenic structure of the schist, which in the end remains only as parallel rows of graphite grains.

The samples analysed from the northeastern part of the zone, at Sukkulansalo, and in its middle part, at Outokumpu, (Table VII, p. 78—79, Nos. 9 and 10) are similar in structure and mineral composition. They are mica-rich, argillaceous schists, in which the bedded structure is disappearing (Fig. 18). They contain an abundance of potash feldspar (8.7—10.2 %), and that which occurs as fissure filling is clear and exhibits a grid twinning. The anorthite content (An_{40-50}) of the plagioclase, the abundance of the mica (about 20 %), and the local occurrence of tremolite and carbonate are indicative of the abundance of magnesium and calcium. The sulphidic matter consists of pyrrhotite, and, in addition to the accessory pyrite, there is a little chalcopyrite and sphalerite.

From an argillaceous black schist in the middle part of the Outokumpu complex (Table VII, No. 10), an iron- poor magnesium mica has been separated and analysed (Table III). It contains more aluminium and less mag-

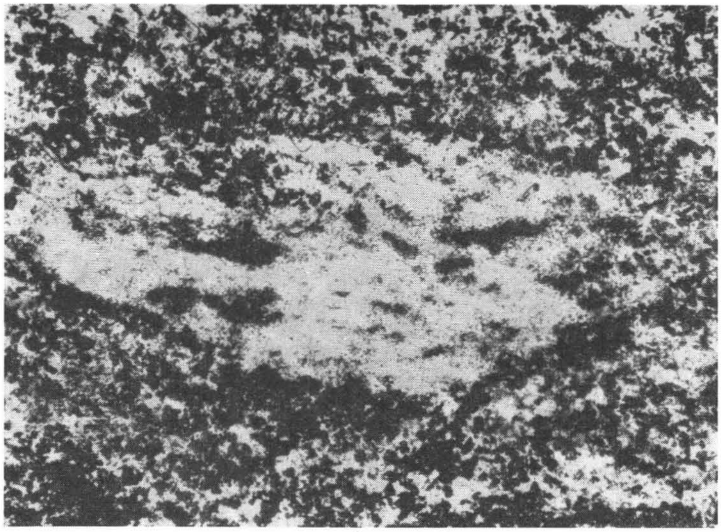

Fig. 19. Pale-coloured porphyroblast of biotite displaces disseminated carbon and sulphides. Part of Fig. 20. One Nicol. 50 x.

nesium than the phlogopite of Kuusamo analysed by Lokka (1943). The chemical composition of the mineral and its optical properties (Table II, No. 6) are in harmony and indicate that the mica is Mg-rich phlogopite. Its chemical formula is close to $(K, Na)_2Mg_3Al\,(OH)_2\,Si_6\,Al_2O_{22}$.

In the argillaceous black schists rich in quartz the grain size varies according to the graphite content. Those richest in carbon are the finest grained black schists in the entire Outokumpu zone, being in places phyllitic and the primary varving is best preserved. As the carbon content decreases, the grain size of the rock increases. The fine-grained, carbon-bearing layers of the schist alternate with layers coarser in grain and richer in sulphide. On account of the strong recrystallization the bedding, however, is not always as regular as in the phyllite area.

The chief minerals of the carbon-bearing, fine-grained layers are quartz and plagioclase, whose anorthite content varies and is oligoclase in the varieties rich in quartz. In the matrix formed by these minerals a certain relationship has been observed between the quality and quantity of the mica and the iron sulphides. The mica-poor layers contain principally pyrite, while the mica is very pale and phlogopitic, whereas in the layers rich in mica there is an abundance of pyrrhotite, while the iron content of the mica varies. In the sulphide-poor, mica-rich bands the mica is a biotite rich in iron. In carbon-poor parts the biotite forms porphyroblasts parallel to the bedding, and these have often displaced the graphite (Figs. 14 and 19), but in the

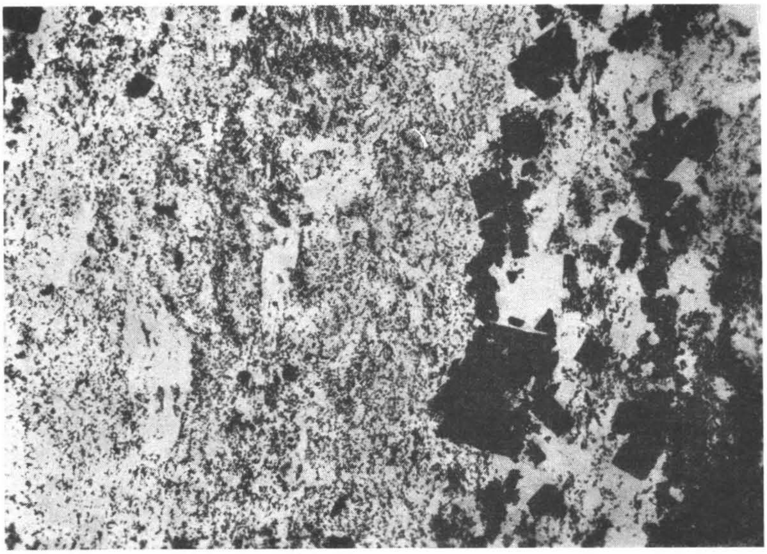

Fig. 20. Quartzose black schist with a fine-grained layer rich in carbon and a coarse-grained layer rich in pyrite, quartz and microcline. Biotite flakes parallel to the schistosity. Outokumpu, the hanging wall complex. One Nicol. 16 x.

carbon-rich varieties the mica remains fine in grain. The carbonaceous matter consists of flaky graphite, whose grain size varies considerably (0.002—0.1 mm), evidently as a result of the different degrees of metamorphism in the different parts of the schist sequence. Ilmenite, sphalerite and chalcopyrite are found as accessories. There is a small amount of sphene, which is totally lacking in the quartz-rich bands. »Thucholite» is often present in small quantities.

The carbon-poor coarse-grained layers contain mainly quartz, potash feldspar and iron sulphides. The potash feldspar and sulphides form rows of grains parallel to the schistosity (Figs. 20, 21 and 22). The mica-poor, quartz-rich argillaceous varieties contain only pyrite, in the form of euhedral grains. In the varieties rich in mica there are coarse-grained mica flakes parallel to the schistosity and plagioclase occurs locally.

In addition to recrystallization, the powerful effects of movements are especially well seen in the black schist horizons. This takes the form of miniature folding in the graphite-rich layers, although it cannot be detected in the carbon-free, coarse-grained interbedded layers (Fig. b, Pl. V). In the sheared, carbon-free bands, there are present more than normal abundances of sulphides, in addition to the larger quartz and potash feldspar grains. This indicates the concentration of siliceous and sulphidic matter particularly in the shearing zones of the black schists (Figs. 3, 22, 31, p. 63 and 37, p. 74).

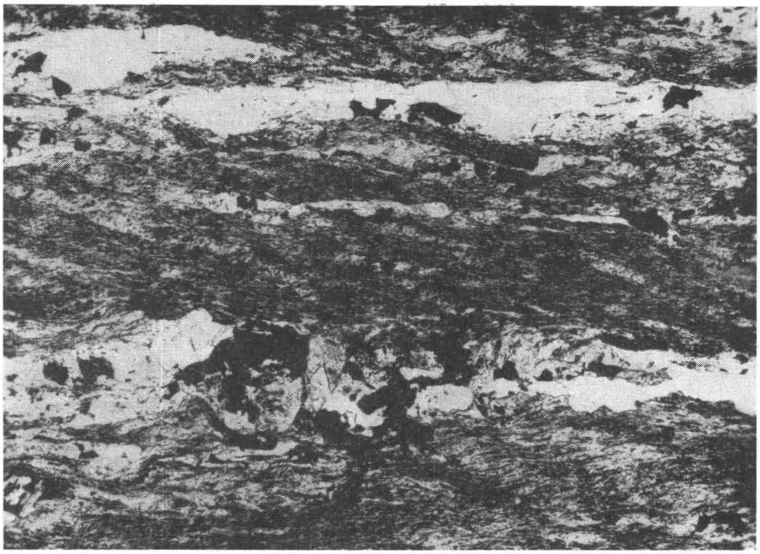

Fig. 21. Banded black schist. Part of Fig. 10. One Nicol. 16 x.

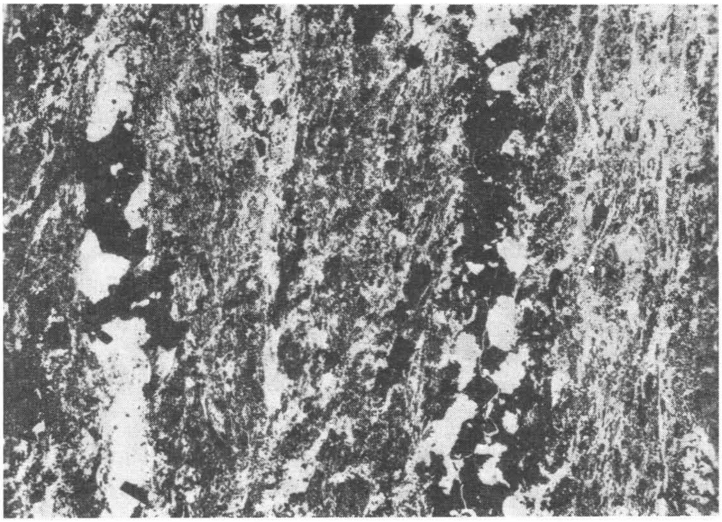

Fig. 22. Thin, coarse-grained quartzose pyritiferous layers alternating with pelitic layers, which consist of (disseminated) carbon, feldspar, sulphides and biotite. Drill hole 104 a, 205 m, Outokumpu. One Nicol. 16 x.

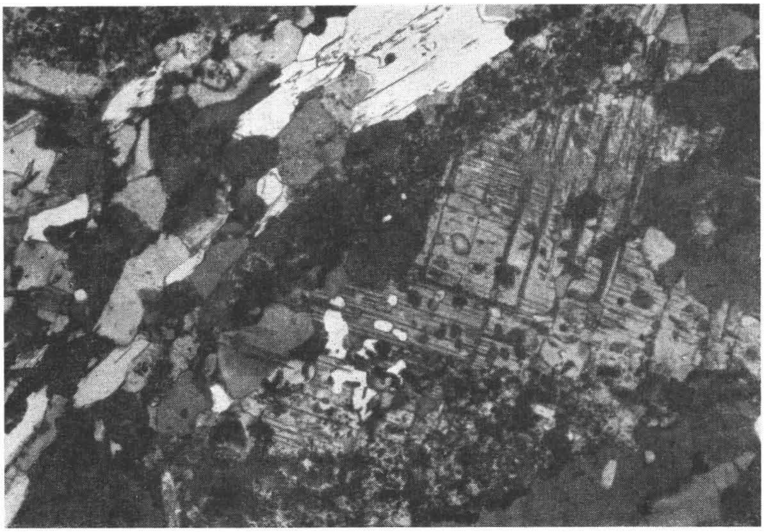

Fig. 23. A porphyroblast of plagioclase enclosing rounded inclusions of quartz and potash feldspar, and bordered by disseminated graphite and iron sulphides. Massive variety of black schist. 200 m NW of Lake Palolampi, Luikonlahti, Kaavi. Two Nicols. 50 x.

As the deformation proceeds, the structures in the mylonitic parts of the black schists begin to disappear, with the uncrushed parts of the carbon-rich layers appearing as scattered eyes in the matrix (Fig. b, Pl. VI). Here the mica and the quartz are recrystallized into twisted patches, while the pyrrhotite and often also the pyrite occur as fissure and fracture fillings in the schist — sometimes as quite thick veins and concentrations (Figs. a, Pl. V; c, Pl. VI and a, Pl. VII). In many places both sphalerite and chalcopyrite may be observed megascopically associated with the coarse-grained pyrrhotite. Secondary alteration is to be noticed in the minerals of the deformed and folded portions of the black schist. The pigment-rich plagioclase porphyroblasts are often sericitized, locally containing muscovite grains.

Between the quartzite-serpentinite formation and the underlying mica gneiss area in the vicinity of the Luikonlahti ore deposit, there occurs a graphite- and sulphide-bearing schist zone about 100 metres thick. This varies in composition and structure and is penetrated in many places by the late-orogenic Maarianvaara granite. This and the black schist zone situated in the upper part of the quartzite-serpentinite complex are closely associated with the mica gneiss formation, and in structure they resemble the strongly metamorphozed parts of the Juojärvi—Haapovaara or Outokumpu zone.

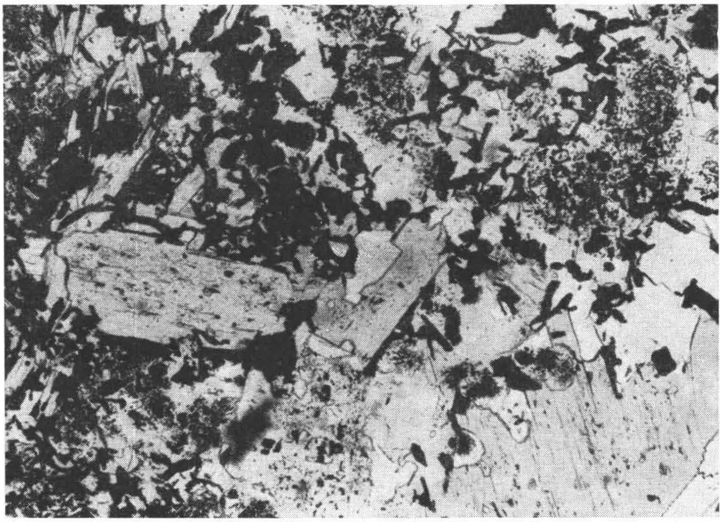

Fig. 24. Granoblastic black schist with pigment-free non-oriented porphyroblasts of biotite. Argillaceous, massive variety. Drill hole R 50, 54 m, Luikonlahti, Kaavi. One Nicol. 50 x.

The influence of the nearby Maarianvaara granite is to be seen especially clearly in the argillaceous, mica-rich varieties of the black schists, which, at the contact with granite grade into coarse-grained, non-orientated, structurally massive rock, in which schistosity occurs only locally.

This massive type of schist is presented in microphotos 23, 24, 26 and 34, p. 71 Neither its mineral nor its chemical composition appreciably deviates from that of the black schists previously descriped (Table VII, No. 8, p. 78). The chief minerals are plagioclase (according to the optical properties An_{35-50}), quartz and mica. The graphite and iron sulphide contents vary, and in addition to them potash feldspar and tremolite occur locally, with sphene as an accessory. Of the original structure of the rock there remain as relicts only isolated, fine-grained pigment layers, which are to be seen occasionally in plagioclase porphyroblasts (Fig. 23) of varying size (0.5—2.0 mm). In addition to abundant sulphidic and graphitic matter, they contain as inclusions quartz, mica, potash feldspar and sphene; the mica occurs in larger grains than the others, which vary from 0.005 to 0.05 mm.

The plagioclase porphyroblasts are in places epidotized and sericitized, and between them and the biotite porphyroblasts, the sulphidic matter and the quartz grains, are found the largest graphite flakes (0.1—0.3 mm), and local potash feldspar and sphene. The pale phlogopitic biotite (Table II, No. 3) is free from graphite and part of the sulphides remain in its cleavages. The borders of the mica against the sulphides are often pale and chloritized. The sulphidic matter is principally pyrrhotite, with pyrite occurring only locally as corroded grains. Inside the pyrrhotite can be seen chlorite, quartz, sphene, tremolite and fuchsite as minute inclusions. The grain size of the quartz varies according to the amount and the grain size of the associated graphite (Fig. 24). Potash feldspar and clear plagioclase occur to a limited extent as fissure fillings. Andalusite porphyroblasts are met with locally. The sphene forms large, irregular porphyroblasts and apatite, tremolite, chalcopyrite, sphalerite, »thucholite» and magnetite are the most significant accessories. Rutile and ilmenite occur as inclusions in the sphene (Fig. a, Pl. I).

The inclusions in the plagioclase and biotite porphyroblasts are conspicuously smaller in grain size than the matrix between them. It is noteworthy that the main part of the carbon of the schist occurs in a fine-grained form in the plagioclase porphyroblasts. The graphite flakes occurring outside the porphyroblasts are invariably coarser in grain.

The sulphidic matter occurs in many places in an exceedingly coarse-grained form, constituting irregular fissure fillings. In the thickest pyrrhotite veins, euhedral pyrite is often present, together with sphalerite and chalcopyrite which are locally visible megascopically.

A sample from a massive graphite- and sulphide-bearing part of the Luikonlahti schist formation has been analysed (Table VII, No. 8, p. 78) and its mineral composition determined by means of the integration stage. The rock contains a small amount of tremolite, differing in this respect from the typical argillaceous black schist. The Niggli-values of the sample exhibit a similarity to other argillaceous, mica-rich black schists, as will be seen from their al- (c + alk) diagram (Fig. 41, p. 83).

The quartz-rich varieties in the region are schistose and in structure and mineral composition are like those described earlier. Recrystallization has, however, developed farther here, and the grain size is coarser. The grain size of the quartz, anorthite-poor plagioclase (An_{30}) and the mica varies from 0.02 to 3.0 mm, and the graphite is as coarse as in the argillaceous varieties.

CALCAREOUS BLACK SCHISTS

In the lower part of the phyllite area, nearer the gneissose granite basement, amphibole-bearing bands are to be seen in many places in the schist formation. They frequently contain graphite and sulphides and in such cases they are closely associated with the other carbon- and sulphide-bearing schists of the area.

In the calcareous black schists the amphibole usually occurs as porphyroblasts orientated parallel to the bedding, and graphite pigment has been preserved as helicitic structures (Fig. 25). The amphibole is quite pale, often

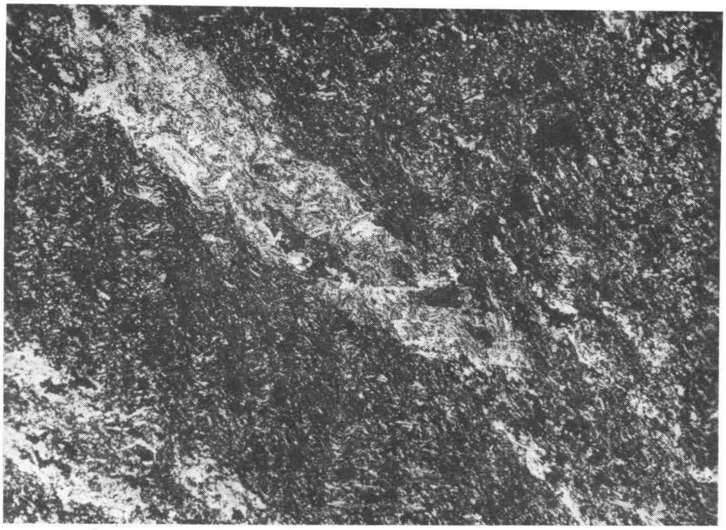

Fig. 25. Microfolded carbonaceous black schist with pigment-bearing porphyroblasts of amphibole parallel to the bedding. Kultakallio, Polvijärvi. One Nicol. 16 x.

colourless, but on account of its graphite pigment it appears almost black when viewed megascopically. The amphibole is close to tremolite in its optical properties. These differ from one another only very slightly in the amphibole-rich black schists in the various parts of the investigated area (Table IV).

When occurring most abundantly, the amphibole porphyroblasts form bands varying in thickness and alternating with the fine-grained phyllite layers. The sulphidic matter occurs mainly in the more coarse-grained and the carbonaceous matter in the fine-grained, amphibole-bearing layers. As the

Table IV. Optical properties of the colourless amphibole in some black schists

N:o	Refractive indices					$\gamma \Lambda C$
	$n\alpha$	$n\beta$	$n\gamma$	$n\gamma - n\alpha$	$2 V\alpha$	
1	1.605	1.618	1.630	0.025	80°	16.5°
2	1.606	1.620	1.632	0.026	80° (±2°)	16.0°
3	1.609	1.623	1.634	0.025	78°	15.5°
4	1.615	1.628	1.639	0.024	78°	16.0°

1. Calcareous black schist. Matovaara, Outokumpu, drill core 112 a.
2. Argillaceous black schist. Phyllite area, Mulo, Pyhäselkä.
3. Calcareous » » Outokumpu mine.
4. Calcareous » » (Table VIII, No 16).

The values of the refractive indices were determined by the immersion method and the figures for $2 V\alpha$ and $\gamma \Lambda C$ on the U-stage (Na-light) by Mr. H. Papunen.

Fig. 26. Non-oriented porphyroblasts of tremolite in black schist rich in amphibole and pyrrhotite. Drill hole R 50, 30 m, Luikonlahti, Kaavi. One Nicol. 12 x.

degree of calcareousness increases, the schists contain carbonate, while the large amphibole porphyroblasts begin to crystallize in random orientation. As the degree of metamorphism increases, the original bedding begins to disappear; also as the amphibole content increases, the rock undergoes a change into amphibole schist (Fig. 26). In such amphibole-rich varieties the coarse tremolite porphyroblasts usually occur as sheaf-like clusters, which has led to the term »sheaf» schist.

The main constituents of the coarse-grained amphibole layers are a pigment-rich, pale amphibole, potash feldspar and sulphides (pyrrhotite). Carbonate and sphene occur in places. Potash feldspar fills the interstices, together with sulphidic and carbonaceous matter. It should be noted that the sulphides consist in general of pyrrhotite in the amphibole-rich schists. Pyrite occurs only sporadically as corroded, scattered grains.

