GEOLOGINEN TUTKIMUSLAITOS

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ON THE SULPHIDE AND SULPHIDE-GRAPHITE SCHISTS OF FINLAND

With an especial reference to the sulphide-graphite schists of Central Pohjanmaa

BY

VLADI MARMO

WITH 12 FIGURES, 3 PLATES AND 18 TABLES

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ABSTRACT

In the present paper, a review of the sulphide and sulphide-graphite schists (»black schists») is given, including the mineralogy with several new chemical analyses.

In particular, however, the minor constituents of these schists and of the sulphides occuring in these rocks, have been discussed. Thereby, about 100 partial chemical analyzes have been published.

The problem of the possible genetical relationship between the sulphide-graphite schists and the ore formation is one of the important questions of the present paper.

INTRODUCTION

Among Precambrian rocks, black, comparatively fine-grained schists often occur, usually forming narrow bands of considerable length. These schists commonly contain graphite and iron sulphides, and they are very similar in chemical composition to the alum shales as well as to the German »Kieselschiefern» of the post-Cambrian formations. Quite probably, both the schists and shales mentioned were originally sapropelic muds. Especially in Scandinavia, such schists have been called collectively »black schists».

For the Precambrian »black schists,» which are rich in sulphides, Marmo and Mikkola (1951) proposed the term »sulphide schists.» This term, in the opinion of the present writer, appropriately covers all the »black schists», rich in iron sulphides, of the earlier writers. In the present paper it will be proposed, furthermore, to split the general and indefinite conception of the »black schists» into three, or rather four groups, as defined by the presence or absence of graphite (shungite) or iron sulphides:

1. Sulphide schists, which contain iron sulphides in abundance, but little or no graphite (for instance the sulphide schists of the Nokia region — see Marmo, 1957);

2. sulphide-graphite schists, which contain both graphite and iron sulphides in abundance (most of the Scandinavian »black schists»);

3. graphite schists, which contain graphite and little or no iron sulphides (a typical graphite schist occurs, for instance, at Jynkkä, as described by Wilkman, 1938, pp. 32—33).

Actually, however, it is necessary to add still a fourth group:

4. shungite, or shungite-graphite schists, which contain shungite instead of or in addition to graphite. This group is of importance, because, as Marmo and Mikkola (1951) have shown, the sulphide and sulphide-graphite schists of the Karelian formation often contain shungite (Marmo, 1953) instead of or together with graphite. Shungite is a form of graphite which may be taken as a »less crystallized graphite,» and was first described in connection with the Karelian sulphide schists by Metzger (1924).

In the sulphide-bearing schists, pyrite or pyrrhotite, or both, may be present, while chalcopyrite, sphalerite, pentlandite, etc., may occur in addition. Concerning the iron pyrites, Väyrynen (1935), who devoted much attention to this question, pointed out, that the sulphur pressure generated during the formation of the respective schists determined, whether pyrrhotite or pyrite evolved. Thus, in general, the amount of sulphur present was of decisive importance; and this sulphur pressure may well have varied from place to place depending upon local tectonic conditions. Thus the kind of iron sulphide present is not necessarily characteristic of the primary composition of the material but rather of the tectonic features of the formation of such schists.

The relative abundance of iron sulphides and graphite (or shungite), on the other hand, certainly depends upon the composition of the material recrystallized into the present schist; and, therefore, the classification proposed in the foregoing has been based especially on these constituents, the kind of iron sulphides present being thereby left unconsidered.

As a whole, the sulphide and sulphide-graphite schists are also petrologically quite inhomogeneous. Therefore, a terminology based solely on the content of iron sulphides and graphite and neglecting the petrological composition of the respective schists has been criticized.

Within the beds of the sulphide and sulphide-graphite schists, an intense alternation of bedlets of varying composition always occurs. The composition of these thin bedlets may vary within a few decimeters from that of a quartz-biotite schist (rich in graphite and sulphides) to that of a diopside skarn (plus graphite and sulphides), as described, for instance, by Sahama (1945) and Marmo (1957). In addition, there may be strips and bedlets of very fine-grained limestone, which, owing to the presence of a dust-like graphite dissemination, is black. Megascopically and without use of acid proofs, such a limestone is indistinguishable from other bedlets of the graphite-bearing sulphide schist. Such bedlets of limestone have often been encountered, as, for instance, in the zinc mine of Vihanti as well as in the sulphide schists of Nokia.

Furthermore, bedlets of amphibolite and quartz amphibolite composition may also be common. Especially in the sulphide-graphite schists of Pohjanmaa, such bedlets may be rather common in some places.

All these variations in composition may be more easily understood if the graphite- and sulphide-bearing schists are considered as being the representatives of a single sedimentation cycle characterized by a rapid fluctuation in the composition of the depositing material. Both the chemical composition and the sulphide and graphite contents of the sulphide and sulphide-graphite schists strongly support the view that they had been deposited as sapropels or muds belonging to the gytja-facies, and this view concerning the origin of the »black schists» has also been mainly adopted (in Finland, for instance: Väyrynen, 1928; Eskola, 1932). As is well known, also the deposition of the recent sapropels has always been accompanied by a rapid and compositionally quite remarkable fluctuation. In the sapropels being deposited at the bottom of the Black Sea, Baltic Sea and Norwegian fjords, this fluctuation appears as the formation of thin bedlets of sand, clay and marl, all irregularly intermingled. Carbon and iron sulphides are, of course, invariably present, and all the bedlets mentioned are rich in these constituents as well. Consequently, the bedlets of sulphide — graphite schists of pelitic base composition have obviously derived from the sandy and clayey interbedlets of the sapropel; those of quartz amphibolite composition may be interpreted as having been formed from a marly clay; amphibolites and, particularly, the diopside skarn-like bedlets may well be regarded as having derived from a marl. The limestone bedlets would then have been formed from the minute layers of the sapropel richest in lime. That all these bedlets are rich in sulphides and graphite is, then, a direct consequence of the fact that, as a whole, the sulphide-graphite schists have primarily been sapropelic sediments. Therefore, there is no reason to base the classification of these »metasapropelites» on the chemical composition of the single bedlets, and still less so because the compositional fluctuation is often too intense to allow any kind of differentiation, on this basis, of different compositions on the geological maps, even on the largest scales usually used. Furthermore, megascopically the distinguishing of bedlets of different chemical composition is, in the overwhelmingly majority of cases, entirely impossible.

In describing sulphide and sulphide-graphite schists, however, it is often advisable to consider the petrological differences as well, especially in cases where some particular composition prevails over the others. Therefore, later on in this paper, the sulphide schists of pelitic composition and those of a calcareous composition will be dealt with separately.

There may be possibilities to distinguish, on a petrological basis, different facies of the mud sediments. It is important to note that the black mud containing iron monosulphide is being at present deposited along the east shore of the Gulf of California (Moore and Hayes, 1958), in a barred marine saltflat. Thus the reducing conditions may exist in some sites of evaporite deposition as well.

One may ask, of course, whether there is, then, any reason to go into a classification based on the content of carbon and iron sulphides? In the opinion of the present writer, there are indeed, some reasons.

The distribution of the sulphide, sulphide-graphite, graphite and graphite-shungite schists usually tends to be regional. Despite local variations in this sense as well, there still always occurs a distinct tendency, characteristic of each area concerned, to be included in one of the four groups mentioned. For instance, the Nokia region and many minor occurrences of schists of this category around Lake Päijänne mainly consist of sulphide schists containing but comparatively small amounts of graphite. In Savo (Hiirola, Juva, etc.), but especially in Central Pohjanmaa, the sulphide-graphite schists are in the overwhelming majority. In Karelia, the shungite-graphite and shungite-graphite-sulphide schists are typical representatives of the respective metasapropelites. Especially in the Jatulian carbon-bearing schists, shungite clearly predominates over graphite.

Furthermore, in his earlier paper (Marmo, 1956) the present author has set forth the following possibility: If life on earth began with organisms not containing carbon and evolved parallel with the increase in the amount of carbon in their organisms, as it has been suggested by several authors, then it is but reasonable to assume that also the sediments related to the sapropels (deposited in basins of stagnant water) would reflect this evolution of life. Of course this is just an assumption which can neither be proved nor disproved. Certain observations, however, may entitle us to reach such a supposition. First of all, evidence exists that the beginning of life could first have developed into organisms related to the sulphur bacteria, not necessarily containing any carbon. Bacteria of this sort could evolve into species built up of organic material. As a matter of fact, such a development could take place even at the present day. But what actually drew the attention of the present writer to this possibility was the observation that in Finland sulphide schists containing only a little carbon are typical of certain Svecofennide areas in southern Finland. The rock basement of Pohjanmaa has been mainly regarded as younger than that of southern Finland, and there the graphite in the sulphide schists of Pohjanmaa is always present in abundance. The Karelian zone has been considered as being still younger than that of Pohjanmaa, and there the carbon is also very abundant. Furthermore, the sulphide-graphite schists are more abundant in this territory, than in any other parts of Finland, and shungite occurs in the metasapropelites together with graphite or instead of it. This modification of carbon again, has been thought to represent a less metamorphozed form (at least of inferior crystal form) of carbon than graphite (Marmo, 1953).

It should further be mentioned that when working in Sierra Leone, West Africa, the present writer could not see any sulphide schists, and, according to the literature dealing with the geology of these parts of the globe, these schists are very uncommon, and may be entirely absent, in the Precambrium of coastal West Africa, in general. The schist belt of the Sula Mountains and the Kangari Hills, Sierra Leone, is probably a very old Precambrian geosyncline; but, instead of the sulphide schists, only banded ironstones occur in the respective places. According to the radiogenic age determinations, however, this schist belt is approximately 10^9 years older than the Precambrian of Finland. In Sierra Leone the graphite occurs as well, though not, however, in the schist belt mentioned but in the charnockite gneisses of the coastal part of the country. The age of these charnockites, is as yet unknown, however, and the graphite occurring in the gneisses mentioned does not resamble in any way the graphite of the sulphide gneisses of Savo, Finland, derived from the metasapropelites—sulphide schists.