In texture and partly in mineral composition the layers rich in carbon are phyllitic. Under the microscope one observes that the fine-grained, pale-coloured biotite and amphibole, as well as the muscovite and pyrrhotite grains are orientated parallel to the bedding, and in many cases adhere to the miniature folding of the schist. The pigment consists of an exceedingly fine-grained graphite (0.001—0.005 mm). Locally there occurs carbonate, potash feldspar ,plagioclase and quartz, the last-mentioned being hard to identify in the fine-grained layers. The quartz content, however, is

Table V. Tremolite from the calcareous black schist, Mulo, Pyhäselkä

	1	1 a					Theor.
	%	%	Mol. prop.	Atomic prop. (O = 24)			
SiO_2	51.70	56.43	9 405	Si	7.8		
TiO_2	0.27	0.30	37	Ti	—	8.0	8
Al_2O_3	3.39	3.70	363	Al	0.2		
Fe_2O_3	1.35	0.94	59	Al	0.4		
FeO	0.05	0.05	7	Fe^{3+}	0.1		
MnO	0.05	0.05	7	Fe^{2+}	—	5.2	5
MgO	20.94	22.86	5 715	Mn	—		
CaO	14.25	13.27	2 370	Mg	4.7		
Na_2O	1.04	1.13	182	Ca	2.0		
K_2O	0.31	0.34	36	Na	0.3	2.4	2
H_2O+	0.60	0.66	367	K	0.1		
F	0.25	0.27	142	H	0.6		
Cl	0.01	—				0.7	2
C	3.95	—		F	0.1		
CO_2	1.64	—					
P_2O_5	0.02	—					
S	0.21	—					
	100.03	100.00					

1. Chemical composition. 1 a. Recalculated composition (excluding graphite, pyrrhotite and calcite).

small. The grain size of the mica varies from 0.01 to 0.1 mm, whereas the tremolite prisms are longer. Sphene occurs as a constant accessory and is highly pleochroic: α = nearly colourless, β = pale brownish yellow and γ = brownish red.

An amphibole-rich black schist layer has been analysed from Mulo, in the southern part of the phyllite area, (Table VIII, No. 15, p. 80); in addition to pale, pigment-rich amphibole, it contains potash feldspar, plagioclase, carbonate and sulphides with very pleochroic sphene as an accessory. The amphibole forms large porphyroblasts, while the other minerals of the schist, including the sulphides, occur as inclusions or fissure fillings. Locally one can see carbonate forming discontinuous layers. Quartz is generally lacking or occurs, like the pale mica, only sporadically. The sulphidic matter is here, too, exclusively pyrrhotite and in places it forms with graphite parallel rows of grains. This constitutes the only surviving primary structure, which is in many cases on the verge of disappearing.

From an amphibole-rich black schist in the phyllite area (Mulo, Pyhäselkä), tremolite has been separated by means of Clerici solution. Its chemical composition is given in Table V, column 1.

The impurities occurring in the sample as inclusions, graphite, pyrrhotite (determined from polished section) and calcite (X-ray determination), have been subtracted from the analysis figures and the balance has been recalcu-

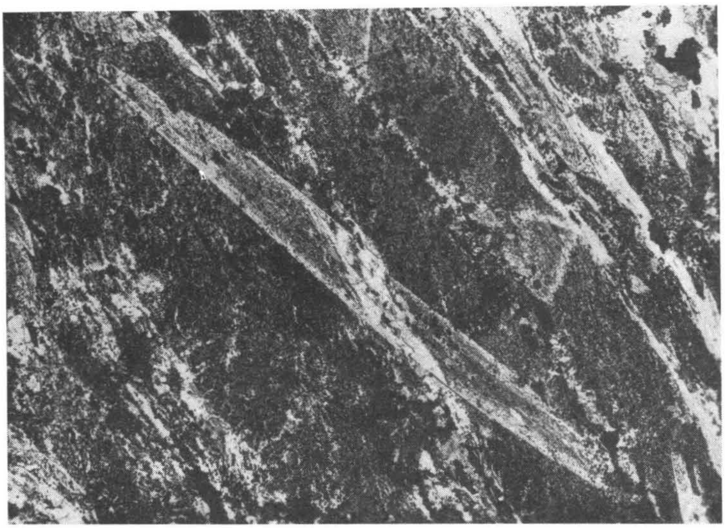

Fig. 27. Stratified calcareous black schist with slender porphyroblasts of amphibole. The margins of the amphibole prisms are free from disseminated carbon. Drill hole 112 a, 639 m, Matovaara, Outokumpu. One Nicol. 16 x.

lated to a hundred (Table V, column 1 a). The chemical composition of the mineral agrees well with the optical properties. The composition and optical properties of the amphibole indicate that it is a common hornblende, according to Winchell's (1956 p. 431) classification. Its low iron and aluminium as well as high MgO- and CaO-contents are characteristic of tremolitic Mg-amphibole.

In the eastern part of the mica schist formation, on the eastern side of Viinijärvi, the skarn layers are similar to the corresponding formations in the phyllite area, but in the western part, in the Outokumpu zone, the thickness of the layers increases and in addition to the amphibole, as Väyrynen (1935) states, one meets increasing quantities of diopside. This is to be seen especially in the middle part of the zone nearer the quartzite-serpentinite complex at Outokumpu. The skarn mineral-bearing rocks are locally graphite- and sulphide-bearing and the thicker ones are associated in many instances with other carbon-bearing formations. An analysis of such a sample is given in Table VIII, No. 17, p. 80.

In the less metamorphozed parts of the mica schists area, in both the Solansaari—Viitalampi and Outokumpu zones, the calcareous black schists have often preserved their bedded structure. In their fine-grained, graphite-rich parts, the tremolite prisms do not occur parallel to the bedding, as was observed in the phyllite area, although the large porphyroblasts, which

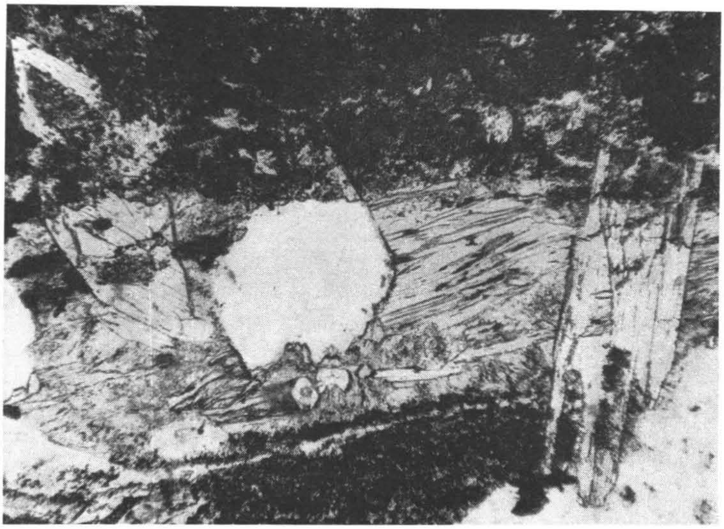

Fig. 28. Coarse-grained micaceous layer in fine-grained calcareous black schist. Porphyroblasts of amphibole at random. Drill hole 112 a, 639 m, Matovaara, Outokumpu. One Nicol. 50 x.

locally grow through into the coarse-grained layers, may tend to do so. In a specimen taken from Matovaara in the Outokumpu mining area, the graphite pigment parallel to the original bedding is to be seen as a helicitic texture in the porphyroblasts, which cut across the primary structure, while graphite pigment is lacking from the tremolite individuals when these are in the coarse-grained layer (Fig. 27).

The fine-grained layers, in addition to the amphibole, usually consist of a fine-grained matrix containing sericitized plagioclase and a little quartz, in which graphite (0.003—0.1 mm) and sulphide grains occur orientated parallel to the bedding. Highly pleochroic sphene is locally abundant. Accessories are potash feldspar, pale brown biotite and carbonate which also occurs as inclusions in the sulphides.

The coarse-grained, graphite-free layers consist principally of tremolite (Table IV, No. 4), potash feldspar and sulphides. The large tremolite porphyroblasts are only partially orientated parallel to the layer, many individuals having crystallized randomly (Fig. 28). The potash feldspar fills the interstices together with the sulphides. The sulphides usually consist of pyrrhotite, which along with the local pale-brown biotite occurs in rows parallel to the schistosity. Carbonate occurs in the parts rich in amphibole and, according to the X-ray data, is in many cases calcite. In addition to the accessory, highly pleochroic sphene, it is possible to detect microscopically apatite, chalcopyrite and sporadic occurrences of pyrite, sphalerite and »thucholite».

In the most highly metamorphozed parts of the mica schist area the sheaf schists are coarse in grain-size. Frequently, only isolated deformed portions are left of the primary structures. The plagioclase, surviving as relicts in the fine-grained parts, is strongly sericitized and contains fine-grained graphite pigment. The biotite in the western part of the area is very pale and often chloritized. At the same time, it is clearer and usually one can see sulphide and graphite grains collected on its borders or in its cleavages (Fig. 19). The same applies to the younger, fine-grained amphibole generation, which occurs in the folded gneissose varieties. It is, in many instances, orientated parallel to the schistosity, replacing, *inter alia*, older, coarse tremolite and biotite porphyroblasts (Fig. 35, p. 72). The tremolite individuals of the younger generation remain smaller in size. The grain size of the graphite is in places as much as 0.3 mm.

The sulphidic matter is generally pyrrhotite, but in the vicinity of the Outokumpu ore one is likely to see locally an abundance of pyrite. In the sheaf schists the mobility of the pyrrhotite increases as the degree of metamorphism increases, and in association with massive, detached portions of pyrrhotite there also occur megascopic chalcopyrite and smaller amounts of sphalerite. Around and within the larger veinlets and patches of pyrrhotite, potash feldspar or quartz often appears as thin fissure fillings. The most highly metamorphozed and deformed, gneissose sheaf schists are penetrated in the western part of the mica schist area, near Juojärvi, by veins of quartz and potash feldspar.

Here, and nearer to the Maarianvaara granite, the amphibole-rich, originally calcareous black schists and its mica-rich varieties alter into non-orientated, structurally massive, coarse-grained rocks. They have not retained any trace of their original structure. The carbonaceous matter occurs as randomly orientated inclusions, and the larger, well-developed graphite flakes range in length up to 0.3 mm. The pale amphibole, whose optical properties are close to those of tremolite, strongly replaces the other minerals, including the sulphides (Fig. 26). Smaller tremolite crystals are present as inclusions in the larger porphyroblasts. The plagioclase exhibits distinct twinning, which like the local occurrence of diopside is characteristic of the more highly metamorphozed schists. The plagioclase is sericitized, containing the finest-grained graphite pigment. The sulphides are here, too, pyrrhotite, pyrite occurring as sporadic corroded inclusions. In addition to the pleochroic sphene and local chloritized pale biotite, carbonate and small amounts of coarse quartz occur.

The amphibole-rich calcareous black schists are all very much alike in their mineral composition. They are mica- and quartz-poor schists, with a striking plagioclase content (20—30 %). The anorthite content of the plagioclase (An_{40-70}) as well as the abundance of pale amphibole indicate the high Ca-Mg-content of the rock, which is also revealed by the analyses (Table VIII, p. 80, Nos. 15—20). They generally contain potash feldspar and the sulphidic matter is usually pyrrhotite. The varieties richer in quartz contain a little mica.

ARENACEOUS BLACK SCHISTS

The argillaceous, graphite-bearing formations are everywhere associated with dark, quartzitic, distinctly stratified schists, which contain small amounts of sulphides and graphite. On occasion they are quite free from graphite, the dark colour being due to the very fine-grained sulphide or oxide pigment. In some instances they contain mica and, in addition, sericitized feldspar in many places (see Table IX, No. 23, p. 81). The rock grades into sericite-quartzite, which occurs as layers not only in the black schists but also in the phyllites, mica schists and, especially, in the purer quartzites of the Outokumpu zone. When associated with carbon-bearing formations, the sericite-quartzite is usually sulphide-bearing, the graphite content being, however, small. Sulphides, which usually consist of pyrite, and less often pyrrhotite, are present also in graphite-free, pale quartzites.

In the transitional zones between the black schists and the quartzites occur different kinds of darker schists varying in their graphite and sulphide contents. Different degrees of transition give rise to various rocks intermediate between the main types. They do not occur, however, as larger deposits.

Among the quartzitic black schists the varieties richest in quartz have best preserved their primary structure. They are clearly bedded (Figs. 10, 11, a, Pl. VI and b, Pl. VIII), and a varved structure is sometimes met with in them (Fig. 29). Even the miniature folding has not destroyed the bedding, which is best seen in the dark quartzites containing a little graphite pigment (Fig. c, Pl. V). The bedded structure, layer thickness and mode of transition into the country rock is not, however, as regular in the mica schist area as in the phyllite area. In the mica schist area, especially in the Outokumpu zone, the depositional conditions are likely to be different, as indicated by the abundant occurrence of quartzites.

The carbon- and sulphide-bearing deposits in the phyllite area contain in many places layers rich in quartzite, whose content of carbon and sulphide is consistently lower. They are in many instances distinctly bedded quartzitic schists whose dark, fine-grained layers alternate with pale-coloured, coarse-grained layers. The dark colour is due to the fine-grained graphite and sulphide pigment, the sulphidic matter being principally pyrite.

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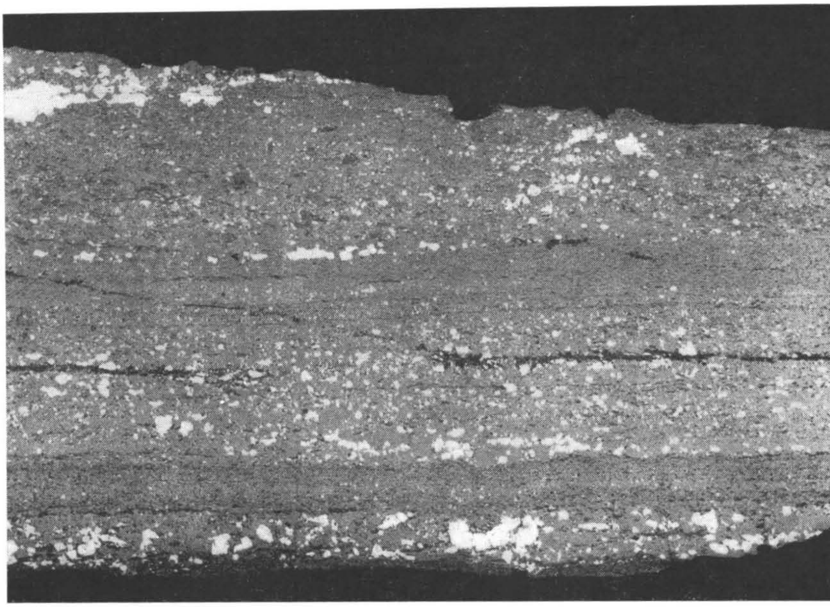

Fig. 29. Graded bedding in quartzose black schist. The amount of graphite decreases and that of pyrite increases towards the bottom of each varve. Outokumpu mine, upper edge of the Lietukka ore body. Polished section. 5 x.

Haapala (1936) and Väyrynen (1939) have described certain dark quartzites from the Solansaari—Viitalampi zone, which are associated with the graphite- and sulphide-bearing formations in that area, and in conjunction with these serpentinite ophiolites as well as purer quartzite layers are present in many places. The dark quartzites often contain chrome-bearing silicates (such as tremolite and fuchsite) as well as small amounts of sulphides and graphite pigment. In the middle part of the zone, at Suopolvi, on the northern side of Lahnajärvi, there occurs in a transverse ditch a phyllitic black schist, in which quartzitic bands with varying contents of carbon and sulphide alternate.

The dark quartzitic layers are very dense, bedded schists, which consist mainly of fine quartz grains. In thin sections graphite pigment occurs in between the quartz grains (grain size under 0.001 mm). The size of the quartz grains varies in the different layers, the layers richer in pigment being finer-grained. Locally present are tremolite porphyroblasts, sulphides (pyrite and pyrrhotite) and, sporadic altered mica flakes arranged parallel to the bedding.

In the Outokumpu zone the dark quartzitic schists usually occur in the transitional zone between the quartzites and the black schists, the thickness

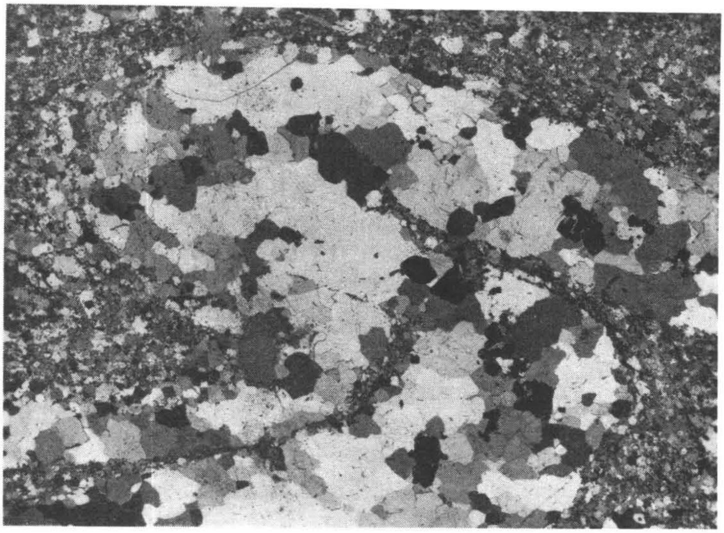

Fig. 30. Coarse-grained quartz layer in intensively folded, pigment-bearing, fine-grained quartzite. Outokumpu mine, upper edge of the Lietukka ore body. Two Nicols. 16 x.

of this zone being as much as 100 metres (to be seen in the cross-section of the Keretti shaft of the Outokumpu mine, Fig. 5). Here also their bedded structure is emphasized by layers varying in pigment content (Fig. a, Pl. VI and b, Pl. VIII). At Outokumpu a glassy, fine-grained quartzite (Table IX, No. 25, p. 81) from the transitional zone of the black schist and the quartzite in the lower part of the complex has been analysed. The content of the strongly sericitized plagioclase (An_{25}), the muscovite and the local chloritized, colourless mica and the diopside are small. In addition to iron sulphide, one finds accessory magnetite, rutile and graphite pigment (0.37 %). The schist is cut by calcite veins.

An arenaceous black schist rich in mica (Table IX, No. 23, p. 81), in which the quartz content amounts to 41.2 % and the mica 15.6 %, has also been analysed from the middle part of the zone near the lower portion of the Outokumpu complex. The schist contains 3.51 % oxidic iron, as a result of which the mica, as the only user of this iron, is a dark biotite. The sulphidic matter consists of pyrrhotite. The anorthite content of the plagioclase An_{20} is typical of the quartz-rich varieties. The carbon content of the schist is low, while the schist is coarser in grain than normal, the grain size varying from 0.05 to 0.5 mm and that of the mica from 0.2 to 1.2 mm. Potash feldspar occurs in the matrix as well as in cracks across the schist.

In certain graphite-free, dark quartzites the colour is likely to be due to an exceedingly fine-grained pyrite pigment, the size of the corroded grains varying from 0.001 to 0.01 mm. The miniature folding, which is quite common, can be readily seen due to the graphite and sulphide pigment (Fig. c, Pl. V). The size of the quartz grains varies from layer to layer according to the pigment content (Fig. 30). In this connection mention should be made of a stylolite formation, which is found in many dark quartzites (Fig. a, Pl. VIII). In many places it occurs parallel to the bedding, with the stylolitic seam containing carbonaceous material. This phenomenon has also been observed in purer quartzites.

As the amounts of the sericitized plagioclase and the colourless mica increase, the dark quartzite grades into sericite-quartzite. The amount of graphite is small, the grain-size varying from 0.005 to 0.05 mm, while the flakes are well-developed and elongated. They are situated in between the quartz grains and often in the sericitized plagioclase. The sulphide content is not very great. It usually consists of pyrite, but pyrrhotite also occurs as clusters of grains parallel to the bedding. Potash feldspar and carbonate occur occasionally as fissure fillings. Characteristic accessories are magnetite and rutile.

THE OPAQUE MINERALS OF THE BLACK SCHISTS IN REVIEW

The petrographic description of the black schists included the opaque minerals only to the extent necessary for the treatment of the subject. Since opaque minerals belong to the black schists as an original component, and their composition and structure as well as the structural interrelationships of the sulphide portion have a significance in elucidating the origin and metamorphic history of the black schists, attention will now be focussed on these aspects.

The most important constituent of the black schists is g r a p h i t e, whose abundance in the examined carbon-rich samples may reach 28.5 % (Table VII, No. 5, p. 78), while the average content in the arenaceous varieties is 5.0 % and in the calcareous ones 4.6 %.

According to X-ray examinations of numerous selected specimens from the area, carried out by Dr. O. Kouvo (personal communication), the degree of graphitization of the carbon material is quite high, and, judging from the marked scattering, the share of noncrystalline carbon slight (Table VI). The specimens for the X-ray slides were taken directly from the rock and not from any separated samples.

The table includes the comparison value Graphite/ASTM 8-415.

Table VI. X-ray examination of the graphite from Outokumpu region

A S T M 8—415		Argillaceous black schist				Calc. black schist Outokumpu Matovaara		Quartzite Outokumpu Mine	
		Outokumpu Mine		Polvijärvi Mertala					
d (Å)	I	d	I	d	I	d	I	d	I
3.37	100	3.37	vs I	3.36	vs I	3.36	vs I	3.37	vs I
2.132	2	2.13	vvw	2.12	m	2.13	ms	2.125	mw
		2.06 [1]	vw						
2.036	3			2.05	w	2.02	w B	2.03	vw
1.682	8	1.68	vvw	1.68	ms	1.68	m	1.68	w B
1.541	2	1.54	f	1.54	w	1.53	w B	1.54	w
1.232	2	1.233	f	1.23	m	1.23	w	1.23	w

s = strong; m = medium; w = weak; vw = very weak; f = faint; B = Broad.
[1]) (probably the strongest line of pyrrhotite)

In the polished section one can clearly observe the strong reflection pleochroism as well as translation, which occurs parallel to the (0001) plane (Fig. b. Pl. I). The anisotropy (N +) in the air is very high and the colour pale brownish gray. In the phyllite area, the anisotropic effect of the carbon material is not always as distinct as in the highly metamorphozed area, and the reflection pleochroism cannot be detected with certainty on account of the fine grain of the material. It is possible that schungite with a lower degree of graphitization may occur locally in the phyllite area.

The graphite occurs in various black schists as fine-grained flakes, parallel to the schistosity, remaining as a helicitic parallel texture in the growing porphyroblasts during the recrystallization. The grain size of the graphite varies according to the grade of metamorphism. In the phyllite area it is usually about 0.001 mm and in association with mica gneisses 0.01—0.3 mm. In shape the crystals are elongated lamellar, in cross-section rounded, hexagonal or rodlike. In addition to the parallel texture, one also encounters a random orientation in the highly metamorphozed parts of the area, and the flakes are in many cases bent and split along the cleavage (Figs. b, Pl. I and 43, p. 94).

Graphite occurs as inclusions in the silicate and sulphide portions of the schist. However, the quartz and potash feldspar are generally lacking in graphite pigment. The graphite pigment occurring as inclusions in porphyroblasts (plagioclase, tremolite, sphene) is considerably finer-grained than the flakes outside them — in between the quartz grains, in the fissures, at the borders of mica and in sulphides. As will later be explained, the older sulphide generation is usually free from graphite inclusions, which occur abundantly in the younger generation. The graphite itself is free from inclusions, but occasionally it contains fine-grained silicates.

As an interesting detail it should be mentioned that, either in association with graphite flakes or independently of them, there sometimes occur spherical phenocrysts (Figs. c and d. Pl. I). According to a personal communication from Ramdohr, they resemble the carbon-like matter (kohlige Substanz) that he had investigated at Witwatersrand (Ramdohr 1958 a) and that is often referred to in the literature as t h u c h o l i t e, containing uraninite grains in varying amounts. It is occasionally possible under high magnification to detect in the uraninite inclusions exceedingly fine grains of galena (Fig. d, Pl. I), the lead content of which is evidently radiogenic. The grain size of the »thucholite» spheroids varies between 0.08 and 0.2 mm, and often the uraninite inclusions are very small in size or even totally lacking. The size of the spheroids depends on the number and size of the uraninite inclusions. »Thucholite» occurs most abundantly in the amphibole-rich, carbonaceous schists, in which the uranium content is also usually the highest (Table X, p. 85).

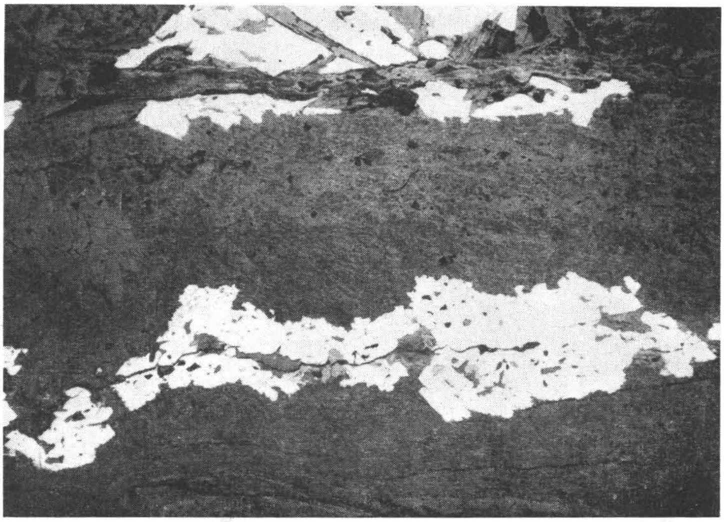

Fig. 31. Concentration of pyrite grains as a conformable streak in phyllitic black schist. Kultakallio, Polvijärvi. Polished section. 21 x.

The spheroids containing the uraninite inclusions have been observed by Mr. Y. Vuorelainen to be carbonaceous matter, because of its combustible properties. The lines 3.17, 2.73, 1.945 and 1.655 shown by a powder photograph taken by him of a certain carbon spheroid correspond in value and intensity to UO_2 rather than (U, Th) O_2. No graphite lines could be detected. One carbon fraction containing carbon spheroids was observed on the basis of an XRF-spectrum to contain a little uranium and lead, whereas thorium, which thucholite usually contains in abundance, was not met with at all.

According to Ramdohr (1955 b) and Joubin (1955), the thucholite and the similar carbon substance occurring as spheroids consisted originally of some hydrocarbon compound that later reacted with uraninite.

With an increase in carbon, the sulphide content of the black schists increases correspondingly, although the relative amounts of sulphides vary.

P y r i t e occurs as concordant aggregates or as concentrations and it predominates in the black schist layers rich in quartz (Fig. 31), whereas the carbonaceous and micaceous layers contain more pyrrhotite (Fig. 32). In the phyllite area the concordant pyrite aggregates are associated with the coarse-grained, quartzose layers of the schist as discontinuous bands, whose thickness varies between a few millimetres and several centimetres (Figs. 3 and 10). They alternate with fine-grained carbonaceous and micaceous layers, which contain pyrrhotite in small amounts. The mode of occurrence of pyrite is the same in the mica schist and mica gneiss areas. The pyrite grains of the

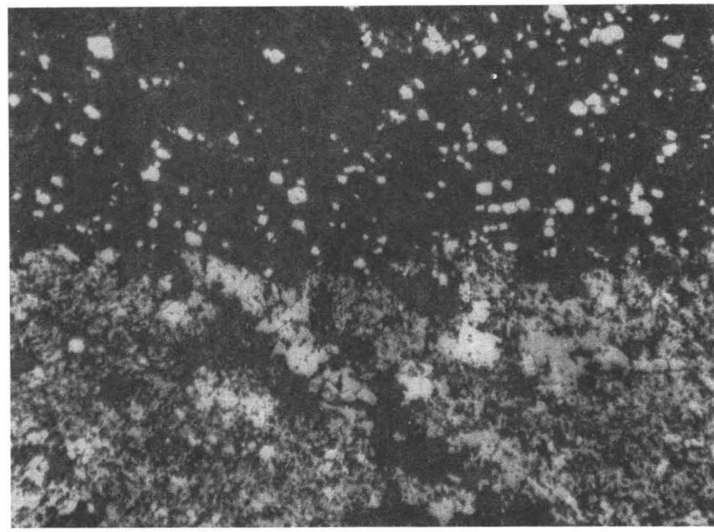

Fig. 32. Pyrite predominating in quartzose layer (top section) and pyrrhotite in micaceous carbon-bearing layer. Drill hole 90 a, 68 m, Outokumpu. Polished section. 35 x.

coarse-grained layers are often as much as 10—100 times as big as in the carbonaceous, fine-grained layers; accordingly, there is a correlation between the grain size of the pyrite and that of the layers.

Pyrite is found in addition to pyrrhotite in many cases as fissure fillings cutting the plane of schistosity in varying directions (Fig. a, Pl. V). The silicate material of sulphide-bearing fissures usually consists of quartz and, to a lesser extent, of potash feldspar. Similar fissures are also encountered in the country rock of carbonaceous schists, as, e. g., in mica schist. In places there occur pure pyrite veins lacking in silicates. The veins are frequently quite thin, being divided into numerous branches.

The grain size of pyrite varies, usually being coarsest in the highly metamorphozed and carbon-poor schists. The pyrite has the finest grain (0.005—0.05 mm) in the carbon-rich schists of the phyllite area as well as in certain dark, quartzitic ones containing a small amount of graphite. The pyrite content is likely to rise in some of the black schists of the mica schist and mica gneiss area to as high as 30 % (Table IX, No. 22, p. 81).

In form the coarse-grained, concordant pyrite grains of the phyllite area are elongated and anhedral (cube faces are rare). They collect together in separate concentrations, which resemble conformable fissure fillings (Figs. 3 and 31). The pyrite aggregates are sometimes cut by silicates, especially amphibole porphyroblasts. Locally the pyrite contains small grains of pyrrhotite and chalcopyrite, but it has no inclusions of carbonaceous material.

Anhedral, corroded pyrite grains ordinarily contain no inclusions of graphite; only in cleavage cracks is it found, in addition to the silicates. Pyrite does not achieve euhedral forms when in contact with carbonaceous material, whereas the graphite-free grain boundaries are more regular and those against the pyrrhotite quite straight and well formed (Figs. a and d, Pl. II).

Euhedral forms prevail in the highly metamorphozed western part, with the pyrite forming cubic »porphyroblasts», especially when enclosed in pyrrhotite (Fig. b, Pl. II). In the pyrite of this generation, graphite occurs as inclusions (Fig. a, Pl. II) in addition to chalcopyrite (Fig. c, Pl. II) and sphalerite (Fig. d, Pl. II). Pyrrhotite is also met with, but more often it replaces cataclastic pyrite along cleavages and fractures (Fig a, Pl. III), and to a lesser extent sphalerite and chalcopyrite occur likewise as a replacement texture.

The anhedral forms of pyrite usually become euhedral with an increase in the amount of sulphide and in the grade of metamorphism, as will be observed in certain thicker sulphide veins and concentrations of the black schists in the mica schist area. The euhedral pyrite grains usually contain graphite inclusions, whereas the corroded and anhedral, coarse-grained pyrite crystals of the phyllite area are generally graphite-free.

The most usual inclusions in the pyrite in addition to the graphite are various silicates, pyrrhotite, chalcopyrite and sphalerite. Locally also rutile has been encountered, but in such cases the customary surrounding leucoxene formation has been absent.

Magnetite and ilmenite occur sporadically.

As mentioned above, p y r r h o t i t e occurs in the phyllite area only in association with the fine-grained, carbonaceous and micaceous layers of the black schists, but upon a rise in the grade of metamorphism it becomes more prevalent also in the coarser bands. The argillaceous and especially calcareous varieties of black schist often contain pyrrhotite alone (pyrite being totally absent), especially in the western parts of the area (Tables VII and VIII, p. 78—80). This is particularly true of certain intermediate, sulphide- and carbon-bearing micaceous schists (Table IX, p. 81 Nos. 23 and 24).

Regional variations can be observed in the mode of occurrence of both pyrrhotite and pyrite. In the phyllite area and in the less metamorphozed parts of the mica schist area, pyrrhotite occurs as concordant, elongate, fine grains. In the mica schist and mica gneiss area where pyrrhotite is more generally present, and in many places predominant, it forms massive, wholly unorientated patches cutting the schistosity of the rock. The fine-grained pyrrhotite as well as the mica and graphite flakes of the carbonaceous and micaceous layers are parallel to the schistosity and, evidently, to the original bedding. The older pyrrhotite generation parallel to the schistosity is displaced in the highly metamorphozed area by a younger massive generation, represented by thicker pyrrhotite veins and concentrations cutting the plane of schistosity in different directions (Fig. b, Pl. III). It is interesting to observe that in pyrrhotite grains parallel to the bedding or the schistosity, graphite inclusions occur very rarely, whereas in pyrrhotite veins and patches cutting the structure of the rock, they do occur. The fine-grained pyrrhotite is often observed as inclusions in graphite and as fillings in its cleavages and in those of mica.

In form the pyrrhotite grains are generally elongated lamellae with irregular grain boundaries. Only sporadically do hexagonal grains occur. The grain size in both cases varies between 0.01 and 0.05 mm. The larger grains are normally without crystal boundaries and often corroded. Pyrrhotite adheres to the cleavage or deformation cracks of different minerals as fissure fillings and veins. Pyrrhotite occurs, e. g., in the cleavages of mica and graphite lamellae, and locally in the transverse fissures of amphibole. Cataclastic pyrite crystals are replaced by pyrrhotite along cleavages and fractures (Fig. a, Pl. III). In graphite-rich schists, pyrrhotite together with graphite often produces an exceedingly fine-grained symplektitic texture. In amphibole-rich black schists the pyrrhotite beautifully fills the interstices of disorientated porphyroblasts of amphibole (Fig. 26). The mode of occurrence and form of the pyrrhotite thus reveal the sulphide to be quite mobile.

Pyrrhotite contains as inclusions various silicates and carbon material as well as pyrite, chalcopyrite and sphalerite. Chalcopyrite and sphalerite are also observed locally to form in the pyrrhotite, starting from the boundaries and proceeding inwards along its fractures, but this is not common. As in pyrite, inclusions of rutile and ilmenite are met with locally in pyrrhotite, without the formation of leucoxene. Sphene has not been met with as inclusions.

Sporadically certain grains of sphene have been found to contain, in addition to extremely fine graphite inclusions, pyrrhotite grains ranging from 0.001 to 0.003 mm in size. Outside the sphene the pyrrhotite and the graphite are coarser (Fig. c, Pl. III), and pyrrhotite is sometimes absent. Extremely small pyrrhotite grains of the same kind are met with as inclusions in sphalerite, where they are orientated parallel to the crystallographic planes of the host (Fig. d, Pl. III). This is held by Ramdohr (1955 a, p. 399) to be the unmixing texture of sphalerite and evidence of the higher temperatures prevailing during crystallization.

In this connection mention should be made of the secondary alteration of pyrrhotite into hydropyrrhotite. This may be noticed in samples taken from the surface of the ground or near to it. Such an alteration has been observed in a drill hole at Luikonlahti to a depth of as much as thirty-five metres. The alteration into hydropyrrhotite starts at the boundaries of the pyrrhotite and along its fractures (Fig. a, Pl. IV), and it advances toward the centre, when the entire grain changes (Figs. a, Pl. II and b, Pl. IV) into a brown, indeterminate mass. Saksela (1923) was the first to describe such an alteration of pyrrhotite (occurring at Otravaara), and subsequently the phenomenon has been observed elsewhere in Finland. Lokka (1943) has demonstrated that such an alteration product contains considerable water (7.95 %), and it is for this reason that Saksela (1947) decided to call it »hydropyrrhotite».

The association of s p h a l e r i t e and c h a l c o p y r i t e with the iron sulphides of black schists, whether as inclusions, replacement, or unmixing textures has been dealt with in various connections earlier. In addition, they occur as accessory components. There is usually a trifle more sphalerite than chalcopyrite, and both can be seen at times with the naked eye in different black schist varieties.

The amount of zinc varies between 0.01 and 0.2 % and the grain size of the sphalerite between 0.01 mm and several millimetres. In pyrite it occurs as rounded or elongate inclusions (Figs. d, Pl. II and c, Pl. IV), where chalcopyrite ex-solution bodies can sometimes be seen. Locally sphalerite occurs as an unmixing texture with pyrrhotite and chalcopyrite in the fissures of (cataclastic) pyrite (Fig. a, Pl. III). Sphalerite, as inclusions in pyrrhotite, occurs megascopically visible in many places, and encloses blebs of both chalcopyrite and pyrrhotite (Fig. d, Pl. IV). These are usually orientated parallel to the crystallographic planes of sphalerite (Fig. d, Pl. III), which is to be interpreted as an unmixing structure. In places the pyrrhotite is cut by a sphalerite vein, at the contact of which there occurs chalcopyrite. In the paragenesis of sulphide minerals, sphalerite and chalcopyrite thus succeed pyrrhotite.

The amount of copper varies from 0.02 to 0.08 % and the grain size from 0.002 to 0.3 mm. The smallest grains occur as ex-solution bodies in the sphalerite (Figs. d, Pl. III and d, Pl. IV), the average size varying between 0.01 and 0.03 mm. The chalcopyrite inclusions in pyrite are of the same order of magnitude (Fig. c, Pl. II). It is coarsest in grain in the fractures in the pyrrhotite and at the boundaries of it and the pyrite. The sphalerite does not usually contain graphite as inclusions, the latter being met with only at the borders of the grain. On the other hand, the chalcopyrite locally contains graphite inclusions.

Attempts have been made to find microscopically the carrier of vanadium in the black schists of the Outokumpu region, for in certain samples the vanadium content rises as high as 0.18 % V_2O_5. There exist indications of a certain mineral whose optical properties correspond to the so-called p a t r o n i t e described by Ramdohr (1955a, p. 684) (Fig. 33). On the

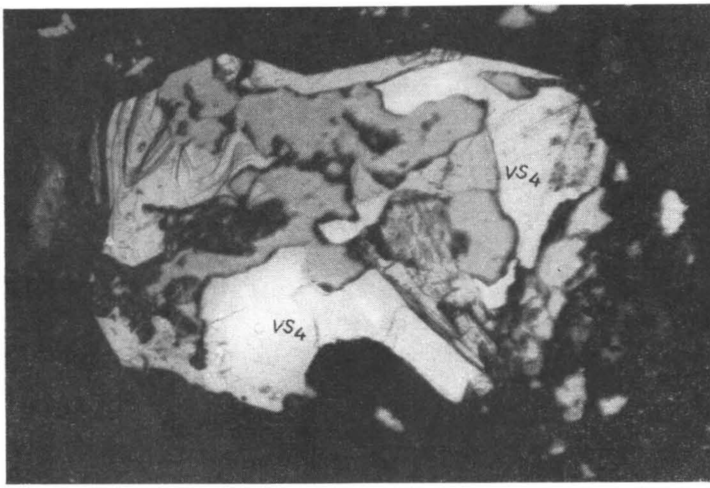

Fig. 33. Questionable »patronite» (VS_4) surrounding an unknown opaque mineral (grey). Quartzose black schist. Outokumpu, upper edge of the Lietukka ore body. Polished section. 750 x. Oil-immersion.

basis of the XRF-spectrum, this mineral has been observed to contain a small amount of vanadium. Investigations are in progress toward identifying the mineral. Ramdohr gives the formula for patronite as VS_4. The mineral occurs as thin, translucent, tabular flakes on the surfaces of other minerals (often pyrite), and for this reason obtaining a sample of it has proved difficult. Its hardness is very low, and its reflection pleochroism very high, resembling molybdenite or graphite. The colours are in air: grayish white-yellowish brown-grey. The anisotropy is exceedingly strong, and on the basis of this property the mineral is easy to find.

METAMORPHIC HISTORY

MICACEOUS SCHISTS

The gradual transition observed in the region from the phyllite into, first, mica schist and then into mica gneiss indicates that the mica schists and mica gneisses represent products of progressive regional metamorphism of phyllitic schists. In spite of the growth of the grain size caused by recrystallization, original sedimentary structures have been preserved in the phyllite and in part of the mica schist area.

The chemical composition of the phyllites and mica schists varies within the same bounds and is comparable to the average composition of the Svecofennian micaceous schists (Table I, No. 4, p. 31). Simonen and Neuvonen (1947), Seitsaari (1951) and Simonen (1953) have described the stratigraphy of different parts of the Tampere schist area as well as the mineral facies variations, and they have established that the greatest part of the Svecofennian sediments have been metamorphozed under the conditions of the amphibolite facies.

The mineral assemblage b i o t i t e-m u s c o v i t e-p l a g i o c l a s e (An_{30-40}), which is to be observed in the western part of the phyllite formation (Table I, Nos. 1 and 2) indicates PT-conditions characteristic of the amphibolite facies. As Seitsaari (1951) noted in the phyllites and mica schists of the northeastern part of the Tampere area, the muscovite is likely to be lacking in many cases. The lack of aluminous silicates, such as andalusite, typical of the amphibolite facies, together with the local occurrence of chlorite and epidote in the phyllites may be regarded as indicative of low-temperature metamorphism. However, the mica of the phyllites of the Höytiäinen area has a predominance of biotite, which has chloritized only locally. Evidently the relatively high potash content of the sediment has retarded the chloritization of the biotite, for it proves that in phyllites rich in potash biotite can be stable down to a low temperature (Th. Vogt, 1927).

The mica schists of the region are representatives of the amphibolite facies. In them, as also in the mica gneisses, there occurs the mineral association b i o t i t e-p l a g i o c l a s e (An_{35}), while muscovite is generally absent. Almandine is met with in them as the common porphyroblastic aluminium silicate, this being an indication of an excess of Al_2O_3 in the original sediment.

BLACK SCHISTS

In structure and texture the various types of black schist represent all degrees of transition from phyllitic to highly metamorphozed gneissose schists.

The original bedded structure occurs in the argillaceous black schists of the Karelian formation, especially in those of the Jatulian type (Eskola, 1932). In the carbon- and sulphide-bearing part of the Outokumpu schist area a varved structure is met with only occasionally, but the black schists are distinctly bedded, with graphite-bearing layers alternating with coarse-grained layers poor in carbon (Figs. 10 and 11).

In the black schists of the phyllite area there are graphite-free bands noticeably coarser in grain than the surroundings (Kultakallio). The carbon-rich layers of different black schist varieties are generally much finer-grained than the carbon-free layers alternating with them. In very carbon-rich layers the grain size generally remains nearly unchanged, and the bedded structure is preserved very distinctly, and even striking in certain quartzitic black schist varieties of the mica schist area (Figs. a, Pl. VI and b, Pl. VIII). Varved structure has even been noticed sporadically occurring in schists of this type in the central part of the Outokumpu zone (Fig. 29).

As the degree of metamorphism increases, the bedded structure begins to disappear. In the carbonaceous and sulphide-bearing schists of the schist area this occurs, however, considerably more slowly and is also dependent on the composition of the black schist as well as the deformation. Minerals like tremolite and biotite, high in the crystalloblastic series, form porphyroblasts, which at first appear parallel to the bedding in the carbon-poor layers of the schist. The lag in the recrystallization of the carbon-rich layers of the schist emphasizes the bedded structure in all the varieties of black schist. The mica flakes in the argillaceous black schists of the phyllite area and the tremolite prisms in the calcareous varieties occur orientated parallel to the bedding (Fig. 25). As the recrystallization of the amphibole becomes more advanced, the tremolite porphyroblasts in the investigated western part of the phyllite area are more coarse-grained than the other minerals, and likewise the amphibole-rich black schists are coarser than the associated rocks.