The sulphides of the sulphide schists have certainly obtained their material from the recrystallized sapropels themselves. Copper, nickel, zinc, vanadium and molybdenum, typical minor constituents of the sulphide-graphite schists, are characteristic of the sapropels, too; and in both sediments they occur in quite similar quantities. Already Väyrynen (1928) expressed this opinion; Bergh (1928) described fossils of the sulphur bacteria occurring in the Swedish alum shales at Kinnekulle, closely resambling the Precambrian sulphide-graphite schists. Caillère and Kraut (1957) have described fossils replaced by pyrite, pyrrhotite, chalcopyrite, sphalerite and pentlandite. The sulphide-graphite schist at l'Anjou is perfectly clastic and rich in quartz. The authors state that this replacement must have taken place at a low temperature, and already at the conditions of sedimentation. Love (1958) has described *Pyritosphaera* and *Pyritella* bacteria, discovered in the Pumpherstone oil shales (Lower Carboniferous of Scotland), which are there pyritized. The pyrite of these bacteria is syngenetic, but, in addition, according to Love, there is a younger generation of pyrite which may well represent, in the opinion of the present writer, the »younger generation» of the sulphides of the Precambrian sulphide schists, described by Marmo and Mikkola (1951), who also proposed a syngenetic origin for the sulphides of the Finnish sulphide schists.

The syngenetic origin of the sulphides of the alum shales and of the German »Kieselschiefern» has been taken for granted by Leutwein (1957), as well.

SULPHIDE-GRAPHITE SCHISTS AND ORES

IN FINLAND

The sulphide and sulphide-graphite schists having originated from the sapropelic sediments, which are usually rich in heavy metals, the theories have been made to explain the formation of certain ores through a sufficient concentration of these heavy metals.

The possible concentration of, say, copper, cobalt, nickel, or molybdenum has been ascribed to the effect of an intrusive body, or to advancing granitization (Gavelin, 1955), or to tectonic features, or to something else. Accordingly, several of the ores originally described as having a diverse origin, have often been re-interpreted and re-explained as having originated from sediments ascribable to some of the afore-mentioned causes, and, in particular, as having derived from the ancient sapropels.

As an example of such a re-interpretation mention may here be made of one especially bound to the geology of Finland, and that is the ore of Outokumpu. This ore has recently been attempted by Saksela (1957) to be explained as having originated from sapropels, or from sulphide-graphite schists — a view completely opposite to all the earlier ones (*e.g.* Mäkinen, 1929, Eskola, 1933; Vähätalo, 1953).

The relationship between the sulphide schists and the ore formation is a question of great importance. The present writer has likewise considered it (*e.g.* Marmo, 1958, 1960), and it will be dealt with in the present paper as well.

It may be the appropriate to approach this problem by discussing some of the known sulphide ores of Finland accompanied by closely situated sulphide-graphite schists.

The ore of Luikonlahti is a copper ore containing minor amounts of zinc (up to 1 %), nickel, silver, etc. In 1958, after sporadic exploration of this ore body during three decades, three closely situated ore bodies had become known. Väyrynen (1939) described the ore body of Luikonlahti. Ragarding the ore itself, Väyrynen wrote (*op. cit.*, p.68): »This sulphide occurrence is associated with a complex composed, in addition to abundant

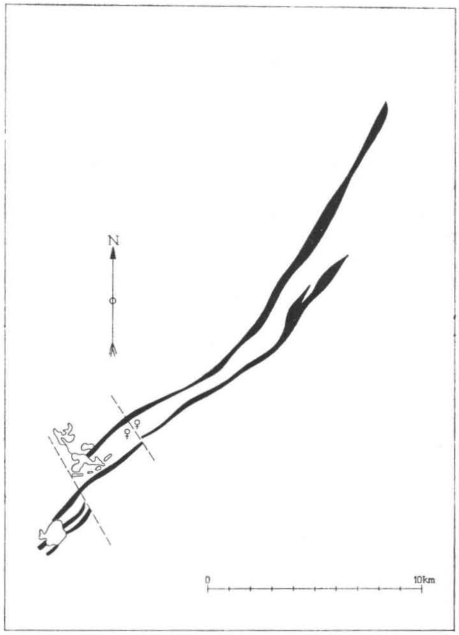

Fig. 1. The sulphide-graphite schists of Outokumpu (Vähätalo, 1953). The signs of copper indicate the ore.

serpentinites, of small layers of quartzite, black phyllites rich in iron pyrites, dolomites, and diopside-tremolite rocks, as well as of penetrating granites, aplites, and pegmatites.» The »black phyllite» forms there rather extensive strips closely associated with quartzites and serpentinites. At Niinivaara, this zone forms a bend, and southwards the »black phyllites» almost disappear from the map. There is still however, a minor strip of sulphide schists to wich the diopside-tremolite rock as well as dolomite layers genetically belong. This is just to the south of the Luikonlahti ore, at Lake Palolampi. According to Mr. E. Heiskanen (oral communication), who most recently investigated this ore field, the relationship between the ore and the sulphide schists, in the field, is a close one. Väyrynen drew attention to the similarity between the ores of Outokumpu and Luikonlahti (*op. cit.*, p. 87): »———, which (Luikonlahti) can well be compared to the Outokumpu ore in the respect that it is closely connected with occurrences of serpentine adjoining a complex composed of quartzites, black phyllites, dolomites, and calc-silicate rocks.»

In Fig. 1, the distribution of the sulphide-graphite schists of the Outokumpu area are shown, as revealed by the geological map of Vähätalo (1953). The ore is also located there. Undoubtedly, also in the respect to the sulphide-graphite schists, the Outokumpu ore has a position very similar, to the ore of Luikonlahti.

The zinc-lead ore of Vihanti likewise has a close connection to the sulphide-graphite schists, which was observed by A. Mikkola (Marmo and Mikkola, 1951, p. 20) during the stage of exploration of this ore; and this relationship may also be noted from a later description for the ore of Vihanti, by Isokangas (1954, p. 30): »The quartzites are in general fine-grained and, owing to the pigment of pyrites and graphite, dark in colour.» These quartzites are closely associated with the ore, and the compositional description by Isokangas indicates that they may also be closely related to the actual sulphide-graphite schists, which are not separately indicated on his geological map.

At Otravaara, a pyrite deposit occurs, and to the north of it there is a strip of sedimentogeneous rocks indicated by Saxén (1923) on his map as »phyllite.» According to his petrological description, however, this »phyllite» must be very close to the actual sulphide schists (p. 17): »Sind sie rostig verwittert, was von dem geringen, aber konstanten Schwefel- und Magnetkiesgehalt herrūhrt. — Ausserdem ist das Gestein voll von dunklen Kohlenpartikeln, die ihm sogar in mikroskopischen Präparaten eine dunkle Farbe verleihen». On p. 39 he wrote, furthermore, that close to the ore the sericite quartzite contains graphite as well, and it may be abundant enough to give to the rock its black colour; and the rock also contains ample iron sulphides. The pyrite ore body of Otravaara is situated just at the southern end of the strip composed of the graphite- and sulphide-bearing phyllite, the petrology of which was just described.

Saksela (1933 b) has also described another pyrite deposit, which occurs at Karhunsaari. There the ore occurs in a sericite-schists in the close vicinity of oligoclase granite and hornblende gabbro, but also conspicuously close to an extensive strip of sulphide-graphite schists, as may be seen in Fig. 2, the map of this figure being drawn according to the original map of Saksela. There the sulphide schists form an arch at the end of which the pyrite ore occurs. According to Saksela, this sulphide-graphite schist had partially been a clay rich in dolomitic material. It contains ample graphite and sulphides, and its biotite is very pale, a feature quite typical of the biotites of the sulphide and sulphide-graphite schists in general (see p. 41). Furthermore, the sulphide-graphite schist there contains a colourless or only slightly greenish amphibole.

All these examples indicate that very often in Finland sulphide ore formations bear a close areal connection with the occurrence of sulphide-graphite schists. These schists do not, however, belong to the commonest rock types met with in the Precambrian areas, and there are quite extensive regions in Finland entirely lacking the strips of sulphide schists; but neither

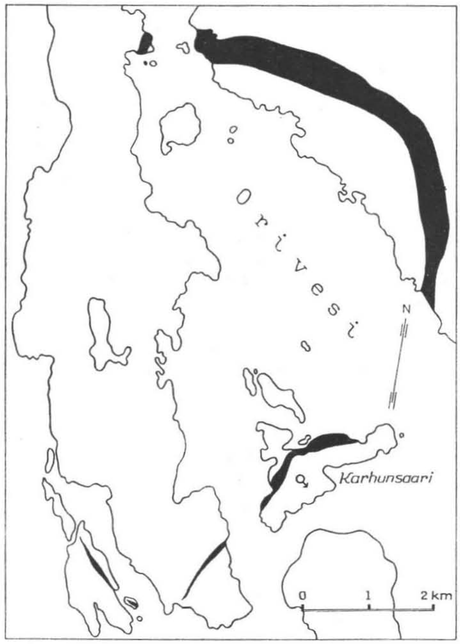

Fig. 2. Area of Karhunsaari (Saksela, 1933 b). Solid black is the zone containing sulphide schists.

have ores been encountered in such areas. Therefore, one can hardly avoid thinking that some kind of relationship, also genetical, must exist between the occurrence of ores and of sulphide and sulphide-graphite schists.

In order to consider such a possibility more thoroughly, some Scandinavian ores of similar character will also be dealt with in the next chapter.

Before that it may be mentioned that Keil (1956) has taken it for granted that the zinc ores of Górny-Slansk (Polland) have also derived syngenetically from sulphide-graphite schists.

ON SOME SCANDINAVIAN SULPHIDE ORES

In Scandinavia there are many instances of sulphide ores occurring close to sulphide-graphite schists. They are well known both in Sweden and in Norway.

The most interesting area of Sweden containing sulphide ores conjoining the sulphide-graphite schists is that of the Skellefte region. Most of sulphide ores occurring there are situated in such a way that a part of the same ore body or group of several ore bodies is inside the sulphide schists, while the rest is in the altered, adjoining rock type (Gavelin and Grip, 1946).

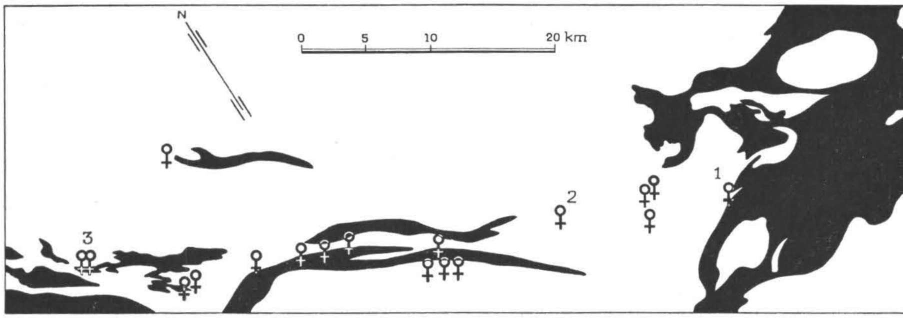

Fig. 3. The distribution of the phyllite series and the ore deposits within the Skellefte area (Grip, 1942). 1 = Boliden; 2 = Renström; 3 = Mensträsk.