As the degree of metamorphism increases in the Solansaari—Viitalampi zone, porphyroblasts begin to appear in the fine-grained, carbonaceous part of the schists, pale mica flakes appearing in the argillaceous layers and

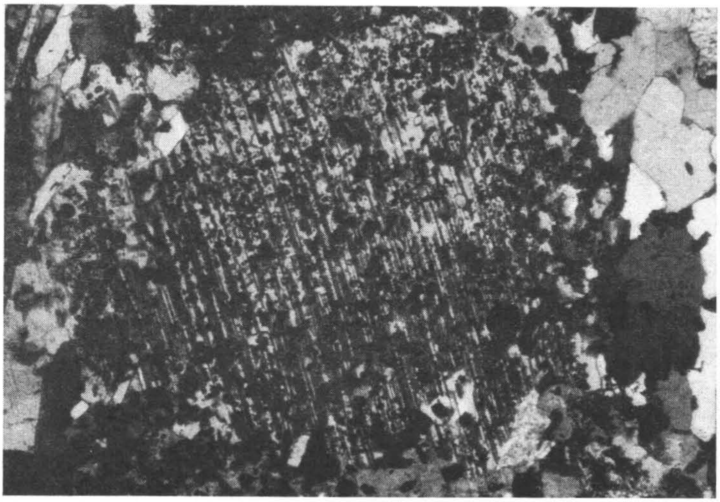

Fig. 34. A porphyroblast of plagioclase containing sulphides, quartz, microcline and disseminated carbon. Argillaceous, massive black schist. 200 m NW of Lake Palolampi, Luikonlahti, Kaavi. Two Nicols. 50 x.

amphibole prisms in the calcareous layers; both enclosing carbonaceous and sulphidic material. At the same time an increase in the grain size can be noticed in the rest of the schist. In the schists poorer in carbon the recrystallization occurs more strongly, and the bedded structure becomes less distinct. A local deformation appears as miniature folding (Fig. 9) and as a transverse cleavage. The mica flakes tend to crystallize in the direction of the transverse cleavage, reducing the clarity of the bedding. This appears in thin section however as a helicitic relict bedding of the graphite grains (Fig. 12). Miniature folding and a transverse cleavage are particularly common in varieties poor in carbon.

The bedded structure and the nature of the contact of the carbonaceous formation with the country rock are less distinct in the Juojärvi—Haapovaara (Outokumpu) zone. In the carbonaceous part of the argillaceous schists the plagioclase and the mica begins to form nebullous porphyroblasts, in which the rest of the minerals of the rock occur as inclusions (Fig. 34). The mica and the plagioclase are often represented by two different generations, the older of which contains an abundance of carbon pigment (see p. 43).

As the metamorphic grade advances, the pale mica has a tendency to free itself of the carbon and sulphide pigment (Figs. 14 and 19); the same process occurs in the younger, fine-grained amphibole, which replaces its paler predecessor as well as the biotite (Figs. 28 and 35). Thus the bedded

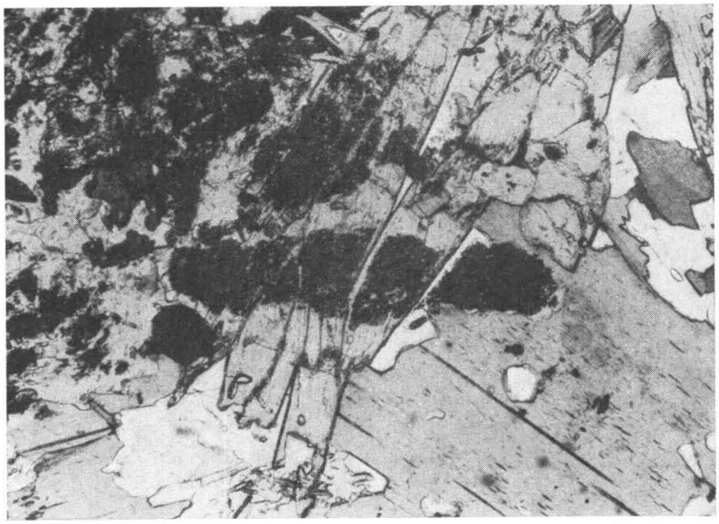

Fig. 35. Biotite porphyroblast (with a dark aggregate of graphite) replaced by colourless prisms of tremolite. Drill hole Oku 129, 40 m, Sukkulansalo, Kuusjärvi. One Nicol. 50 x.

structure of the micaceous and amphibole-rich black schists gradually disappears. Only the varieties rich in quartz (Figs. a, Pl. VI and b, Pl. VIII) and the carbonaceous layers in general (Fig. d, Pl. V) preserve their bedded structure.

In the highly metamorphozed black schists of the Outokumpu zone, only detached portions (Figs. 18 and 36) of the fine-grained layers are left with their original bedding, which in many cases is also preserved as a helicitic structure. The black schists are schistose in structure, although in many places they exhibit gneissose features.

Nearer the Maarianvaara granite the micaceous and amphibole-rich varieties of the black schists grade into coarse-grained, disorientated rock massive in structure (Figs. 24 and 26). In them the protective effect of carbon has finally ended, for even the carbon material has recrystallized into coarse-grained, disorientated graphite flakes (Fig. b, Pl. I), permitting also the fine-grained quartz to recrystallize.

Regional variation may be noticed also in the mode of occurrence of the sulphides contained in black schists. Their structural relations reveal features that indicate recrystallization occurring at the same time as that of the silicates.

In the phyllite area the pyrite occurs as anhedral aggregates or concentrations orientated parallel to the bedding and the pyrrhotite as elongate grains similarly parallel to the bedding. As the degree of metamorphism increases,

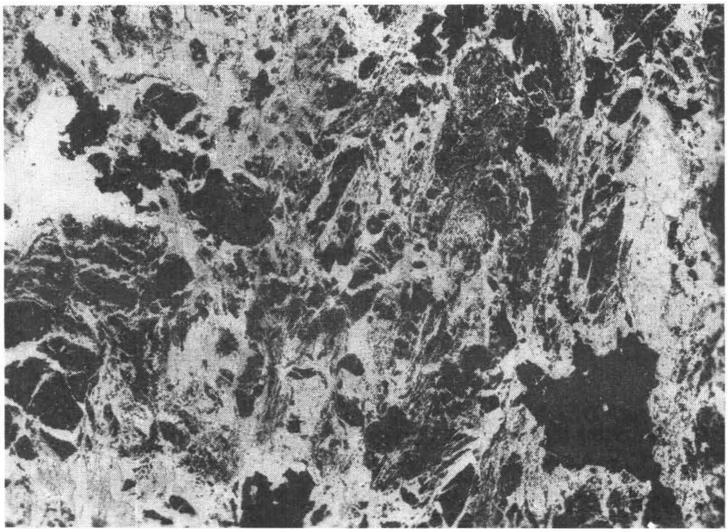

Fig. 36. Deformed and recrystallized argillaceous black schist with gneissose structure. Drill hole Oku 129, 48 m, Sukkulansalo, Kuusjärvi. One Nicol. 16 x.

the replacing effect as well as the amount of pyrrhotite increases. The effect of the metamorphism and deformation is more easily detected in pyrrhotite than in the silicates, as the former exhibit a more rapid growth in the size of the grains and show displacement and replacement structures already in the area of low-temperature metamorphism. In more highly deformed layers pyrrhotite and, in many cases, pyrite follow fractures in the schist and form in places fairly substantial veins (Figs. a, Pl. V, c, Pl. VI and a, Pl. VII). Sphalerite and chalcopyrite are observed megascopically in places in association with coarse-grained pyrrhotite.

In addition to recrystallization, deformation causes changes in the structure of the black schists as well as the concentration of sulphides and certain silicates into structurally favourable places of the schist and its environment (Saksela, 1957). In intervening layers of black schist poorer in carbon and weaker in resistance, deformation is manifested in the more abundant occurrence of quartz, potash feldspar and particularly sulphides, together with a more marked growth in the size of grains. In the carbonaceous, fine-grained layers the traces of shearing appears as folding in the carbon pigment (Fig. b, Pl. V). The shearing apparently occurs at first in the carbon-poor layers parallel to the bedding and is revealed by the drag folding seen in places in the neighbouring carbonaceous layers. The abundant occurrence of sulphide in the carbon-poor layers as conformable concentrations would seem to indicate their mobilization during the initial stage of

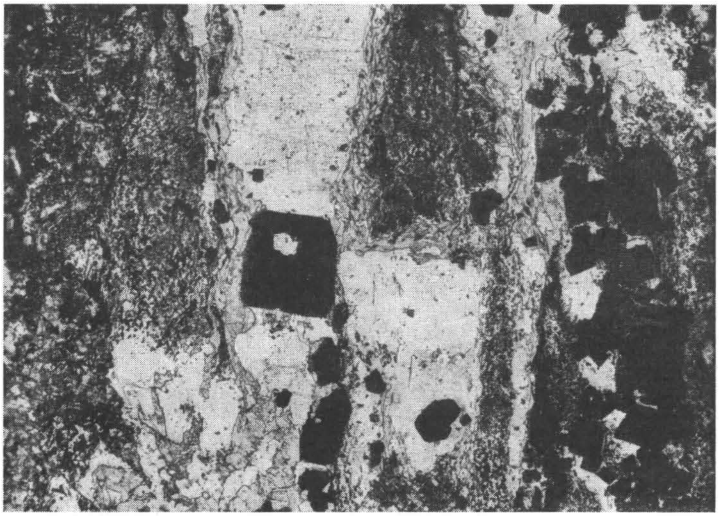

Fig. 37. Sheared pyritiferous black schist rich in microcline. Outokumpu mine, Keretti shaft, + 320 level. One Nicol. 16 x.

deformation particularly in shear zones parallel to the bedding of the black schist (Figs. 3, 17, 22, 31 and 37).

In the highly deformed, mylonitic schists rich in graphite and sulphide, the bedding has totally disappeared, and the brecciated parts of the carbonaceous layers form randomly orientated inclusions in the coarse-grained matrix (Fig. b, Pl. VI). Mica is crystallized into coarse-grained, bent flakes and fissure-fillings, with which are usually associated sulphides, coarse-grained quartz and potash feldspar, filling in places opened fractures as clearly-defined veins.

In the sheared and folded portions one meets with alteration products, which indicates secondary recrystallization occurring later under conditions of lower temperature. In deformed zones the plagioclase is sericitized and in many cases epidotized, often with potash feldspar as fine-grained inclusions (Fig. 38). The biotite exhibits chloritization and simultaneous formation of potash feldspar (Fig. 39). The margins of the biotite against the sulphides have in many cases grown pale or chloritized; the change may be complete. Frequently chlorite occurs as an inclusion in pyrrhotite.

Apparently the primary metamorphism has taken place in the most highly metamorphozed black schists under conditions of the amphibolite facies. An indication of this is the occurrence of the same mineral assemblage biotite-muscovite-plagioclase, which is characteristic of the mica schists of the environment. A high-temperature facies is revealed in

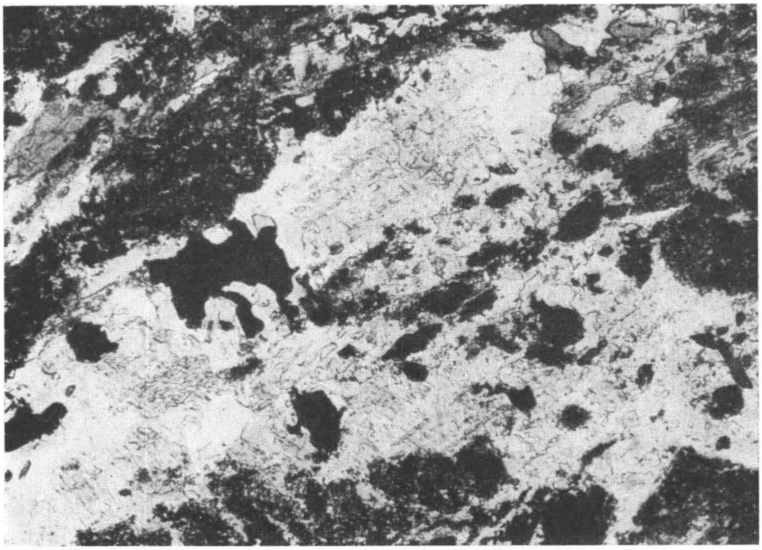

Fig. 38. A porphyroblast of plagioclase containing small lenses and grains of potash feldspar. Sukkulansalo, Kuusjärvi. One Nicol. 50 x.

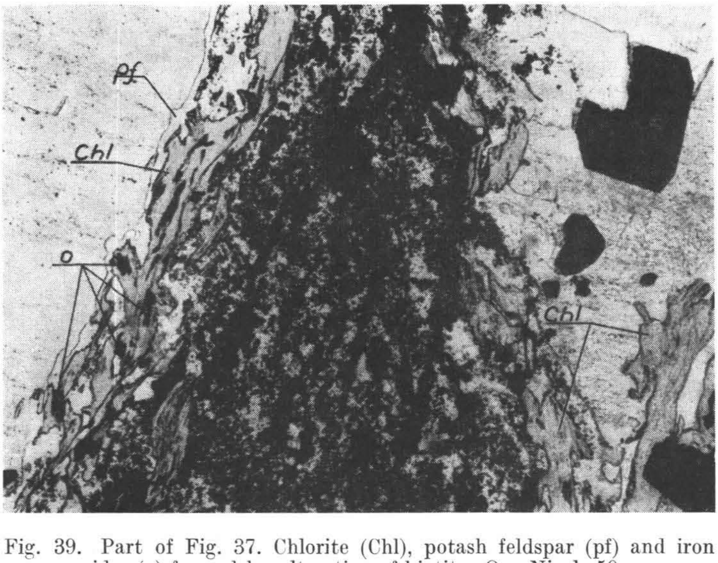

Fig. 39. Part of Fig. 37. Chlorite (Chl), potash feldspar (pf) and iron oxides (o) formed by alteration of biotite. One Nicol. 50. x.

calcium-rich schists by the sporadic occurrence of diopside (Table VIII, No. 17, p. 80) and the previously described unmixing texture of pyrrhotite in sphalerite (Fig. d, Pl. III), which Ramdohr (1955 a) reports as occurring only in formations originating at high temperatures.

Nevertheless, in carbon-rich formations of the phyllite and the mica schist areas, there are mineral assemblages whose crystallization has occurred in a facies of lower temperature. In argillaceous varieties the biotite, owing to the higher potash content of the sediment, can be stable down to a lower temperature, so that the association biotite-chlorite-muscovite-plagioclase (An_{25-40}) can be stable also under the conditions of the albite-epidote-amphibolite facies. In calcareous varieties the mineral assemblage tremolite-plagioclase (labradorite)-epidote-microcline is prevalent, and, in varieties containing potash in excess, subsequently chloritized biotite is often present.

CHEMICAL COMPOSITION AND GEOCHEMISTRY

MAIN ELEMENTS

A number of the phyllites and mica schists analysed from the area are very much alike in chemical composition, resembling furthermore numerous argillaceous Archean sediments characterized by a rather high content of aluminium, iron and potash as well as a low calcium content. For the sake of comparison, Table I, p. 31 (No. 4) presents the average composition of the Svecofennian mica schists (Simonen, 1953). The phyllites and mica schists of the Outokumpu region are, however, generally richer in calcium and sodium and lower in their iron and potassium content. This is revealed in their mineral composition by a higher plagioclase and lower mica content.

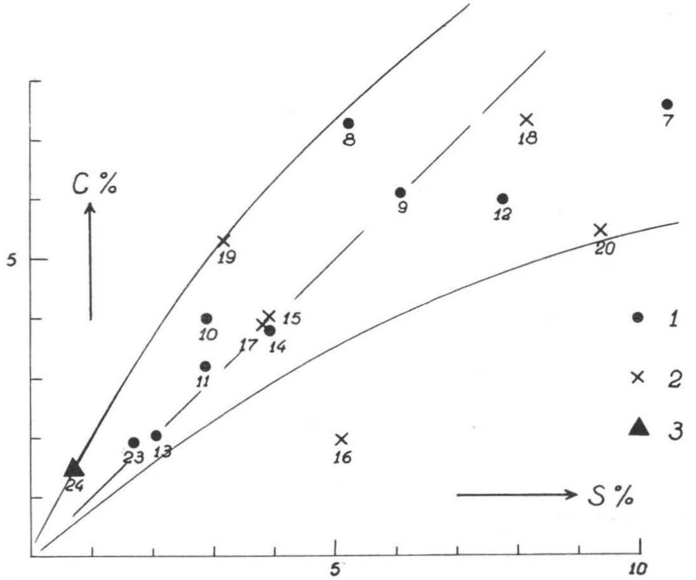

Fig. 40. Carbon and sulphur content in the black schists. 1. argillaceous black schists; 2. calcareous black schists; 3. carbonaceous mica schists. The numbers refer to the chemical analyses in Tables VII, VIII and IX.

Table VII. Analyses of the argillaceous black schists.

	5		6		7		8		9	
	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.
SiO_2	33.00	5 500	34.80	5 800	40.50	6 750	49.14	8 190	48.36	8 060
TiO_2	1.45	181	1.03	129	0.98	122	0.92	115	0.62	78
Al_2O_3	16.75	1 642	20.19	1 979	13.01	1 275	13.22	1 296	11.28	1 106
Fe_2O_3	—	—	—	—	—	—	—	—	—	—
FeO	1.40	194	1.40	194	1.39	193	1.47	204	2.94	408
MnO	0.04	6	0.04	6	0.04	6	0.04	6	0.03	4
MgO	3.17	792	3.27	817	6.95	1 737	5.62	1 405	4.45	1 113
CaO	8.53	1 523	7.66	1 368	4.42	789	3.62	646	2.70	482
Na_2O	1.82	293	1.09	176	1.72	277	2.48	400	1.97	318
K_2O	0.48	51	1.70	181	2.52	268	1.89	201	3.14	334
H_2O+	1.08		2.17		1.00		1.62		2.10	
H_2O-	—		—		—		—		0.14	
P_2O_5	0.16	11	0.09	6	0.10	7	0.01	—	0.01	—
C	28.42		13.36		7.62		7.26		6.08	
CO_2	0.04		0.07						0.10	
F	0.10		0.13		0.22		0.06		0.08	
S	1.45		5.32		10.48		5.26		6.10	
Fe(S)	2.33		7.52		9.19		6.80		9.65	
FeS_2	(—)		(2.20)		(19.60)		(3.75)		(—)	
FeS	(3.78)		(10.50)		(—)		(7.95)		(15.54)	
V_2O_5	0.04		0.23		0.20		0.10		0.09	
	100.26		100.07		100.34		99.51		99.84	
Niggli numbers										
si	122		123		148		197		214	
ti	4.0		2.7		2.6		2.9		2.1	
al	36.5		41.9		28.1		31.3		29.5	
fm	22.0		21.6		42.5		38.9		40.4	
c	33.9		29.0		17.3		15.4		12.8	
alk	7.6		7.6		12.1		14.4		17.3	
k	0.15		0.50		0.49		0.33		0.51	
mg	0.80		0.80		0.90		0.87		0.73	
c/fm	1.54		1.34		0.41		0.40		0.32	
qz	—8		—7		0		+39		+45	
Mineral composition.										
Weight percentage	1)		1)		1)					
Plagioclase	An_{70} 49.3		An_{78} 45.0		An_{45} 26.7		An_{35-45} 32.9		An_{40} 26.7	
Quartz	—		3.8		10.0		20.0		21.2	
Potash-feldspar	2.8		9.4		3.0		2.7		10.2	
Tremolite	9.2		1.1		10.7		4.4		1.3	
Diopside	—		—		—		—		—	
Biotite	—		} 11.3		17.9		18.8		16.9	
Chlorite	—				—		—		—	
Muscovite	—		—		—		—		—	
Iron sulphides	3.8		12.7		19.7		}		}	
and oxides	—		2.0		2.0		} 19.0		} 22.0	
Graphite	28.5		13.4		7.6		}		}	
Sphene	2.4		1.3		2.4		2.2		1.5	
Calcite	—		—		—		—		0.1	
Accessories	4.0		—		—		—		0.1	
	100.0		100.0		100.0		100.0		100.0	

1) Calculated from the analysis.

5. Graphite-rich layer of black schist. Mertala, Polvijärvi.
6. Brecciated graphite- and pyrrhotite-rich schist. Outokumpu mine, Keretti shaft, 320-level.
7. Phyllitic black schist interbedded with pyritiferous »layers». Island of Kultakallio, western part of Lake Höytiäinen, Polvijärvi.
8. Massive, argillaceous, graphite- and sulphide-bearing rock. Luikonlahti, Kaavi.
9. Black schist. Sukkulansalo (drill core Oku 129, between 48.1—55.3 m), Kuusjärvi.

(Analysed in the laboratories of Outokumpu Co)

10		11		12		13		14		Average comp.
%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	
58.50	9 750	60.08	10 013	52.10	8 683	62.90	10 483	61.36	10227	50.07
1.08	135	1.06	133	0.47	59	0.93	116	0.59	74	0.91
12.92	1 267	14.78	1 449	10.73	1 052	13.98	1 370	12.24	1200	13.91
—	—	0.44	27	—	—	1.37	86	—	—	0.18
2.14	297	1.79	249	3.17	440	0.40	56	0.51	71	1.66
0.03	4	0.04	6	0.03	4	0.03	4	0.03	4	0.035
5.21	1 303	3.15	787	3.40	850	2.94	735	3.14	785	4.13
2.80	500	3.30	589	2.43	434	4.53	809	2.04	364	4.203
1.47	237	3.19	514	1.68	271	2.22	358	2.95	476	2.06
3.34	355	2.13	226	1.62	172	2.11	224	2.79	297	2.172
		1.37		1.12		0.78		1.30		1.46
				0.19				0.26		
0.05	4	0.04	3	0.02	1	0.18	13		—	0.073
4.00		3.22		6.00		2.03		3.82		8.18
		0.05		0.11		0.18		0.11		0.082
		0.03		0.10		0.07		0.03		0.091
2.90		2.83		7.80		2.04		3.90		4.81
4.50		2.83		9.75		3.56		5.05		6.12
(—)		(4.17)		(6.68)		(—)		(2.88)		(3.93)
(7.17)		(1.30)		(10.68)		(5.54)		(5.93)		(6.84)
0.09		0.11		0.11		0.11		0.06		0.114
99.03		100.44		100.83		100.36		100.18		100.26

246	257	270	281	329
3.5	3.3	1.9	3.2	2.2
32.0	37.3	32.7	36.7	37.4
40.3	28.5	40.2	26.0	27.1
12.6	15.2	13.4	21.7	11.2
15.1	19.0	13.7	15.6	24.3
0.60	0.31	0.39	0.38	0.38
0.81	0.71	0.66	0.76	0.91
0.31	0.53	0.33	0.83	0.41
+86	+81	+115	+119	+132

					[1]		[1]		[1]
An$_{50-60}$	25.5	An$_{35-55}$	39.5	An$_{35-45}$	25.5	An$_{50}$	38.0	An$_{25-35}$	33.2
	30.5		28.5		36.0		31.9		30.5
	8.7		5.2		0.7		6.2		9.8
	—		—		—		—		—
	—		—		—		—		—
	20.8		13.8		13.4		11.8	}	12.5
	—		—		—		—		
	—		—		—		—		—
}		}			17.4		5.6		8.8
	13.8		11.2		0.4		1.9		—
					6.0		2.0		3.8
	0.5		1.6		0.6		2.2		1.4
	—		—		—		—		—
	0.2		0.2		—		0.4		—
	100.0		100.0		100.0		100.0		100.0

10. Argillaceous black schist. Outokumpu mine, Mökkivaara shaft, 320-level.
11. Argillaceous black schist. Solansaari, Polvijärvi.
12. Phyllitic argillaceous black schist with pyritiferous »layers». Suopolvi, Polvijärvi.
13. Quartz-rich argillaceous black schist disseminated with pyrrhotite. Island of Kultakallio, western part of Lake Höytiäinen, Polvijärvi.
14. Quartz-rich argillaceous, phyllitic, black schist. Viitalampi, Polvijärvi.

Table VIII. Analyses of the calcareous black schists.
(Analysed in the laboratories of Outokumpu Co)

	15		16		17		18		19	
	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.
SiO_2	43.08	7 180	48.34	8 057	50.77	8 462	44.28	7 380	53.90	8 923
TiO_2	0.59	74	0.57	71	0.53	66	0.50	63	0.60	75
Al_2O_3	8.03	787	10.86	1 065	10.86	1 065	8.49	832	10.72	1 051
Fe_2O_3	—	—	—	—	—	—	—	—	—	—
FeO	0.70	97	1.54	214	1.07	149	1.20	167	1.58	219
MnO	0.08	11	0.07	10	0.02	3	0.04	6	0.04	6
MgO	10.89	2 722	8.03	2 007	8.32	2 080	7.61	1 902	7.17	1 792
CaO	14.70	2 625	9.43	1 684	9.39	1 677	5.91	1 055	6.88	1 229
Na_2O	0.74	119	1.82	293	2.03	327	1.38	222	1.94	313
K_2O	1.85	197	1.10	117	1.99	212	1.16	123	2.53	269
H_2O+	0.98		1.42		1.11		1.10		1.42	
H_2O-			0.10							
P_2O_5	0.12	8	0.02	1	n. d.		0.00		0.00	
C	4.01		1.96		3.88		7.29		5.28	
CO_2	4.12	936	0.38	86	0.10					
F	0.15		0.04		0.06		0.07		0.04	
S	3.93		5.10		3.80		8.23		3.20	
Fe(S)	6.23		8.75		5.68		12.72		4.36	
FeS_2	(—)		(—)		(0.63)		(—)		(1.83)	
FeS	(10.06)		(13.66)		(8.61)		(20.75)		(5.66)	
V_2O_5	0.14		0.13		0.18		0.06		0.06	
	100.34		99.66		99.79		100.04		99.72	
Niggli numbers										
si	109		150		154		171		184	
ti	1.1		1.3		1.9		1.4		1.6	
al	12.0		19.7		19.2		19.2		21.5	
fm	43.1		41.5		40.5		48.3		41.4	
c	40.0		31.2		30.5		24.6		25.2	
alk	4.9		7.6		9.8		7.9		11.9	
k	0.63		0.29		0.39		0.35		0.47	
mg	0.96		0.90		0.93		0.91		0.87	
c/fm	0.93		0.75		0.75		0.51		0.61	
qz	—11		+20		+15		+39		+36	
Mineral composition.										
Weight percentage		[1]		[1]						
Plagioclase	An_{68}	19.1	An_{55}	34.1	An_{40-46}	31.7	An_{50-55}	21.9	An_{45-50}	30.5
Quartz		—		6.3		6.0		12.8		12.3
Potash-feldspar		10.8		6.5		11.7		2.2		12.3
Tremolite		44.8		35.3		26.0		25.8		26.9
Diopside		—		—		10.2		—		—
Biotite		—		—		—		} 8.1		
Chlorite		—		—		—				2.1
Muscovite		—		—		—		—		1.7
Iron sulphides		10.0		13.6		} 13.1		} 28.0		} 12.8
and oxides		—		—						
Graphite		4.0		2.0						
Sphene		1.4		1.2		1.3		1.2		1.4
Calcite		9.4		0.9		—		—		—
Accessories		0.5		0.1		—		—		—
		100.0		100.0		100.0		100.0		100.0

Notes on the braces: in column 18, one value (8.1) is given for Biotite and Chlorite together. In columns 17, 18 and 19, one value is given for Iron sulphides and oxides and Graphite together.

[1] Calculated from the analysis.

15. Amphibole-rich black schist. Mulo, Pyhäselkä.
16. » »sheaf» schist. Sukkulansalo (drill core Oku 129), Kuusjärvi.
17. Calcareous black schist. Matovaara (drill core 112a, 639 m), Outokumpu.
18. Gneissose amphibole-bearing black schist. Mielonen, Itkonsalo, Kuusjärvi.
19. Amphibole-rich black schist. Luikonlahti, Kaavi.
20. Coarse-grained amphibole-bearing black schist. Ulla (drill core 115 a), Kuusjärvi.

Table IX. Analyses of the intermediate sulphide- and graphite-bearing schists (Analysed in the laboratories of Outokumpu Co)

20		Average comp.	21		22		23		24		25	
%	Mol. prop.		%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.	%	Mol. prop.
48.21	8 035	48.09	53.24	8 873	39.27	6 545	65.97	10 995	69.02	11 503	87.04	14 507
0.65	81	0.57	1.50	187	0.49	61	0.66	83	0.67	84	0.21	26
9.90	971	9.81	17.79	1 744	10.17	997	12.51	1 226	11.99	1 175	1.06	104
—	—	—	—	—	—	—	—	—	—	—	0.12	8
1.05	146	1.19	1.22	169	2.23	310	3.51	488	4.86	675	0.54	75
0.02	3	0.04	0.04	6	0.04	6	0.04	6	0.03	4	0.03	4
4.53	1 133	7.75	3.55	887	2.74	685	2.99	748	2.13	532	1.28	320
5.37	959	8.61	6.12	1 093	4.48	800	1.72	307	2.76	493	2.20	393
2.14	345	1.67	3.27	527	1.01	163	2.94	474	2.32	374	0.23	37
2.16	230	1.79	2.87	305	3.88	413	2.35	250	1.68	179	0.23	24
0.85		1.16	1.10		3.20		1.37		n. d.			
					0.02						0.53	
n. d.		0.03	0.35	25	0.08	6	0.01	1	n. d.		0.02	1
5.45		4.64	0.05		2.61		1.96		1.49		0.37	
0.10		1.17	0.42				n. d.		0.08		1.22	
0.07		0.07	0.18				0.06		n. d.		0.08	
9.40		5.61	3.30		15.36		1.66		0.70		1.83	
9.86		7.93	5.34		13.38		2.67		1.12		2.25	
(12.91)		(2.56)	(—)		(28.74)		(—)		(—)		(1.27)	
(6.13)		(10.81)	(8.60)		(—)		(4.33)		(1.73)		(2.66)	
0.08		0.10	0.05		n. d.		0.06		0.01		0.04	
99.84		100.23	100.39		98.96		100.48		98.86		99.28	
212			187		194		313		335		1 511	
	2.1			4.0		1.8		2.3		2.3		3.1
	25.6			36.7		29.6		35.0		34.4		10.4
	33.8			22.6		29.9		35.6		35.3		42.7
	25.3			23.0		23.7		8.8		14.3		40.6
	15.3			17.7		16.8		20.5		16.3		6.3
	0.40			0.37		0.72		0.35		0.33		0.33
	0.88			0.83		0.67		0.60		0.44		0.80
	0.75			1.02		0.79		0.25		0.41		0.95
+ 51			+ 16		+ 27		+131		+170		+1 386	
	1)			1)		1)				1)		1)
An_{30-40}	30.2		An_{30-40}	45.9	An_{58}	20.2	An_{20}	31.3	An_{33-38}	31.9	An_{25}	2.6
	11.9			15.1		14.0		41.2		41.7		84.0
	11.5			7.2		18.5		3.9		—		—
	18.5			2.8		—		—		—		—
	—			—		6.9		—		—		2.6
	1.8			—	}	6.6	}	15.6		18.7	}	2.4
										—		
	—			14.6		—		—		—		
	19.0			8.6		28.8				1.7		4.0
	—			—		1.2	}	6.3		0.4		0.7
	5.5			—		2.6				1.5		0.4
	1.6			3.6		1.2		1.6		1.1		—
	—			1.0		—		—		—		2.8
	—			1.2		—		0.1		3.0		0.5
	100.0			100.0		100.0		100.0		100.0		100.0

21. Arkosic layer in phyllitic black schist. Kultakallio, Polvijärvi.
22. Sheared pyrite-rich black schist. Outokumpu mine, Keretti shaft, 320-level. Analyst. H. B. Viik.
23. Graphite- and sulphide-bearing quartz-rich black schist. Kyykeri, Outokumpu.
24. » » » quartz-rich mica schist. Kupinpuro, Polvijärvi.
25. Black quartzite. Outokumpu mine, Keretti shaft, 285-level.

The most characteristic feature distinguishing the black schists of the Outokumpu region — and setting them apart as a separate species of rock — is their rather high carbon and sulphide content. It ranges from a few per cent to 30 %, the mean carbon content being about 5 %. The sulphur content analysed represents the same order of magnitude; in the argillaceous varieties rich in mica it corresponds to the carbon content, varying within the same limits (Fig. 40). In the fine- and coarse-grained layers of the schist, as has been previously observed, the carbon and sulphide contents differ. The term black schist is applied in this study to schists in which both the carbon and the sulphur content exceeds about 1 %. At this point the schist begins to assume a black colour (see p. 100).

Although the iron content of the carbon-beaiing schists is usually considerable, only a small part of it is linked with the silicates. The dark colour of the black schists is due exclusively to the fine-grained graphite, the FeO-content ranging from 1 to 2 %. This is a characteristic feature of different black schist varieties, revealed as a poverty of iron in their silicate minerals. Only in certain black schists intermediate to mica schist is the FeO-content greater. The same might be said of the alumina and silica-contents; the latter is considerably lower than in the phyllites and mica schists. The quantities of calcium and magnesium are always greater in all the black schists (Tables VII, VIII and IX).

The aluminium content of the argillaceous black schists is relatively constant both in the quartz-poor and quartz-rich varieties. Only in the schist layers containing carbon in abundance has the alumina content been observed to rise as high as 20 % (Table VII, No. 6). On the other hand, the amounts of calcium and alkalies vary in such a way that the layers poor in quartz and rich in carbon contain calcium in greater abundance and alkalies in lesser abundance. The plagioclase of the black schists poor in quartz and rich in carbon is rich in anorthite. The extreme carbon-rich specimens also apparently contain an abundance of plagioclase, but on account of their fine grain it cannot be identified, and the assumption is based on the mineral composition obtained from the chemical analysis (Table VII, Nos. 5—7).

As the amount of quartz increases, the amount of alkalies increases, while the calcium correspondingly diminishes. Thus the sum of the c- and alk-values remains approximately unchanged, with the al-values varying within narrow limits. As will be seen from the al- (c + alk) diagram (the aluminium excess) (Fig. 41), the argillaceous black schist varieties occupy the same horizontal field below the mica-rich phyllites and mica schists of the region. The mean excess aluminium of the mica-rich schists is approx. + 10.0 and of the argillaceous black schists + 1.5.

As might be expected, the MgO-content and the mica content of the schists correspond to each other. A moderate mica content, varying between

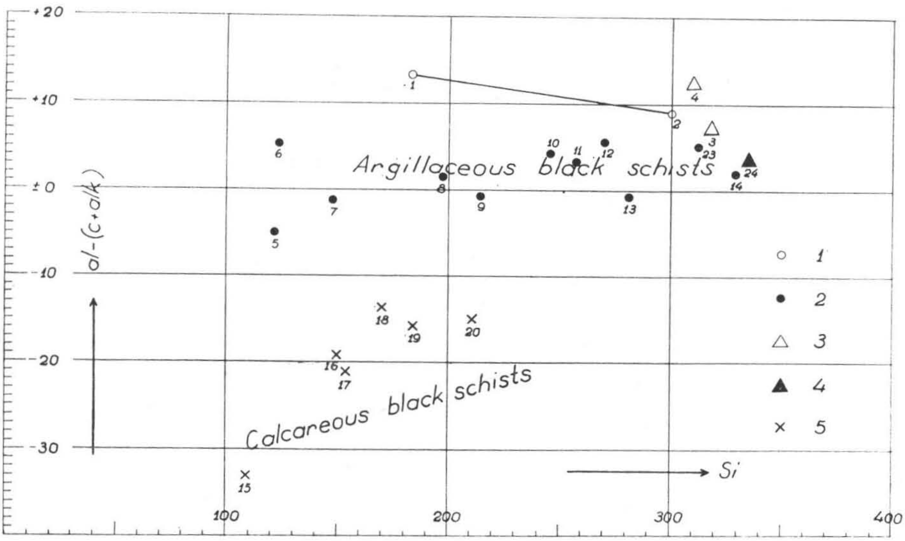

Fig. 41. The al- (c + alk) diagram of the Karelian supracrustal rocks in the Outokumpu region. 1. phyllites; 2. argillaceous black schists rich in mica; 3. mica schists; 4. carbon-bearing mica schists; 5. calcareous black schists rich in amphibole. The numbers refer to the chemical analyses in Tables I, VII, VIII and IX.

12 and 21 %, is a common feature of all the argillaceous black schists, but they are nevertheless consistently poorer in mica than the associated phyllites and mica schists. The mean al- (c + alk) value (+ 1.5) reflects their low aluminium excess.

As the black schists grade into dark, quartzitic varieties, their carbon and sulphide content may be observed to decrease rapidly. The same thing occurs in regard to the other components, the amount of calcium rapidly diminishing, as shown by the decrease in the anorthite content of the plagioclase. As was observed in the course of the mineralogical examination of the black schists, the region is lacking in originally arenaceous formations rich in carbon. The dark quartzites, which occur in the transitional zones of the carbon-bearing schists, usually contain some sulphides (mainly pyrite), but only locally are there small amounts of graphite (Table IX, No. 25).

The al- (c + alk) diagram of the carbon- and sulphide-bearing schists shows, furthermore, that the calcareous, evidently originally marly, black schists stand apart most clearly as a separate group. Common to the amphibole-rich »sheaf schists» is a high CaO- and MgO-content and a marked deficiency of alumina, the average Al_2O_3-content being about 3 % and the SiO_2-content about 6 % lower than in the argillaceous black schists. The alkali contents are also smaller, causing corresponding changes in the mineral composition. Typical, alongside the abundant amphibole (approx. 20—45 %), is an anorthite-rich plagioclase (An_{40-70}), ranking next in quantity, a low content of quartz (0—10 %) and mica (2—8 %), and the regular presence of potash feldspar, the content of which is likely to be as high as 10 %. In many places there is, in addition, carbonate, which on the basis of X-ray determinations has been observed to consist of calcite.

The amounts of carbon and sulphides are of the same order as in argillaceous varieties rich in mica, but they are not so closely dependent on each other or on the amount of quartz. The amount of iron bound to the sulphides is comparatively larger than in the argillaceous varieties and is revealed in the predominance of pyrrhotite, typical of the amphibole-rich, calcareous varieties.

The amounts of iron linked to the oxygen and sulphur have been indicated separately in the accompanying tables VII, VIII and IX, while the proportions of pyrite and pyrrhotite have been calculated (in parentheses). This has been possible on the basis of the determination of oxidic iron planned by Mr. L. Kosomaa and performed in the Outokumpu laboratory of the Outokumpu Company.

The specimen from which the total iron, S, Cu, Zn, Ni and Co had previously been determined, was dissolved in hydrochloric acid (1 : 4) within a boiling flask furnished with a vertical condenser, and from the dissolved part the Cu, Zn and Fe were determined. The dissolved iron was regarded as having been derived from the pyrrhotite and chalcopyrite, always observed in the polished section of the specimens in question. The amount of iron corresponding to the dissolved Cu was subtracted from the total iron dissolved, whereupon the iron of the pyrrhotite was obtained and from this the pyrrhotite itself. Further, the sulphur content corresponding to the Cu, Zn, Ni and Co contents of the whole sample and of the dissolved pyrrhotite were added together and their sum subtracted from the total sulphur, from which the sulphur content of the pyrite and the amount of pyrite itself were obtained. Finally, the sum of the iron bound by the pyrite, pyrrhotite and chalcopyrite was subtracted from the amount of total iron. The result was oxidic iron (generally indicated in the tables as FeO).

On account of the fine grain, the mineral composition of the samples has in many cases had to be calculated from the analysis. The mineral composition of only the coarse-grained black schist samples has been determined by means of the integration stage and given in the accompanying tables as weight percentages (for the sake of uniformity). With the exception of a sample analysed by Dr. H. B. Wiik at the Geological Survey of Finland (Table IX, No. 22), all the analyses appearing in the tables have been carried out at the laboratories of the Outokumpu Company at Pori and at Outokumpu.

TRACE ELEMENTS

In addition to the major elements, a number of trace element determinations were carried out at the laboratories of the Outokumpu Company, a considerable part being performed spectrographically. Some of the determinations were carried out by means of different methods. The vanadium determinations (accurate to the second decimal place) were done colorimetrically by using filters as well as a spectrophotometer.

Those trace elements have been chosen for investigation which are known from a geochemistry basis to become enriched in carbon- and sulphide-bearing marine sediments and which occur in great abundance in the black schists of the region (Table X). For the sake of comparison the corresponding trace element determinations in the other rocks of the region have been included (Table XI). These are largely taken from the publications of Haapala (1936) and Vähätalo (1953).

Table X. Contents of trace elements in various carbon- and sulphide-bearing schists. For the specimen numbers see Tables VII, VIII and IX

No	%													g/t	
	TiO_2	MnO	Cr_2O_3	V_2O_5	U_3O_8	Cu	Ni	Zn	Co	Pb	Mo	C	S	Se	Ag
	Argillaceous black schists														
5	1.45	0.04	0.45	0.04	0.001	0.03	0.04	0.01	0.02	0.005	0.030	28.42	1.45	n. d.	n. d.
6	1.03	0.04	0.15	0.23	0.002	0.07	0.10	0.07	0.01	0.010	0.030	13.36	5.32	17.0	5.0
7	0.98	0.04	0.15	0.20	0.001	0.07	0.04	0.03	0.05	0.010	0.030	7.62	10.48	3.0	3.0
8	0.92	0.04	0.10	0.10	0.014	0.03	0.04	0.01	0.10	0.003	0.003	7.26	5.26	6.0	7.0
9	0.62	0.03	0.03	0.09	0.004	0.07	0.08	0.03	0.03	0.003	0.007	6.08	6.10	n. d.	n. d.
10	1.08	0.03	0.12	0.09	0.008	0.08	0.02	0.09	0.01	0.007	0.030	4.00	2.90	30.0	1.0
11	1.06	0.04	0.05	0.11	0.001	0.02	0.03	0.01	0.02	0.003	0.010	3.22	2.83	n. d.	n. d.
12	0.47	0.03	0.03	0.11	0.005	0.06	0.05	0.05	0.02	0.005	0.015	6.00	7.80	n. d.	1.0
13	0.93	0.03	0.12	0.11	0.004	0.02	0.02	0.01	0.01	0.005	0.010	2.03	2.04	n. d.	1.0
14	0.59	0.03	0.03	0.06	0.002	0.05	0.02	0.01	0.02	0.005	0.010	3.82	3.90	n. d.	1.0
	0.83	0.04	0.08	0.11	0.005	0.05	0.04	0.03	0.02	0.005	0.014	5.00	5.16	(13.0)	2.0
	Calcareous black schists														
15	0.59	0.08	0.05	0.14	0.001	0.03	0.04	0.02	0.01	0.007	0.010	4.01	3.93	4.0	2.0
16	0.57	0.07	0.03	0.13	0.003	0.07	0.04	0.03	0.02	0.003	0.007	1.96	5.10	n. d.	n. d.
17	0.53	0.02	0.08	0.18	0.010	0.08	0.01	0.12	0.01	0.003	0.047	3.88	3.80	60.0	1.0
18	0.50	0.04	0.07	0.06	0.011	0.06	0.10	0.03	0.01	0.007	0.010	7.29	8.23	7.0	n. d.
19	0.60	0.04	0.10	0.06	0.012	0.02	0.03	0.01	0.01	0.003	0.003	5.28	3.20	5.0	n. d.
20	0.65	0.02	0.11	0.08	0.007	0.08	0.06	0.03	0.01	0.007	0.030	5.45	9.40	50.0	2.0
	0.57	0.05	0.07	0.11	0.007	0.06	0.05	0.04	0.01	0.005	0.018	4.65	5.61	25.0	2.0
	Intermediate carbon- and sulphide-bearing mica schists and quartzites														
23	0.66	0.04	0.15	0.06	0.006	0.02	0.04	0.01	0.01	0.005	0.005	1.96	1.66	2.0	n. d.
24	0.67	0.03	0.01	0.01	n. d.	0.02	n. d.	0.07	n. d.	n. d.	n. d.	1.49	0.70	n. d.	n. d.
25	0.21	0.03	0.18	0.04	0.001	0.01	(0.19)	0.01	0.01	0.003	0.008	0.37	1.83	n. d.	2.0

Table XI. Contents of the trace elements of the rocks of the Outokumpu region (The figures in parentheses represent a smaller number of determinations than indicated below.)