Furthermore, Gavelin and Grip point out that the ores there are situated at the boundary zone between the phyllite series (which includes the sulphide-graphite schists) and the volcanic porphyry series. The authors explain this feature as depending upon the folding ability of phyllitic rocks, which is different from that of volcanic rocks.

The superior elasticity of the sulphide-graphite schists as compared with other rock types has also been stressed by Oftedahl (1955), who, in regard to the folding ability of the alum shales of the Oslo region, wrote that »— — — the alum shales served as a lubrication zone, upon which the Ordovician shales and limestones moved during the folding.»

Later on, Gavelin (1955) ascribed the concentration of the ore material into the ore bodies to the advancing granitization, in front of which the ore bodies had been formed.

The distribution of the phyllite series (including the sulphide-graphite schists) and the ore deposits within the Skellefte region is illustrated on the map of Fig. 3 (according to the map of Grip, 1942).

The ore body of Mensträsk reveals an interesting feature. In Fig. 4 (according to Grip, 1951), one can see the contact between the sulphide-graphite schist and the coarser sediment. Obliquely to this contact lie the sulphide ore bodies and also the faults by which the emplacement of the ores had obviously been controlled.

Also in Norway, there are several sulphide ore deposits connected with the occurrence of large belts composed of the sulphide-graphite schists.

In Norway, such mineralizations have been classed as 1.) »vasskis,» and 2.) »gangkis.» This classification is old, and it is well known especially among miners.

In the Norwegian sulphide-graphite schists, pyrite and pyrrhotite may form a dense dissemination, sometimes compositionally approaching an ore. This kind of mineralization is the »vasskis» of the Norwegian miners. Ore

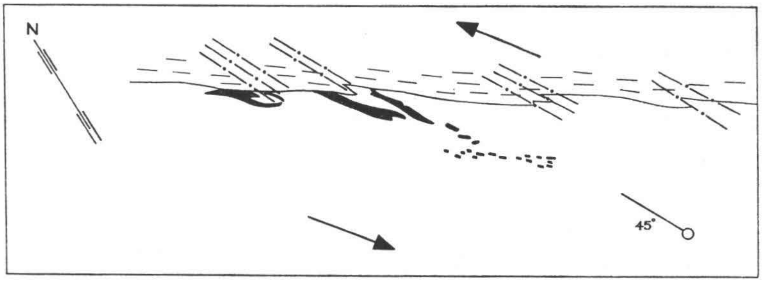

Fig. 4. The ore deposit of Menstrask, Skellefte area (Grip, 1951). Schematic map of the 250 level in the mine. Graphite- pyrrhotite slates are stripped, solid black is the ore. Foults are marked in dotted lines.

of this kind has been mainly taken as being of sedimentary origin and emplaced in connection with volcanic activity and resulting from chemical and biochemical processes (Carstens, 1931, 1944). Such a sulphide may often be brecciated by a lighter and coarser pyrite (Bugge, 1948). This brecciating pyrite probably corresponds to the »younger generation» of pyrites described by Marmo and Mikkola (1951) in connection with the sulphides of the Finnish sulphide and sulphide-graphite schists.

Among the economically significant Norwegian occurrences of »vasskis,» the deposits of Stordø, Leksdalen, and Løkken may be mentioned.

»Gangkis,» on the other hand, has been mainly considered as epigenetic; and its occurrence has often been connected with intrusions of saussurite gabbro or trondhjemite, and still it usually occurs in the schists (Røros, Løkken, Sulitjelma). According to Carstens (1944) it is of hydrothermic origin, and it forms large compact veins.

Bugge (1948) points out, however, that the »gangkis» is usually present together with the »vasskis.» At Røros, the »vasskis» is, in his opinion, the oldest sulphide generation of the whole mountain chain, and in this particular locality he proposed basing the prospecting for »gangkis» on the distribution of »vasskis.» In other words, in his opinion, the »gangkis» (often rich in copper) is a product of a remobilization and recrystallization of the »vasskis.» In the eastern parts of the area of Trondheim, the »vasskis» is sparser than in the west; there occurs, however, what can be interpreted as an intermediate between »vasskis» and »gangkis.» In actual fact, also Schneiderhöhn has considered it possible that the »gangkis» were a product of remobilization of the »vasskis.» In the first edition of his textbook (1944) he classed the Norwegian sulphide deposits with his »dislokations metamorphe Kieslager,» and held it possible that the deposits had been formed as the result of an accumulation of palingenetically mobilized material.

Also Foslie (1939) surmised that the ore deposits of Grong, similar to those considered by Schneiderhöhn, had been emplaced metasomatically.

Though as yet refraining from expressing any definite opinion in this matter, one cannot dispute the fact that the occurrence of all the ores of the aforementioned examples, in respect to the sulphide-graphite schists in their close vicinity, is strikingly similar.