No	%													g/t	
	TiO_2	MnO	Cr_2O_3	V_2O_5	U_3O_8	Cu	Ni	Zn	Co	Pb	Mo	C	S	Se	Ag
1	(0.01)	0.05	0.01	0.014	n. d.	3.80	0.12	1.00	0.24	0.005	(0.001)	n. d.	25.3	47.0	9.0
2	0.01	0.02	0.23	0.019	(0.001)	0.01	0.12	0.04	0.01	(0.003)	0.005	n. d.	n. d.	n. d.	(2.0)
3	0.02	0.11	(0.15)	0.012	n. d.	0.02	(0.10)	0.05	0.01	n. d.	n. d.	0.06	n. d.	n. d.	n. d.
4	(0.01)	0.11	0.21	(0.017)	n. d.	(0.03)	(0.10)	(0.10)	(0.01)	n. d.	n. d.	tr	0.25	n. d.	n. d.
5	0.01	0.14	0.52	0.011	n. d.	0.03	0.18	(0.16)	0.01	n. d.	n. d.	n. d.	(1.60)	n. d.	n. d.
6	0.77	0.03	0.02	0.030	(0.003)	0.02	(0.01)	(0.01)	(0.02)	(0.003)	0.001	0.70	0.70	n. d.	n. d.
7	0.83	0.05	0.02	0.040	0.003	0.02	0.01	0.01	0.02	0.005	0.002	0.67	0.80	n. d.	(2.0)
8	0.71	0.04	0.08	0.110	0.006	0.06	0.04	0.04	0.02	0.005	0.016	4.85	5.35	20.0	2.0

1. Outokumpu ore, average composition.
2. Quartzite from different parts of the mine. Average composition of four specimens.
3. Skarn rock from different parts of the mine. Average composition of six specimens.
4. Dolomite rock, the middle part of the Outokumpu zone. Average composition of five specimens.
5. Serpentinite, the middle part of the Outokumpu zone. Average composition of eight specimens.
6. Mica schist from the Outokumpu zone. Average composition of three specimens.
7. Phyllite, average content of two specimens in Höytiäinen area.
8. Black schist, average content of 17 specimens.

TITANIUM

The rocks richest in titanium are the micaceous, Al_2O_3-rich schists, the amounts ranging in the phyllites and mica schists from 0.71 to 0.87 % TiO_2 (Table I, Nos. 1—3) and in the argillaceous black schists from 0.47 to 1.45 % TiO_2 (Table X, Nos. 5—14). As in the case of the phyllites and mica schists, the titanium content of the black schists is observed to be approximately proportional to the Al_2O_3-content. The average titanium content of the argillaceous, carbon-bearing schists is 0.83 % TiO_2, the corresponding value in the aluminium-poor, calcareous varieties being 0.57 % TiO_2 (Table X). In this connection it might be mentioned that titanium in the aluminium-rich schists of southern Lapland varies, according to Sahama (1945) from 0.91 to 1.05 % TiO_2, and the TiO_2-content of the black schists there rises as high as 4.60 % (Mikkola 1941). According to Goldschmidt (1954, p. 411), the average titanium content of hydrolyzate sediments is 0.46 % Ti.

CHROMIUM

The chromium content of micaceous schists is very low, varying in phyllites and mica schists from 0.015 to 0.04 % and in black schists from 0.03 to 0.15 % Cr_2O_3. The chromium is known to substitute in the silicates for trivalent iron and aluminium and to become enriched together with these elements in hydrolyzate sediments and the weathering residues. The

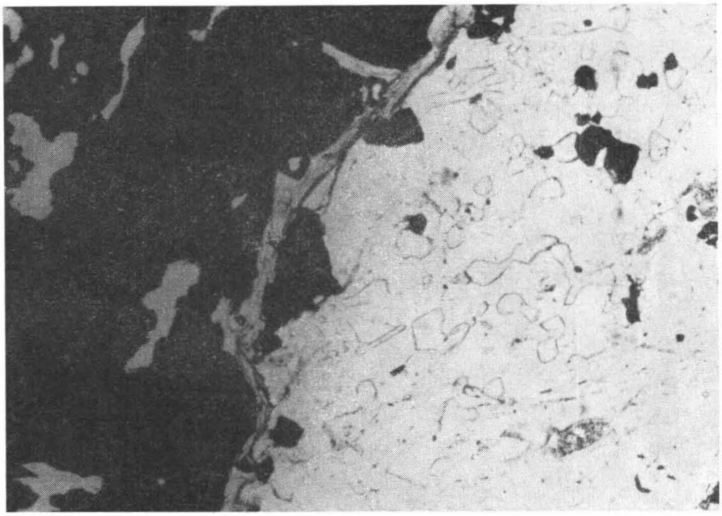

Fig. 42. Fuchsite as a long, coherent stripe at the contact between granite and black schist. Drill hole R 51, 87 m, Luikonlahti, Kaavi. 50 x.

chromium content of the hydrolyzate sediments is reported by F. W. Clarke (1924) to be 500 ppm. Cr_2O_3; but according to other researchers the value 200 ppm. Cr is closer to the mean value (0.03 % Cr_2O_3).

The mean chromium content of the black schists, 0.08 % Cr_2O_3, is somewhat above the value 0.02 % Cr_2O_3 for the phyllites and mica schists of the area. No appreciable variation among the different varieties of the black schist is to be detected (Table X). In certain portions of the schist rich in carbon and aluminium, the chromium content rises locally to 0.45 % Cr_2O_3. According to Sahama (1945), the black schists of Lapland contain an average 0.06 % Cr_2O_3, while Leutwein (1951) reports the chromium content of the carbon-bearing alum schists in the Thüringen region to vary 0.006—0.03 % Cr_2O_3. The local concentration of the chromium in metamorphic reduzate sediments is explained to be due to the precipitation of chromium under reducing conditions.

One should take a critical view of the chromium contents reported from the region on account of the abundant occurrence of serpentinite. The chromium mineralization encountered near the ultrabasic formations is obviously hydrothermal-metasomatic, as Saksela (1923), Eskola (1933), Haapala (1936) and Vähätalo (1953) have pointed out.

Scattered grains of fuchsite are met with in the black schists, often being arranged along the margins of the sulphide as seams consisting of several grains (Fig. 42) or, less often, as inclusions in the pyrrhotite.

VANADIUM

The vanadium contents determined in the phyllites and mica schists of the Outokumpu region vary within the same limits, in the phyllites, 0.03 to 0.05 % V_2O_5 and in the mica schists, 0.02 to 0.04 % V_2O_5. These values correspond to those of similar though younger formations: according to K. Jost (1932), the V_2O_5-content of shales is about 0.02 % (120 ppm. V), the values presented by Clarke (1924) for normal hydrolyzate sediments vary from 120 to 240 ppm. V, while the average content of V. M. Goldschmidt's (1921) Ordovician phyllites of the Stavanger district is 200 ppm. V (0.04 % V_2O_5).

In examining the vanadium contents of the different rocks of the region, one's attention is drawn primarily to the black schists, whose mean V_2O_5 % (0.11) stands clearly apart from the others and is highest (Table XI). The amount varies in both the argillaceous and calcareous black schists from 0.06 to 0.20 % V_2O_5 (Tables VII and VIII). In certain layers extremely rich in carbon and aluminium, the vanadium content is higher still. The vanadium content of mica schists and dark quartzites poor in sulphide and graphite is smaller and varies within the same limits as in the phyllites and mica schists (0.01—0.06 % V_2O_5) (Tables IX, X and XI).

The carbon-bearing clay sediments and younger shales have consistently been observed to be richer in vanadium than the corresponding carbon-free sediments. According to Archangelsky and Koptschenowa (1930) the vanadium content of the deeper bottom sediments completely free from oxygen in the Black Sea is 0.03—0.06 % V (0.05—0.1 % V_2O_5). The same may be said of the more highly metamorphozed derivatives of these sediments. Jost (1932) observed that the highest vanadium contents generally occur in clayey, bituminous schists, whose average content in Central Sweden, according to Lundegårdh (1946) is 1 000 g/ton V or 0.18 % V_2O_5. The vanadium content of the Ordovician Dictyograptus schist of Sweden and Norway is still higber (1 000—3 000 g/ton V). According to Rankama (1948), the shungite of East Fennoscandia (1st variety from Shunga, KFSSR) contains 0.12 % V_2O_5, the carbon of the phyllites of the Tampere schist area contains 0.001—0.011 % V_2O_5 (Corycium), the graphite in various carbon-bearing phyllites (Kalkkimaa, Kemi) and schists (Paakki, Paltamo) contains 0.04 % V_2O_5 and the graphite of Mäntyharju 0.12 % V_2O_5. The alum shales investigated by Leutwein (1951) in Central Europe contain significant amounts of vanadium, particularly the shales richest in carbon, which contain 250—2 500 g/ton V, the average content being 700 g/ton V (0.12 % V_2O_5). James (1951) has observed a V_2O_5-content of 0.15 % in the graphite shales of the Iron River district. Marmo (1957) reports the vanadium content of the graphite-bearing amphibolites of Nokia to vary from 0.005 to 0.1 % V_2O_5.

The consistency observed by Jost between the vanadium content and the organic matter is not always to be perceived in the black schists of the Outokumpu region. However, it is roughly valid for the varieties of schists richest in carbon and for the carbon-poor mica schists and quartzites. According to Assarson (1941), the vanadium (as well as molybdenum and wolfram) contents of the alum shales of Sweden are not proportional to their content of organic matter, and he assumes that these metals have originally precipitated as sulphides.

Signs tending to support such an assumption are provided by certain observations which have been made in investigating the possible vanadium mineral in the black schists of the Outokumpu region (see p. 67).

COPPER, ZINC AND MOLYBDENUM

In the distribution of copper and especially molybdenum in the various rocks of the region, one notices the same type of regularity as in the occurrence of vanadium (Table XI). They are contained in greatest amounts in the black schists, the molybdenum varying from 0.003 to 0.047 % Mo, and the copper from 0.02 to 0.08 % Cu. On the other hand, no corresponding enrichment in the zinc content can be detected, although sphalerite is often to be seen megascopically as local concentrations. The average contents in the black schists are: 0.06 % Cu, 0.04 % Zn and 0.016 % Mo. As a significant observation regarding the distribution of these elements in different carbon- and sulphide-bearing schists, it should be pointed out that the black schists richest in molybdenum are usually also rich in copper, vanadium and chromium. This is observed to be true in the case of both argillaceous and calcareous varieties (Table X). Evidently the concentration of these elements in the black schists corresponds to their general geochemical character in exogenic differentiation.

The concentration of Cu, Zn and Mo in carbon- and sulphide-bearing schists has been thoroughly investigated for formations of different ages. For example, the copper content of the Ordovician black schists of Sweden and Norway is usually 0.1 % Cu. According to Leutwein (1951), the copper and zinc contents of the alum and sulphide shales of Westphalia vary from 0.001 to 0.05 %. The range of variation of molybdenum there is from 0.001 to 0.01 % Mo and the average content in the sapropelites of Thüringia is 0.025 % Mo. In the shungites of eastern Fennoscandia the Mo-content rises, according to Sudovikov (1937) and Rankama (1948), to between 0.005 and 0.01 % MoO_3. According to Marmo (1957), molybdenum occurs in small amounts in all the schists of the Nokia region (SW-Finland). The copper content of the region's sulphide schists varies from 0.005 to 0.025 % Cu.

URANIUM AND LEAD

Uraninite has frequently been observed in the black schists, and the content of uranium varies from 0.001 to 0.014 % U_3O_8. The uranium contents have been determined only from the schist formations of the region, and the highest values occur in the black schists. Radiation measurements carried out in the Outokumpu mine with a Geiger counter or a scintillometer, show that the strongest anomalies consistently occur in conjunction with the black schist horizons.

In the black schists of the Outokumpu region, a substance closely resembling thucholite has been observed under the microscope (Fig. c, Pl. I). Under very high magnifications, the uraninite inclusions in the middle of the »thucholites» are usually seen to contain galena in the form of minute grains (Fig. d, Pl. I), which are interpreted according to Ramdohr (1958 b) as daughter products of the uranium. Part of the lead of the black schists would thus be radiogenic.

ORIGIN

In examining the mode of occurrence and stratigraphy of the black schists, one will notice the conformable appearance of all the different horizons, many of which have a great lateral extent. The variations in the characteristic compositions and structural features of the black schists are recurrent from layer to layer. Their close association as layers alternating with phyllites, mica schists and, in part of the region, with quartzites, and their conformable gradations in the transitional zones, indicate that the depositional environment of the carbonaceous schists is the same as that of whole schist formation.

Like the phyllites and in many places the mica schists, the black schists are often clearly bedded in structure. The varved structure, which may be observed in better preserved forms in the phyllites, occurs sporadically in the black schist deposits. Accordingly, it cannot be decided for sure whether graded bedding is a characteristic structural feature of the original carbon- and sulphide-bearing sediment. Nevertheless, a bedded structure has been met with in certain younger Jatulian phyllitic black schists (Eskola, 1932). The fine-grained micaceous layers are usually carbon-rich and correspond to the original argillaceous layers, while the coarse-grained quartz-rich layers represent the original arenaceous layers. A similar sort of alternation also occurs in the calcareous black schists, the coarse layers being amphibole-rich, representing original marly deposits. Such variation between individual layers must be regarded as a feature preserved from the bedding of the original sediment. It is even observed in the most highly recrystallized black schists. The alternation of layers rich in mica, amphibole and quartz thus reflects variations in the composition of the original sediment.

The thinness of individual layers reflects slow sedimentation, which is characteristic of numerous carbon- and sulphide-bearing formations of different ages. In corresponding younger formations, according to Pettijohn (1957 p. 363), a paper-thin bedding is due in part to colloidal material being pressed together after sedimentation. Carbonaceous layers in the phyllite area have been observed to vary in thickness between 0.3 and 3.0 mm, while corresponding carbon-free layers are ten times as thick.

The carbon-rich layers of different black schist varieties are consistently finer in grain-size than the carbon-poor or -free layers alternating with them. Recrystallization due to the increasing intensity of metamorphism, which is to be noticed in the carbon-free schists as a gradual transition into mica schists and gneisses, takes place in carbon-bearing layers considerably more slowly. In the carbon-rich varieties of the more highly metamorphozed black schists, a bedded structure is therefore to be seen, still as distinct as the original. The effect of the carbon in preserving the original sedimentary structure provides, in Eskola's (1932) opinion, strong evidence for the assumption that the carbon is an original constituent of the sediment. The most highly metamorphozed, graphite-bearing deposits of the Outokumpu region — which are often massive in structure — constitute in this respect an exception. In them the protective influence of the carbon can no longer be detected, for all the carbonaceous matter in them has recrystallized, along with the other minerals, into coarse-grained graphite flakes.

In addition to the carbon, the sulphides occur in all the varieties of black schist, irrespective of metamorphic grade. The sulphide content increases in the argillaceous black schists simultaneously with an increase in the carbon content (Fig. 40). This is regarded by Laitakari (1925), Väyrynen (1928) and Pettijohn (1943) as evidence for the common origin of the sulphides and the carbon. The original depositional conditions are also reflected by variations in the composition of the sulphides in different layers; the fine-grained, micaceous layers contain pyrrhotite, whereas the coarse- grained, quartz-rich layers are often rich in pyrite. Evidence of the simultaneous recrystallization of the sulphides and the silicates is provided by the orientation of the sulphide crystals parallel to the mica minerals and at the same time to the original bedding. This is explained by Skinner (1958), working on the pyritic formation of Nairne (South Australia) as due to the orientation of the mica, with its greater force of crystallization, and the emplacement of the sulphides in the interstices. The syngenetic origin of the sulphides helps to explain the absence of graphite inclusions from the sulphides of the less metamorphozed schists, whereas the inclusions are consistently found in the sulphides cutting through the bedding (see pp. 65—66 and Fig. b, Pl. III).

According to Laitakari (1925) and Eskola (1932), the Archean carbon- and sulphide-bearing schists correspond to bituminous shales and are thus original sapropelic sediments, in which the carbon is organic. The genesis of carbon and sulphides presupposes reducing conditions, a requirement satisfied only by marine conditions (Pettijohn, 1943). According to Mac Carthy (1926), the black or dark-grey colour of the black schists is in itself a guide to the nature of the reducing environment. Rankama's (1948) studies on the carbon of the *Corycium enigmaticum* found in the Tampere schist area, and that of certain graphite-bearing schists show, according to the isotope ratios C^{12}/C^{13} an organic origin. Thode (personal communication to Dr. O. Kouvo) and Ault (1957) have investigated the isotopic contents of the pyritic sulphur contained in the black schists of the Outokumpu region. The s^{32}/s^{34} ratio varies from 22.32 to 22.45 (Kouvo, 1958, p. 60).

The trace element contents of the black schists of the Outokumpu region show regularities in the distribution of certain elements. These can be ascertained to correspond to the geochemical character of the element in the exogenic differentiation and to be in harmony with the genesis of the carbon- and sulphide-bearing formations. The occurrence of trace elements in the reduzate sediments and their metamorphic derivatives of different ages has been thoroughly investigated. A number of such rather rare trace elements, generally associated with original sapropelites, have been described in connection with the chemical study of the black schists of the Outokumpu region, comparisons having been made with analogous formations of the same or younger age and with the other rocks of the region (see pp. 85—90).

In the different black schist varieties of the region the amounts of vanadium, molybdenum and copper are the same as those characteristic of the sapropelic sediments; the correlation is not quite so perfect for zinc, chromium, nickel and uranium. In their vanadium and molybdenum contents, the carbon- and sulphide-bearing schists are conspicuously different from the other rock types of the region. The copper, zinc and uranium contents are higher than in the other schists, but because of the serpentinites, the chromium and nickel contents can not safely be compared with the other schists. As evidence of the intimate association of trace elements with the black schists, the sulphide- and graphite-rich varieties contain trace elements in greater amounts than normal, whereas the intermediate mica schists and quartzites with a lower carbon and sulphide content are just as poor as the corresponding carbon-free mica schists. The cited trace element contents provide evidence of the quite different depositional conditions of the black schists and the other metasediments.

The concentration of the metals in the sapropelic sediment is explained as due to the precipitating effect of hydrogen sulphide-bearing deeper waters under the reducing conditions of a barred basin. In general, the metals are assumed to be precipitated as sulphides, while vanadium and certain other elements, such as uranium, are precipitated as hydroxides by reduction to lower valency states. It is very likely that the actual fixation of vanadium takes place as a sulphide, or as a sulpho-salt of some heavy metal.

Thorium has not been found in the Outokumpu black schists. In the kolm-schists of Sweden the thorium-uranium ratio is approximately 0.01 (Koczy, 1949) and in the Chattanooga shales 0.1 (Adams, Richardson and Templeton, 1958).

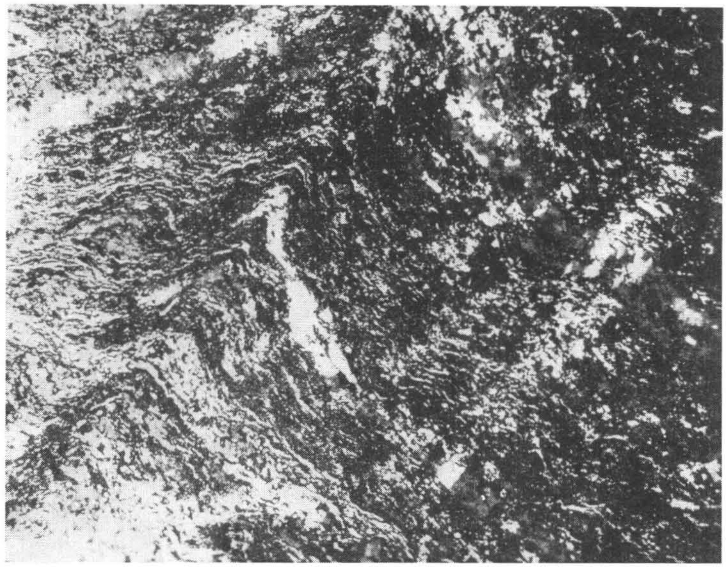

Fig. 43. Paper-thin and folded beds (lamination) in pelitic black schist rich in carbon. Mertala, Polvijärvi. One Nicol. 16 x.

The bulk composition of the carbon- and sulphide-bearing schists, which is ordinarily argillaceous and in many cases associated with calcareous or quartzitic layers, is analogous to numerous corresponding Pre-Cambrian and younger formations. The composition of different black schist varieties depends on conditions and factors connected with the original sedimentation. Slow deposition, which gives rise to thin lamination (Fig. 43), presupposes conditions under which the amount of clayey material transported from land to sea is small and slow and the sedimentation is largely chemical and biochemical. For this reason the original sapropelic sediment is likely in places to be rich in chemically or biochemically precipitated constituents. In the metamorphic derivatives this has had the effect of enhancing the content of carbonaceous, calcareous, sulphidic and possibly even the arenaceous matter. The black schists of the Outokumpu region are usually argillaceous. As their calcium and magnesium content increases, they become amphibole-rich, calcareous schists. Quartzite-like carbon- and sulphide-bearing schists occur locally, particularly in the transition zones of black schists and quartzites or as thin layers in the quartzite.

As has already been remarked, the mode of occurrence, the conformable alternation and the gradual transition of the black schists into other metasediments reveal that they originally belong to the surrounding schist formation. Their occurrence as continuous zones in the middle of the phyllite and mica schist formation reflects an exceptional change in the depositional environment and conditions in the geosynclinal basin. This is also indicated by the quartzites regularly associated with the black schist formation of the region, in the transition zone of which sulphide- and carbon-bearing varieties of quartzite are often encountered. The occurrence of the quartzites and quartzitic schists in association with the original sapropelic sediments is quite common elsewhere, in both older and younger analogous formations.

ANALOGIES AND COMPARISONS

The Kalevian schists of the Kainuu region are divided by Väyrynen (1928) into two different groups; the lower, the so-called Jaurakka facies, consists of conglomerates and quartzites, and the upper, the so-called Kaleva facies, of various phyllites, carbon- and sulphide-bearing schists and mica schists. In the upper schist sequence there are, first, strongly bedded phyllitic mica schists, which contain quartzitic and calcareous horizons. Above them are carbon- and sulphide-bearing phyllitic schists (termed by Väyrynen »carbon-bearing phyllites»), which alternate with quartzite, limestone and dolomite beds; highest in the stratigraphic sequence occur mica schists.

The mode of occurrence of the lower parts of the Kalevian formations in Kainuu is highly irregular, some deposits being locally absent. This is interpreted by Väyrynen as signifying a relief in the surface of the basement of deposition. Before the sedimentation of the Kalevian schists, there evidently took place considerable orogenic movements, because in character the Kalevian schists correspond to the flysch sediments of the other orogenic belts (Eskola, 1941).

The upper part of the Kainuu schist area and its stratigraphy resembles in many respects corresponding formations in North Karelia. In the Solansaari—Viitalampi and Outokumpu zones, lowermost in the former zone is a well-bedded, coarse-grained phyllite and lowermost in the latter zone a mica schist. They grade upwards in the stratigraphic sequence into black schists, which occur associated with quartzites and originally calcareous deposits. Uppermost occur micaceous schists as in the Kainuu region.

Saksela (1933 a) has described a sulphide- and graphite-bearing schist formation from Karhunsaari, in Liperi commune, which overlies a locally exposed basal complex, resembling in stratigraphy and composition corresponding occurrences on the western and northwestern side of the Sotkuma cupola. The basal complex consists of a cupola-like granite gneiss as well as arcosic, quartzitic rocks occurring as a weathering residue on the original floor. The thickness of the black schist zone varies between 50 and 500 meters and overlying it is a biotite-plagioclase gneiss (paragneiss), which in places rests directly on the basal formation.

In composition the black schists occurring in Karhunsaari resemble originally calcareous, carbonaceous deposits, with their abundant content of potash feldspar, pale amphibole and pyrrhotite. There also occurs pale magnesium mica, quartz, sphene and plagioclase, as in the argillaceous black schists of the Outokumpu region.

The carbon and sulphide material is regarded by Saksela as original, as indicated by the structure of black schists, and in composition they represent dolomite-bearing clay sediments.

The Lapponian system described from central Lapland by E. Mikkola (1941) consists mainly of quartzites and mica schists. Associated with them occur abundant volcanic greenstones and ultrabasic rocks. The quartzites are highly metamorphozed and the mica schists are in places rich in alumina.

The Lapponian system, which like the Kalevian schists have flysch characteristics (Eskola, 1941), in many places includes black schists. Among these, the carbonaceous varieties poor in alkali are associated with the graywacke slates of the area, whereas the soda-rich ones occur in association with volcanic greenstones and jasper quartzites. There also occur soda-rich sulphide schists which are nearly totally lacking in carbon. These have preserved a beautiful varved structure, in which coarse-grained pyrite layers grade upward into fine- grained black phyllite poor in sulphide. The thickness of the varves ranges from a few millimetres to one centimetre. The structure is regarded by Mikkola as original.

The carbon- and sulphide-bearing phyllites rich in chlorite and mica are associated in the Central Lapland area with dark hornblende-bearing schists. Sometimes the amphibole is cummingtonite, enclosed by anthophyllite. The hornblende is an indication of the original carbonate content of the sediment, and limestones frequently occur with the black schists. In the amphibole-bearing schists bedding is occasionally seen.

In regard to the structure and thickness of the layers, the black schists of Central Lapland resemble the phyllitic, carbonaceous and sulphide-bearing schists of the Höytiäinen area. The most striking difference in the chemical composition is a high (oxidic-) iron content, bound up in the dark biotite and hornblende, while there is a total absence of tremolite. Furthermore, the soda content differs from that of corresponding formations in the Outokumpu region. However, it should be noted that the ratio of alkalies in the carbon-rich schists is the same. The genesis of the sodic, carbon-poor schists of Central Lapland appears to be remotely related to the volcanic activity.

The Jatulian, comparatively weakly metamorphozed sediments of the Karelidic cycle include carbon- and sulphide-bearing rocks, which have afforded a splendid basis for comparison with, on the one hand, Pre-Cambrian carbonaceous schists and, on the other, Paleozoic and even younger alum-schists. Their generally clayey composition, sulphide content and better preserved sedimentogenic structure are characteristics common to them all.

In the upper part of the Jatulian system there are carbonaceous occurrences of the kind Metzger (1924) has investigated in the Suojärvi area, Hausen (1930) at Soanlahti and Sudovikov (1937) at Shungu, on the western coast of Äänisjärvi (Lake Onega). The most carbonaceous rocks are called shungite and they occur in many places with carbonaceous slates and dolomites, reflecting marine conditions of sedimentation.

Eskola (1932) considers not only the Jatulian but also the oldest carbonaceous phyllites of the Tampere area and the highly metamorphozed graphite-bearing paragneisses as derivatives of Pre-Cambrian alum schists. This is indicated by the aforementioned similarities in bulk composition and structure.

Argillaceous graphite-bearing deposits occur in abundance in the Archean area of Central and Southern Finland, where Sederholm (1897) demonstrated, according to the actualistic principle, that the Bothnian phyllites had originated under the same conditions as the present varved shales. The carbon sacs occurring in the varved phyllites of Aitolahti were described by him as fossils, which he termed *Corycium enigmaticum*. Rankama (1948) in his studies ascertained the carbon contained in them to be organic.

According to Laitakari (1925), the graphite occurrences of Finland are in origin either sedimentogenic, magmatic or metasomatic. Sedimentogenic are the occurrences involving limestones, phyllites, mica schists and paragneisses; the graphite content of clayey schists is regarded by Laitakari as being organogenic. In addition, he mentions that the graphite-bearing gneisses contain more aluminium than would be required for the formation of feldspar, the excess giving rise to cordierite, sillimanite and garnet. Andalusite and staurolite occur also in such gneisses (Eskola 1932). The potash content is small, while there is an abundance of calcium and hence plagioclase is present.

Almandite and andalusite occur occasionally in the gneissose black schists of the Outokumpu region. They are restricted by the abundant calcium content of the schists, which utilizes the Al_2O_3-content of the argillaceous sediment in the production of plagioclase.

In the black schists of Central Ostrobothnia (Keski-Pohjanmaa) described by Saksela (1932) there occur both micaceous and amphibole-rich varieties. The former consists of chlorite or biotite, microcline (locally abundantly), quartz and plagioclase. The varieties containing amphibole represent, according to Saksela, marly sediments, and together with actinolite, they include microcline, plagioclase and small quantities of sphene and quartz. The sulphide material occurring as an impregnation consists exclusively of pyrrhotite. In mineral composition these rocks are wholly analogous to the calcareous black schists of the Outokumpu region.

The black schists of Central Ostrobothnia and the basic volcanics associated with them in many cases overlie the leptite formation, which is the lowest member of the supracrustal complex. Higher up in the stratigraphic sequence are quartzites and limestones, while biotite-plagioclase gneisses and mica schists are the highest members of the entire schist formation.

Marmo and Mikkola (1951) apply the name sulphide schist to fine-grained schistose rocks whose primary components are quartz, mica, pyrrhotite and also sometimes graphite and shungite. A characteristic feature is their occurrence as alternating layers in micaceous schists that include calcareous or quartzitic layers. Further volcanic rocks are often associated with them. According to Marmo (1957), the sulphide schists of the Nokia area may be interpreted as marginal facies between the geosyncline and foreland. The skarn-like rocks found at Nokia would seem originally to have been lime-rich muds.

The graphite content of the Tampere schist belt and the sulpide schists of southern Finland is low. In the western parts of Central Finland the sulphide schists are richer in graphite; this is also true of the Karelian schist area of eastern Finland.

According to Marmo and Mikkola, the sulphide minerals constitute two generations in the sulphide schists. The sulphides of the older generation occur as narrow veins and lenses concordant to the schistosity, whereas the sulphides of the younger generation often follow crosscutting fractures. The younger sulphides contain graphite as inclusions, as in the Outokumpu region.

Chalcopyrite and sphalerite contained in sulphide schists occur most abundantly in the sulphides of the younger generation. This has also been observed in the Outokumpu region, especially in more highly metamorphozed black schists; in the micaceous varieties of these, pyrrhotite is the dominant sulphide, as Väyrynen (1935) has pointed out in examining the paragenetic relations of the sulphide minerals of Outokumpu and Polvijärvi. The order of crystallization of the younger sulphide generation — pyrite-pyrrhotite-sphalerite-chalcopyrite — prevails elsewhere.

According to Marmo and Mikkola the sulphides become mobile during metamorphism and concentrate in structurally favourable horizons. These workers also compare the composition of the sulphide schists to sapropelic sediments and note that the two correspond closely to each other in their contents of certain trace elements (copper, zinc, vanadium). They conclude that the sulphides contained in sulphide schists are sedimentogenous.

Some comment is necessary on the terminology of black schists. Frosterus (1902), Laitakari (1925) and Eskola (1927, 1932) used the designations carbon- or graphite-bearing schists for primarily argillaceous schists containing sulphides in addition to carbon. Similar schists in the Kainuu region were designated by Väyrynen (1928) as carbon-phyllites, although sulphide-free, carbonaceous phyllitic schists occur there as well. Saksela (1932, 1933 a, 1933 b) applied the term black schist to carbon- and sulphide-bearing occurrences, and he has extended its scope to include also amphibole-rich, originally marly clay sediments. On the other hand, the black schists dealt with by E. Mikkola (1941) lack sulphides, and oxides are met with in addition to the carbon; conversely, when carbon material is lacking, the black colour of the pyritiferous schists rich in plagioclase (An_{10}) and mica is apparently due to the oxide pigment abundantly present.

In this study, the term black schist has been applied to sulphide- and graphite-bearing schists (in the Outokumpu region) with a carbon content exceeding one per cent. An increasing carbon content causes the colour of the schist gradually to turn, first, to grayish black, and, then, when the carbon content reaches two per cent, to true black. This applies to both argillaceous and calcareous black schists. An exception is provided by some originally arenaceous schists, which are likely to be quite dark in colour, even when the carbon content is considerably below one per cent.

Since, furthermore, in the black (particularly argillaceous) schists of the Outokumpu region the sulphur content corresponds to that of carbon, with the two varying inside the same limits (Fig. 40, p. 77), the definition of black schist may be extended by adding that the sulphur content of rocks so designated likewise exceeds one per cent.

SUMMARY AND CONCLUDING REMARKS

The black schists of the Outokumpu region are mostly mica-rich, originally argillaceous sapropelic sediments. Amphibole-rich calcareous black schists have evolved from marly sediments rich in Ca and Mg, and an increase in the SiO_2 content gave rise to quartzitic arenaceous black schists. The latter do not ordinarily occur as independent deposits, but as thin intervening layers in the transitional zones between black schists and quartzites.

Like the phyllites and the less highly metamorphozed mica schists, the black schists are also layered in structure. The layers rich in carbon and mica are commonly fine-grained and correspond to the originally clay-rich layers of the sediment, while the coarse-grained layers rich in quartz and, in many cases, sulphide, represent arenaceous sediments. The same kind of alternation also occurs in the amphibole-rich varieties, with amphibole in the fine-grained and the quartz in the coarse-grained layers. Such alternation of layers indicates a rhythmic deposition of the original sediment. Chance observations of the preservation of varved structure are sufficient to indicate the probability of seasonal variation in the sedimentation.

The carbon-rich beds of the black schists are generally finer in grain than the carbon-poor or -free layers alternating with them. The survival of such an original sedimentary structure and of the fine grain of fragmented carbon-rich schists in the highly metamorphozed parts of the area, indicates that the carbon was a primary constituent of the sediment and had from the very beginning acted to delay recrystallization. A relict bedding is often present in coarse-grained black schists as a helicitic texture, the graphite flakes forming parallel rows inside porphyroblasts. Close to the Maarianvaara granite, the carbonaceous matter in graphite- and sulphide-bearing rocks has entirely recrystallized into coarse graphite flakes, leaving no trace of the original bedding.

The carbonaceous matter is usually graphite; only sporadically are modifications with a lower degree of graphitization present. The graphite content ranges from one to thirty per cent, the average carbon content being five per cent. The graphite grains vary in size from 0.001 to 0.3 mm.

The consistent occurrence of sulphides (pyrite, pyrrhotite) in black schists differing in composition and their sympathetic correlation with the amount of carbonaceous matter provide evidence of the common origin of the carbon and the sulphide. The variations in the character and the amounts of the sulphides in layers of differing composition reflect variations in the original composition of the sediment. The pyrrhotite often follows the micaceous, carbon-rich and sulphur-poor layers, while the pyrite (richer in sulphur than the pyrrhotite) occurs abundantly in the paler portion of the schist. The syngenetic origin of the sulphides is indicated by the lack of graphite inclusions in the sulphides of the less metamorphozed schists, and by the concordant orientation of the pyrrhotite lamellae and the graphite flakes in the black schists of the phyllite area.

The sulphide content varies between one and thirty per cent, the average being approximately five per cent. The abundant carbon and sulphide content indicates that the black schist was formerly a sapropelic sediment (sapropelite).

The black schists of the Outokumpu region contain amounts of copper, zinc, vanadium, molybdenum and uranium characteristic of sapropelic sediments. The content of trace elements in reduzate sediments and their metamorphic derivatives of different ages has been subject to much investigation. The abundances of trace elements in carbon- and sulphide-bearing schists is in harmony with the genesis of the sapropelic sediments, and they correspond to the general geochemical behaviour of elements in the exogenic differentiation.

»Thucholite» spheroids occur in the black schists containing central grains of uraninite. The rest of the trace elements studied occur in the sulphide phases, but the chromium occurs as a silicate (fuchsite) or is camouflaged in tremolite.

Although the iron content of the black schists is important, only a small fraction of it occurs in the form of silicates. This is a feature common to all the black schist varieties in the Outokumpu region, and it is illustrated by the poverty of iron in the silicate minerals, which distinguishes them (in addition to their lower content of alumina and SiO_2) from the silicates in the carbon-free, mica-rich schists. The contents of calcium and magnesium in all the black schists are greater than in the mica schists. In the argillaceous black schists this is made manifest by an anorthite-rich plagioclase (An_{25-50}) and by the presence of a magnesium-rich mica (phlogopite). As the CaO- and MgO-contents increase, the amount of amphibole increases, and the schist finally changes into sheaf schist. The amphibole-rich, calcareous black schists are in many cases mica-free, with the potash content of the schist occurring as microcline. As the black schists grade into dark, quartzitic varieties, the carbon and sulphide contents decrease rapidly. Calcium similarly drops and this gives rise to a plagioclase poor in anorthite.

The TiO_2-content of the phyllites, mica schists and black schists of the region is directly proportional to the alumina content. Sphene is typical of all the black schists, whereas ilmenite and rutile are the prevailing titanium minerals in the phyllites and mica schists.

In structure and texture, all degrees of transition from the fine-grained phyllitic schists to the highly metamorphozed gneissose schists are also represented in the different black schist varieties of the Outokumpu region. Dis-orientated, massive graphite- and sulphide-bearing rocks occur in the proximity of the Maarianvaara granite. In addition to the carbon content, recrystallization is dependent on the composition and deformation of the schist. The amphibole-rich varieties are coarsest of grain; the argillaceous black schists are intermediate, while the quartzitic varieties are finest in grain-size. This is due to the difference in the ability of the dominant minerals to attain to large size, this ability decreasing in the order: amphibole — mica — feldspar — quartz.

Regional variations are also observed in the mode of occurrence of the sulphides. In the phyllite area they occur, like the silicates, concordant to the original bedding, the pyrite as groups or aggregates of grains and the pyrrhotite as parallel, elongate lamellae. As the degree of metamorphism increases, the grain-size of the pyrite and the pyrrhotite grows, along with the degree of mobilization of the sulphides. Accordingly, in the mica schist area, the pyrrhotite and, often, the pyrite locally fill irregular fractures in the schist; in some cases, the veins are pronounced.

Recrystallization and deformation produce changes in the structure of the black schists and mobilization of sulphides and certain silicates into structurally favourable parts of the schist and the surrounding rock. In the carbon-poor, less resistant beds in the black schists, the deformation gives rise to a secondary concentration of quartz, potash feldspar and sulphides, together with a more vigorous growth of the grain size; whereas in the carbon-rich, fine-grained layers the traces of deformation can be seen better in the folding of the seams of carbon pigment. Shearing occurs at the initial stage of deformation, particularly in the carbon-poor layers, as indicated by the drag folding noticeable in the adjacent carbon-rich beds. As the deformation proceeds, the bedding of the black schists begins to disappear, and the carbon-rich layers undergo mylonitization, coarse-grained sulphides and silicates forming a matrix for the fragments. In the silicates of the sheared and folded portions there occur secondary alterations, such as sericitization and epidotization of the plagioclase and chloritization of the biotite.

The black schists form numerous horizons of considerable lateral extent conformable with the enclosing rocks. The characteristic compositional and structural features vary and recur from layer to layer. Their occurrence interbanded with layers of phyllite, mica schist, mica gneiss and quartzite, and their gradual marginal transitions to other rock types indicate that the black schists were originally deposited together with these other sediments in the Outokumpu region.

The occurrence of the black schists as continuous zones (Solansaari — Viitalampi and Juojärvi — Haapovaara), often in association with quartzite, in the middle of the phyllite and mica schist area reflects an exceptional change in the sedimentation conditions. Such changes might be variations in the relief of the basement of deposition, in the water level of the sedimentation basin, in the circulation conditions and in the character and volume of the chemical and biochemical precipitation. The composition of different black schist varieties is also dependent on these original sedimentary factors. Slow deposition, which gives rise to thin lamination, presupposes stable conditions during which the volume of muddy material transported from the land is small and the sedimentation is to a marked extent chemical and biochemical. Depending upon the above factors, the original sapropelic sediment may be argillaceous, calcareous or arenaceous and its carbon and sulphide content may vary.

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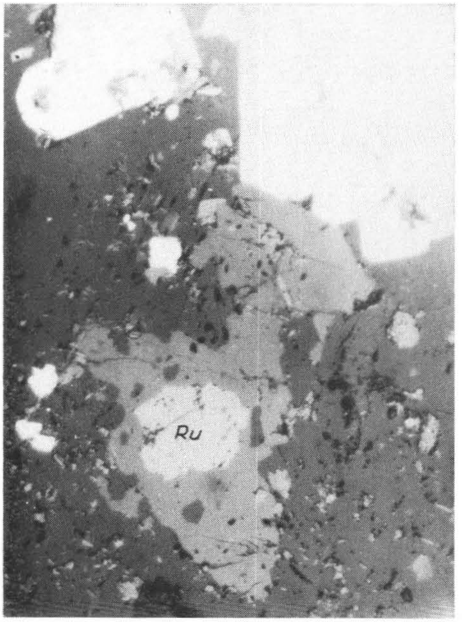
PLATE I

Fig. a. Rutile (Ru) partly altered to sphene (leucoxene). Keretti shaft, + 320 level, Outokumpu. Polished section. 100 x.

Fig. b. Coarse (up to 0.3 mm) graphite flakes showing distinct reflection pleochroism. Massive black schist rich in amphibole. Drill hole K. 51, 81 m, Luikonlahti. Polished section. 100 x.

Fig. c. Uraninite as inclusion in spherical »thucholite» grain. Calcareous black schist. Kultakallio, Polvijärvi. Polished section. 750 x.

Fig. d. »Thucholite» spheroid enclosing a larger grain of uraninite (U) with minute (radiogenic) galena inclusions (PbS). Phyllitic black schist. Kultakallio, Polvijärvi. Polished section. 680 x. Oil-immersion.



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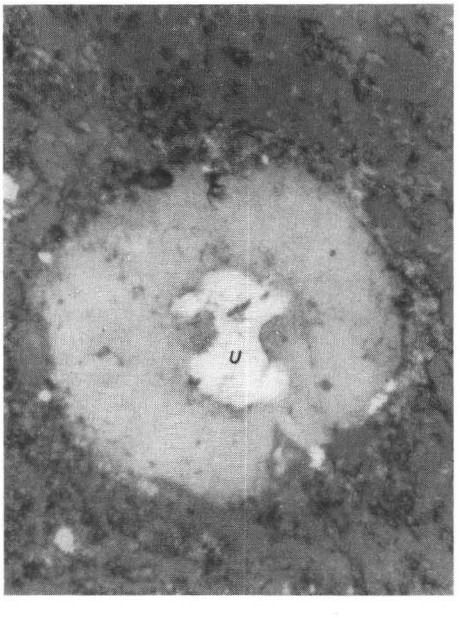

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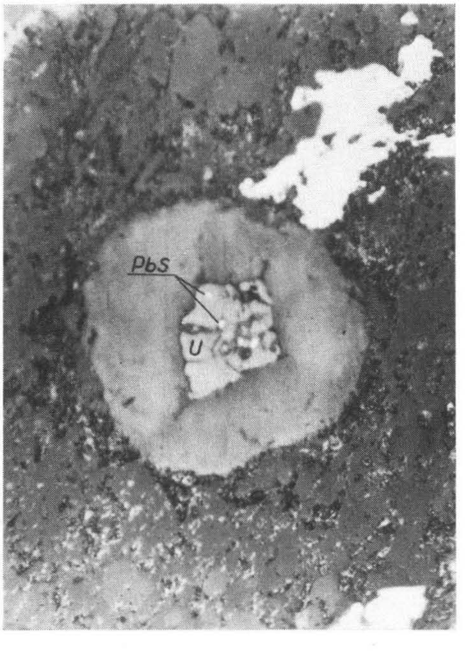

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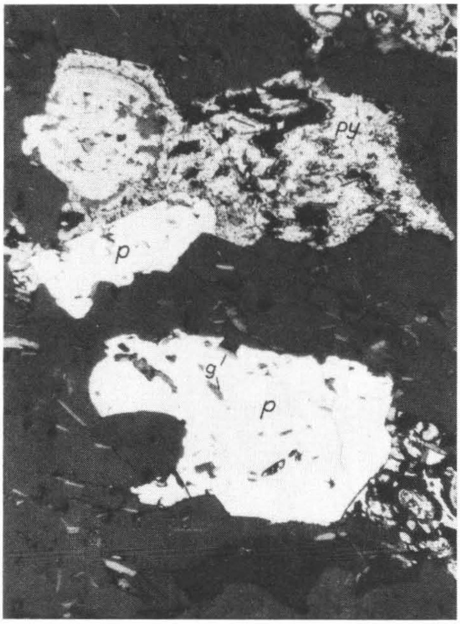
Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.