THE DISTRIBUTION OF THE SULPHIDE AND SULPHIDE-GRAPHITE SCHISTS IN FINLAND

On old geological maps the »black schists» including the sulphide-graphite schists have not always been differentiated. Therefore it is impossible to give any map illustration based on the pre-existing geological maps to elucidate the distribution of the metasapropelic sediments in Finland.

The sulphide and sulphide-graphite schists always being rich in pyrrhotite, they stand out well on aeromagnetic maps. The aeromagnetic survey so far covers, however, only a limited area of Finland, but along the western coast of Finland this survey has served as an excellent guide for tracing of the distribution of sulphide-graphite schists.

In the explanatory notes accompanying the geological maps of Finland — also in the oldest ones — the »black schists» have usually been mentioned, but rerely also described.

From all the available data it may be concluded that the occurrences of »black schists» are mainly bound to definite schist and gneiss zones. These zones, and especially those belonging — according to the view prevailing at present — to the Svecofennides, strikingly embrace the area of Central Finland, mainly composed of synkinematic rocks ranging from quartz diorite to granodiorite (and granite), and varying from gneissose to massive in texture. The zones of Karelides, along their whole length beginning from Lake Ladoga in the south and continuing to Lapland and Sweden beyond the Arctic Circle, are characterized by the presence of sulphide-graphite and, in the southern parts, also of shungite-graphite schists.

In general, the regional distribution of the sulphide and sulphide-graphite schists in Finland is as follows:

1. Southern Finland. To the west of Lake Päijänne, and to the south of the railway line between Pori and Haapamäki, there are only few and comparatively small strips of sulphide schists. Among the largest coherent occurrences of sulphide schists within this area is that of the Nokia region (Marmo, 1957). There the sulphide schists are enclosed by phyllitic rocks belonging to the Bothnian formation of the Tampere area (Sederholm, 1897; Simonen, 1953). The sulphide schists of this region consist mainly

Fig. 5. Geological map of the gneiss zone (including the zone of sulphide schists) of Pohjanmaa

of quartz, pale biotite and pyrrhotite. Graphite is sparsely present. The sulphide schists of amphibolite composition containing thin bedlets of fine-grained, black graphitic limestone, are present as well.

2. Pohjanmaa (Ostrobothnia). In the western parts of Finland, within the region of Pohjanmaa, the zone composed of gneiss and including sulphide-graphite schists is rather extensive and continuous; the sulphide-graphite schists of this zone have probably been examined more thoroughly than any other zones of sulphide-graphite schists in Finland. (Fig. 5). Saksela (1932) considered the sulphide-graphite schists of Pohjanmaa as

having originated from marls, at least to some extent, and the sulphides and carbon of these schists as primary constituents. Furthermore, Saksela stressed the fact that the sulphides of these schists are predominantly represented by pyrrhotite (*op. cit.*, p. 19). In 1933 Saksela paid more attention to the »black schists,» and especially to those of the parishes of Ullava and Kaustinen, later examined by the present author, too. As regards these sulphide-graphite schists, Saksela listed the following mineral assemblages observed by him:

a. chlorite + microcline + quartz + albite;
b. biotite + microcline + intermediate plagioclase + quartz;
c. actinolite + microcline + sphene + albite;
d. actinolite + intermediate plagioclase + microcline + quartz.

Laitakari (1942) has described the »black schists» of the communes of Evijärvi, Laihia and Lappajärvi, hence sulphide-graphite schists belonging to the same zone as those described by Saksela, but occurring south of them. Laitakari points out that in the sulphide-graphite schists of southern Pohjanmaa, diopside often occurs instead of actinolite — an observation which is well confirmed by the experience of the present writer in regard to the sulphide-graphite schists occurring to the north of Lake Tastula, in the commune of Kaustinen.

3. Savo. In the southeastern part of Finland, several minor strips of sulphide and sulphide-graphite schists also occur. There these strips are, however, seldom continuous, but mostly they form isolated strips of rather limited dimensions and in more or less the same fashion as they occur in southern Finland. Already Frosterus (1903) mentioned »sulphide gneisses,» which in actual fact are slightly granitized representatives of the sulphide-graphite schists.

Marmo and Metzger (1953) have described the sulphide-graphite schists of Hiirola, which consist mainly of biotite, quartz, graphite. In the vicinity of these schists, there occur beds of calcitic and dolomitic limestone.

Wilkman (1938) and, later on, Preston (1954) have described the sulphide-graphite schists of the Kuopio region. There the environment of »black schists» is made up of mica schists rich in quartz and feldspar, and they are stratigraphically situated above quartzites. The sulphide-graphite schists consist there mainly of quartz, biotite, muscovite, graphite, plagioclase (albite) and pyrite. Occasionally they also contain tremolite (Wilkman, 1938). One analysis of these sulphide-graphite schists is given in Table 2 (Anal. 1). The largest sulphide-graphite schist bed described from this region is that of Hukanniemi, where it is 300 to 500 meters thick. Wilkman drew attention to the paleness of the biotite occurring in the sulphide-graphite schists.

4. The Karelian sulphide-graphite and shungite-bearing schists form extensive zone, which follows the general strike of the Karelian schist formation.

Frosterus and Wilkman (1920) mentioned the rusty, pyrrhotite- and graphite-bearing schists of Vaivio, Sotkuma and Polvijärvi, which occur alternating with beds of a pale quartz schist and a dark hornblende schist.