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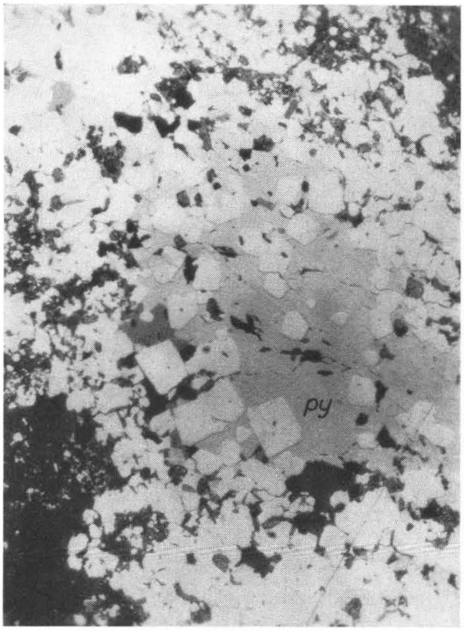

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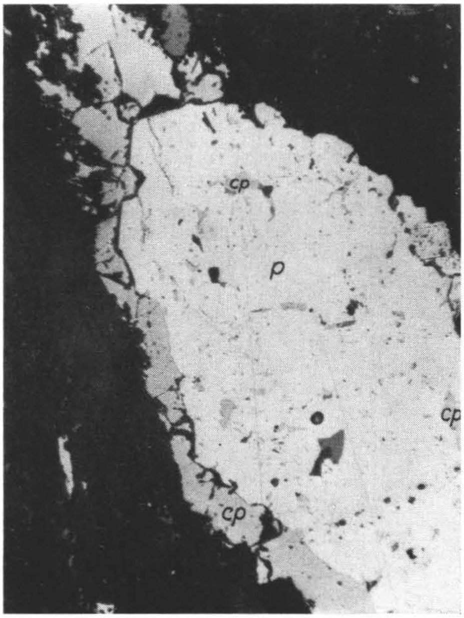

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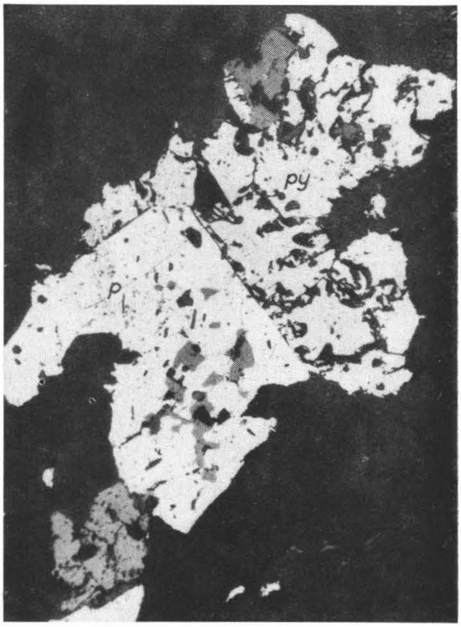

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Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.

PLATE II

Fig. a. Pyrite (p) containing graphite inclusions (g). Pyrrhotite (py) altered to »hydropyrrhotite». Graphite- and sulphide-bearing mica gneiss. Luikonlahti, Kaavi. Polished section. 35 x.

Fig. b. Pyrite as euhedral idioblasts in pyrrhotite (py). Drill hole 104 a, 205 m, Outokumpu. Polished section. 35 x.

Fig. c. Pyrite (p) with minute inclusions and coarser marginal seam of chalcopyrite (cp). Drill hole 3 a, 99 m, Outokumpu. Polished section. 100 x.

Fig. d. Partly corroded pyrite (p) replaced by enclosing sphalerite (dark grey). The border against pyrrhotite (py) is rectilinear. Luikonlahti, Kaavi. Polished section. 35 x.

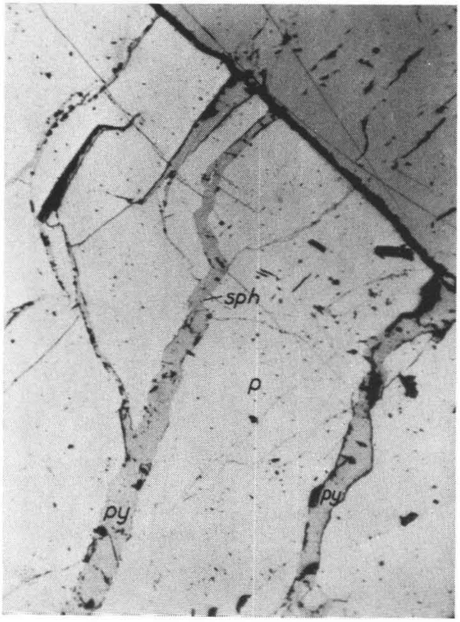
PLATE III

Fig. a. Cataclastically deformed pyrite (p) replaced by pyrrhotite (py) and sphalerite (sph) along cleavages and fractures. Drill hole KT 11, 210 m, Outokumpu. Polished section. 35 x.

Fig. b. Two generations of pyrrhotite. The older generation occurs as narrow veins or impregnations parallel to the schistosity. Drill hole Oku 129, 40 m, Sukkulansalo, Kuusjärvi. Polished section. 64 x.

Fig. c. Graphite and pyrrhotite inclusions, considerably smaller in sphene (ti) than in other silicates. Drill hole R 50, 13 m, Luikonlahti, Kaavi. Polished section. 35 x.

Fig. d. Pyrrhotite (py) exsoluted from the sphalerite (sph), which also contains minute blebs of chalcopyrite (cp). Pyrrhotite exsolution bodies are oriented parallel to the crystallographic planes of sphalerite. Drill hole K 1301, 381 m, Outokumpu shaft, + 285 level. Polished section. 128 x.



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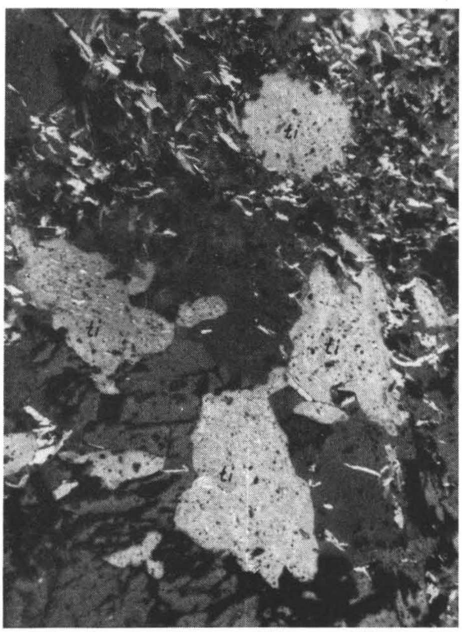

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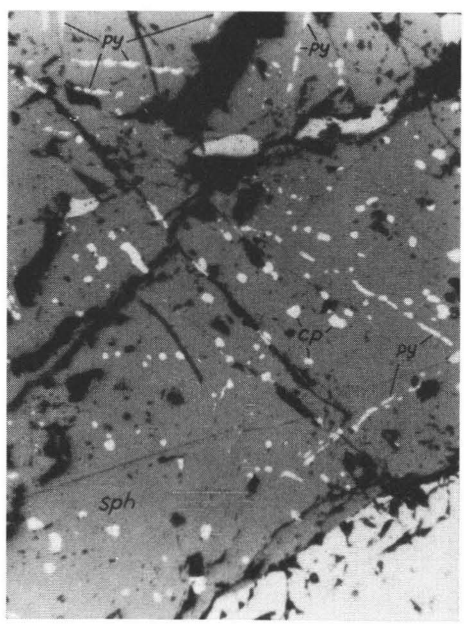

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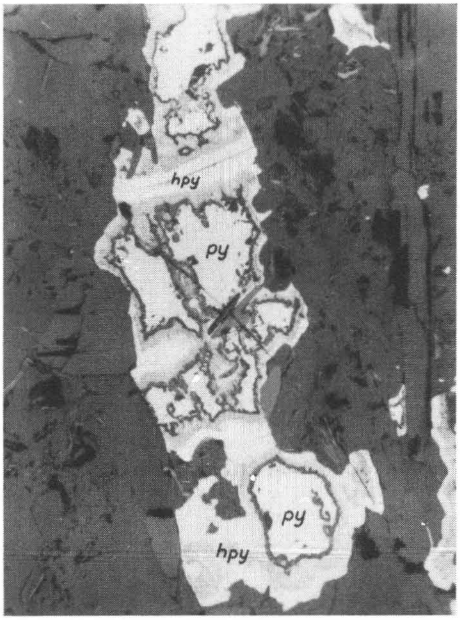
Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.



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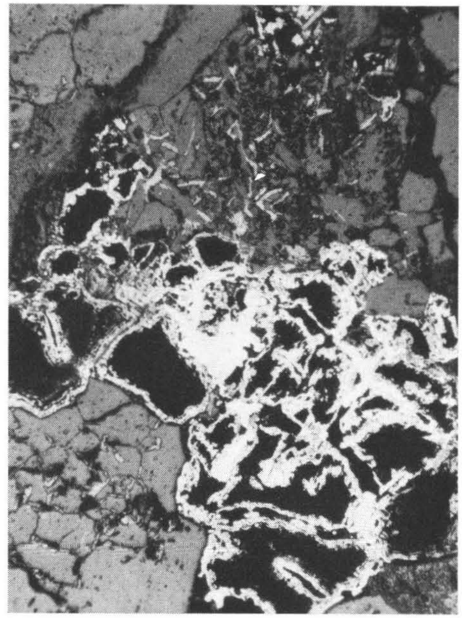

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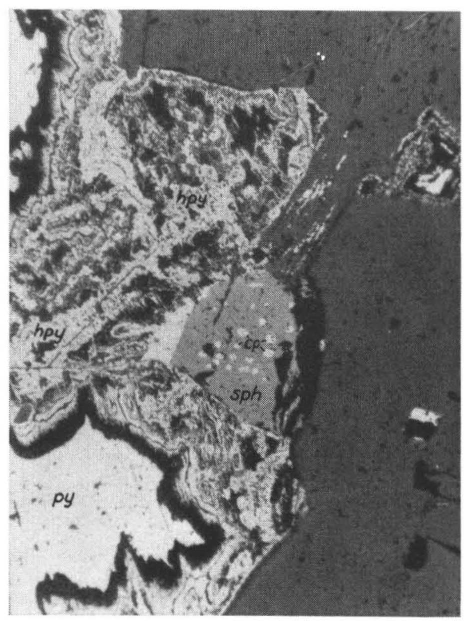

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Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.

PLATE IV

Fig. a. Incipient alteration of pyrrhotite (py) to hydropyrrhotite (hpy) along cleavage cracks and borders. Black schist rich in amphibole. Niinivaara, Kaavi. Polished section. 64 x.

Fig. b. Complete alteration of pyrrhotite to hydropyrrhotite. Argillaceous massive black schist. Luikonlahti, Kaavi. Polished section. 35 x.

Fig. c. Sphalerite (sph) in pyrite (p). Replacement of pyrite beginning from central parts of crystal. Argillaceous black schist. Mökkivaara shaft, + 320 level, Outokumpu. Polished section. 64 x.

Fig. d. Pyrrhotite (py) altered to hydropyrrhotite (hpy). Unaltered sphalerite (sph) containing minute exsoluted bodies of chalcopyrite (cp). Massive black schist. Luikonlahti, Kaavi. Polished section. 35 x.

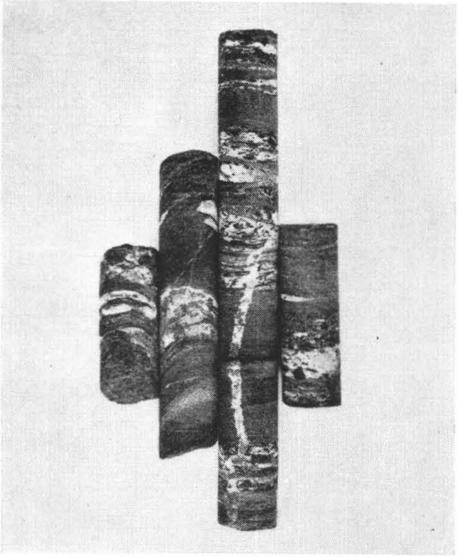
PLATE V

Fig. a. Conformable and transecting quartz veins with iron sulphides. Quartzose black schist specimens from the middle and NW parts of the Outokumpu zone.

Fig. b. Argillaceous black schist alternating with mica schist layers and showing distinct minor folding. Kaasila, Outokumpu.

Fig. c. Intensively folded quartzose black schist (1 and 2) and carbon-bearing quartzites (3 and 4) from the middle part of the Outokumpu zone.

Fig. d. Banded calcareous black schist with carbonaceous and light-coloured amphibole-bearing layers. Drill hole 63 a, 46 m, Outokumpu.



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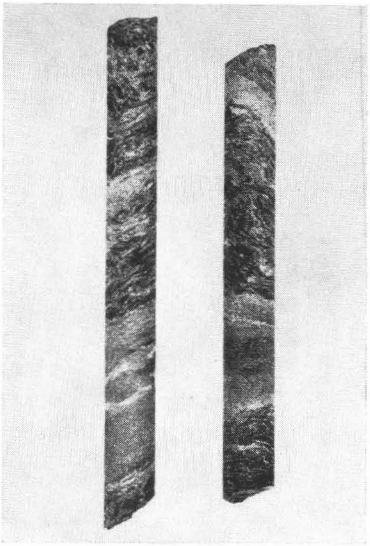

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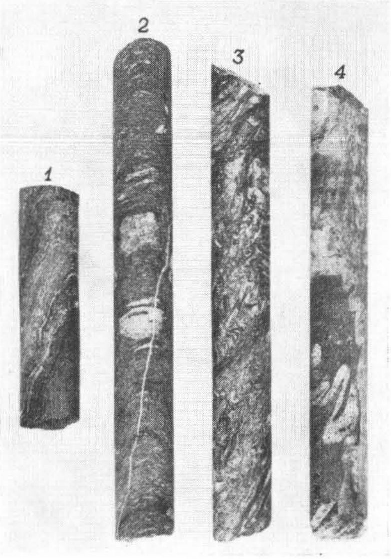

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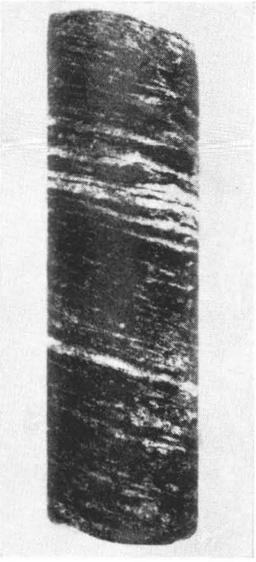

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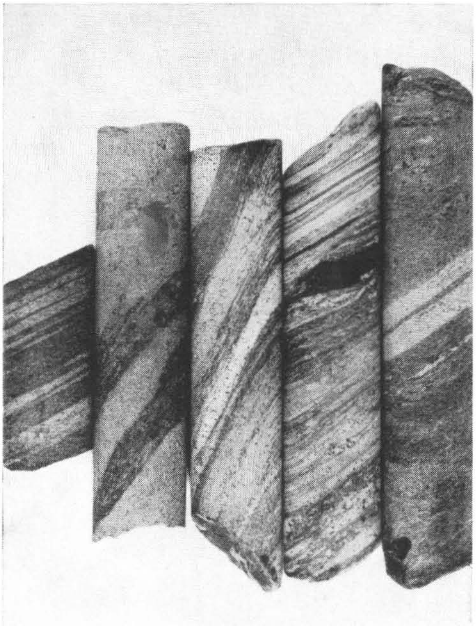
Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.



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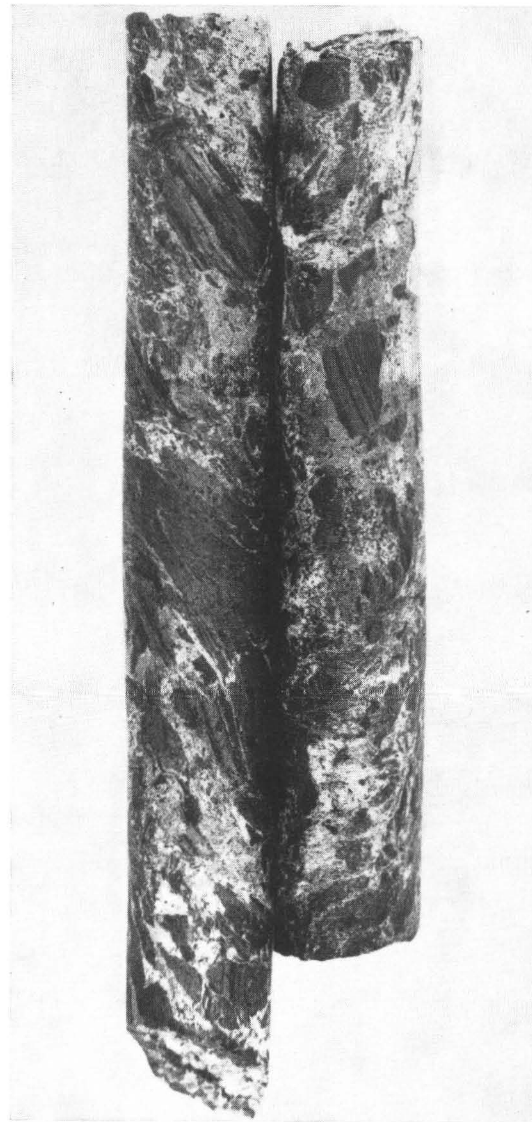

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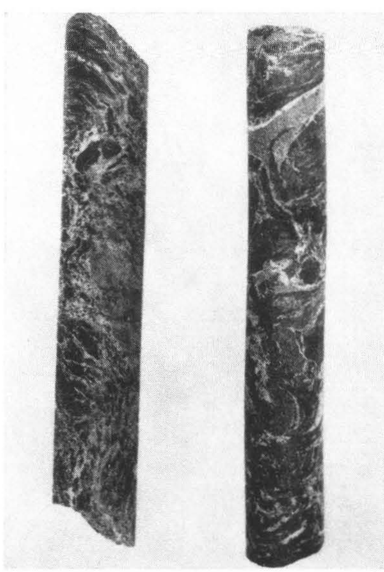

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Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.

PLATE VI

Fig. a. Banded quartzitic varieties of black schist from the middle and NW parts of the Outokumpu zone.

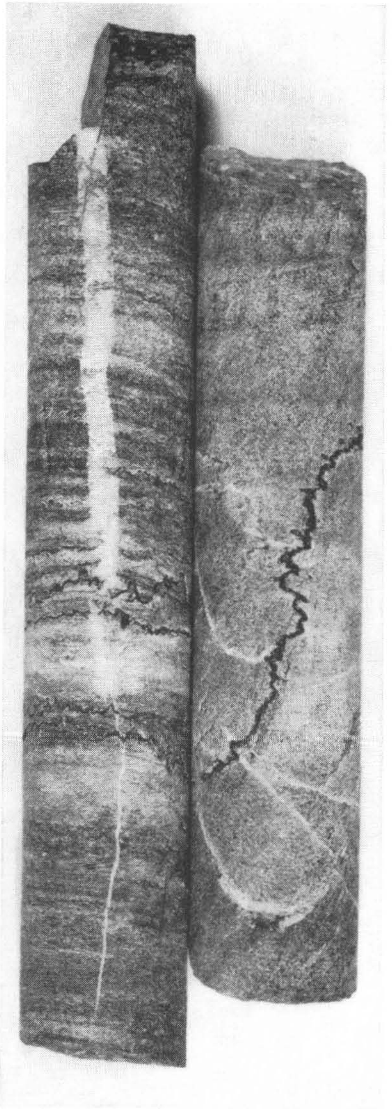
Fig. b. Mylonitic black schist. Brecciated pelitic fragments, showing the primary banded texture of carbonaceous phyllitic schist, in coarse-grained matrix of quartz and feldspar. Drill hole K 1402, 127 m, Outokumpu mine.

Fig. c. Intensively deformed and recrystallized black schist with coarse-grained biotite flakes and pyrrhotite veins. Drill holes K 1402 and K 1403, Outokumpu mine.

PLATE VII

Fig. a. Pyrrhotite (py) and pyrite (p) as lenses, concentrations and narrow veins in fractured black schist. Drill hole Oku 273, Outokumpu station. Diameter of cores about 3 cm.

Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.



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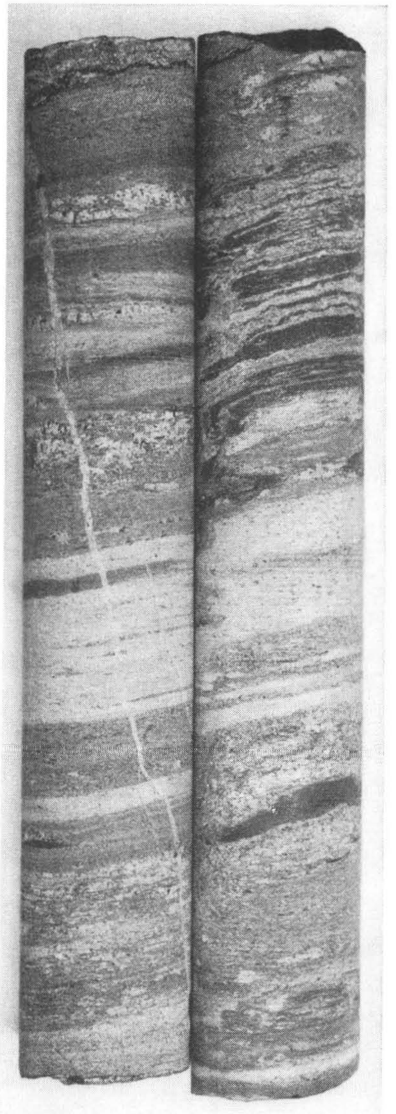

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Esko Peltola: On the black schists in the Outokumpu region in eastern Finland.

PLATE VIII

Fig. a. Stylolites in quartzite parallel to the bedding. Dark carbonaceous matter along stylolitic seam. Outokumpu mine. Diameter of core about 2 cm.

Fig. b. Banded quartzitic varieties of black schist. Drill hole Oku 273, Outokumpu station. Diameter of cores about 3 cm.

AEROMAGNETICAL MAP OF THE OUTOKUMPU REGION (TOTAL INTENSITY)