Wilkman (1921) has described a graphite-bearing phyllite intercalated with quartzose schist layers at Jormasjärvi. This graphite phyllite consists, according to Wilkman, of quartz, pale biotite, pyrrhotite and much graphite.

Hackman and Wilkman (1929) have described the graphite schists of Niluttijärvi, where they form a bed 10 meters thick and contain very pale biotite, muscovite and quartz. The sulphide-graphite schist bed of Niluttijärvi is situated between beds of phyllite and dolomite.

The sulphide-graphite schists of Polvijärvi were later carefully described by Väyrynen (1935), who also published an excellent description of the sulphide-graphite schists of the Outokumpu ore field and its environment (Väyrynen, 1939). There the sulphide-graphite schists are associated with quartzites, and the former form intercalations in the latter. Quartz, biotite, graphite and iron pyrites are the main constituents of these sulphide-graphite schists, which sometimes contain prisms of amphibole as well.

At Polvijärvi and Outokumpu, the varieties containing amphibole are often adjoined by intercalated, pale-greenish tremolite schists, in which a coarse calcite full of black graphite pigment is usually present. According to Vähätalo (1953, p. 93): »— — — both the quartzite and conjoining black-schist formations genetically belong to the same formation series as the mica-schist, which forms the wall-rock.» He also points out that the biotite of the sulphide-graphite schists is there slightly pleochroic and almost colourless, and that it is orientated parallel to the schistosity. In the near future, the sulphide-graphite schists of Outokumpu will be described by Mr. E. Peltola of the Outokumpu Co.

The sulphide-graphite schists of the Kainuu region have been extensively described by Väyrynen (1928) and by Wilkman (1931). As for the sulphide-graphite schists of Salmijärvi, Väyrynen points out that the sulphide there is exclusively pyrite. Pyrrhotite has never been met with there. The schist consists mainly of quartz, pale biotite, graphite and sulphides in abundance. An analysis of this variety of schists is seen in Table II (Anal. 2). Regarding the origin of sulphide-graphite schists, Väyrynen considers them as having been deposited in a basin of stagnant water.

That the main sulphide of the sulphide-graphite schists of the Kainuu region is pyrite and not a pyrrhotite has likewise been stressed by Wilkman (1931). He has also mentioned the presence of an »amorphous» carbon in these schists — according to later investigations of Marmo and Mikkola, (1951), it is presumably a shungite. The localities described by Wilkman are Jormaskylä, in the commune of Sotkamo, and several localities in the communes of Paltamo and Ristijärvi. All the sulphide-graphite schists described by him are rich in carbon and pyrite, and they have the bulk composition of a phyllite.

Saksela (1933 b) has described the »black schists» conjoining the pyrite deposit of Karhunsaari (p. 14).

The »black schists» intercalated with hornblende schists and occurring approx. 4 km SW of Tohmajärvi have been described by Hackman (1933). There, together with the schists mentioned, schistose layers conspicuously rich in quartz also occur.

There are several investigations concerning the sulphide-graphite and shungite schists of that part of Karelia, which since 1944 has been a part of Soviet Karelia. Metzger (1924) has described the shungite-bearing schists of the commune of Suojärvi. It may be repeated here that the shungite is a variety of graphite, first described by Inostranzev from the Shunga Peninsula in Soviet Karelia. Marmo and Mikkola (1951) have shown that the presence of shungite is characteristic of many sulphide schists of the Karelian formation, but it has never been met with in the sulphide-graphite schists of southern »Svecofennian» Finland.

Hackman (1933) has described the »black schists» of Soanlahti and Suistamo; at the last-mentioned locality the schists are composed of quartz, graphite, muscovite and biotite, and they contain magnetite, hematite, and rutile, too. The composition of this schist is represented by Anal. 8 of Table II.

According to Laitakari (1925), the »black schists» of Soanlahti contain, on the average, 10 per cent carbon, and in exceptional cases this amount may rise up to 30 per cent. This occurrence of graphite has also been described by Hausen (1930), according to whom the »carbon phyllite» alternates with the gray layers of limestone.

5. Sulphide schists also occur in Lapland. Excepting the sulphide schists of Central Lapland, geochemically examined by Sahama (1945) and described by E. Mikkola (1941), there are many areas of sulphide-graphite schists about which only scanty data are available.

According to Sahama, the »black schists» of Lapland vary considerably in their composition. Among them, residual grauwacke sediments, hydrolysates and phyllites may be distinguished. In addition to the sulphides, these schists may contain iron oxide ore, as well as ilmenite, which is the principal Ti-mineral of the sulphide-graphite schists described by Sahama.

The most extensive zone in Lapland composed of sulphide-graphite schists occur in association with the Lapponian formation of E. Mikkola (1941). The representatives of these schists are well exposed in the River of Kitinen (at and to the north of the village of Petkula), and along the middle course of the Luiro River. But, according to E. Mikkola, there too the modifications exceptionally rich in graphite or sulphides are of limited occurrence. Furthermore, he reports, the carbonate rocks seem preferably to be associated with the »black schists.» The present author has met with large clusters of graphite in similar schists along the river of Jeesiönjoki, to the west of Sodankylä. According to the geophysical date, the graphite-sulphide schist zone there is of considerable extent.

From the western shore of the Kitinen river (at the village of Kersilö), E. Mikkola (1941, p. 207) has described a sulphide-graphite schist (Table II, Anal. 6) which contains large grains of ilmenite up to 5 mm thick with minor portions of hematite. These grains are surrounded by haloes of quartz. Still richer in TiO_2 is the sulphide-graphite schist of Kittilä (Table II, Anal. 9), which is also unusually sodic. In this schist, the ilmenite occurs as a fine dissemination, but greater lumps of ilmenite enveloped by quartz are likewise present in the locality.

6. For the sake of completeness, the occurrence of the sulphide-graphite schists in Petsamo, now belonging to Russia, and there accompanying the large nickel ore deposit (Väyrynen, 1938) should be mentioned, as well as the sulphide- and graphite-bearing schists on the Fisher's Peninsula (Kalastajasaarento), at the edge of the Arctic Ocean. This occurrence has been briefly described by v. Fieandt (1912) and by Lupander (1934). There the ordinary sandstone, within a distance of approximately 5 meters, is gradually getting darker and finer-grained, and, finally, it grades into a sulphide-graphite schist, which forms a bed about 70 meters in thickness.

SULPHIDE SCHISTS OF PELITIC COMPOSITION

The sulphide schists of Nokia (Marmo, 1957), and the sulphide and sulphide-graphite schists of Hiirola (Marmo and Metzger, 1953) are mainly composed — excepting amphibolitic or diopside-bearing strips and interlayers — of quartz, mica, and sulphides, which are mainly pyrrhotite. Graphite may or may not be present. Such a rock type is represented by Fig. 6. At Nokia, the sulphide schists grade into pelite; the very pale biotite of the sulphide schists thereby becomes brown and »normal» in the pelites.

The mineral composition of these sulphide schists suggests their origin from clays or silt, which deposited in stagnant water and therefore became enriched in iron sulphides. Under such circumstances, all intermediates between the real sulphide schists very rich in iron sulphides and pelitic sediments without any sulphide minerals must, of course, occur. The principal material in all these cases, must still, however, be very similar, and in the metamorphic schists it is mainly made up of quartz and mica.

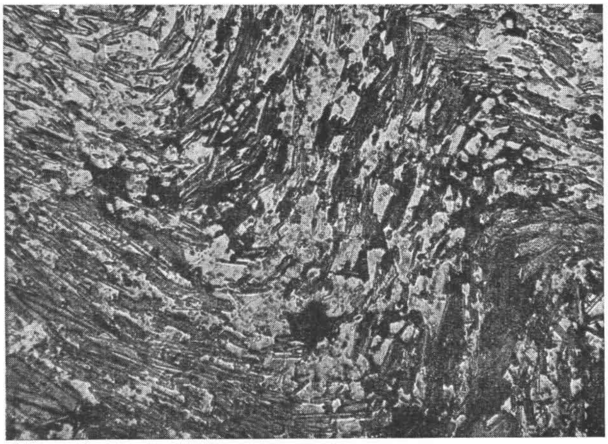

Fig. 6. Sulphide schists of pelitic composition, displaying a miniature-folding, Nokia. N //, 30 ×.

But there are clastic bedlets, too, which obviously have derived from sandy muds (Plate I, Fig. 1). In such bedlets, the sulphides may form the cement between well-rounded grains of quartz.

In Table 1, a comparison is made between the chemical compositions of a recent clay of the Littorina time and the Precambrian sulphide-graphite schist of Kittilä, Kiistala. The clay has been taken from southern Pohjanmaa by Dr. Martti Salmi, Geological Survey of Finland, who kindly gave the sample for the present investigation. The sulphide-graphite schist is from Lapland, and it contained quartz, muscovite, pale brownish biotite, a little albitic plagioclase, graphite and pyrrhotite.

When comparing the »norms» of the two analyses of Table 1, some striking similarities appear: The amounts of the normative Ab, Or, $Al_2O_3 \cdot SiO_2$, and Q are almost exactly the same in both. The ratio Ab:Or is in the recent clay somewhat lower than in the sulphide-graphite schist, which is a phenomenon to be expected, because the recent sediments are also in general somewhat richer in potassium than are their metamorphic derivates. The actual K_2O content, however, is even higher in the sulphide-graphite schist than in the clay. This fact may well indicate that the metamorphic features leading to the transformation of a sapropelic clay sediment into a sulphide-graphite schist could not have been accompanied by any large-scale transportation of potassium, or of any other constituents of the clay, but that these metamorphic phenomena obviously took place under more or less isochemical conditions. The transformation has appeared as a change in the mineralogical rather than the chemical composition. The removal of potassium from a sediment has been suggested to result in the formation of late-kinematic aplites and granites. That such rocks are entirely absent from the areas occupied by the sulphide schists at Kiistala (as well as at Nokia and Hiirola) is just an additional indication that within the sulphide-graphite schists, no potassium transportation has taken place. As revealed by Table 2, however, in most of the analyses presented, the N_2O-content is definitely higher than that of K_2O.

The iron content of the sulphide schist is expectedly higher than that of the Littorina clay because the former has from the very beginning probably been iron sulphide-bearing.

At Kaustinen, and in Pohjanmaa, in general, sulphide-graphite schists of general pelitic composition are less common than those to be dealt with on the forthcoming pages, which are supposed to have derived from marly sapropels.

The »pelitic sulphide-graphite schists» are, however, quite typical of the metasapropelites of Lapland (the communes of Kittilä and Sodankylä). They are common in the Kuopio region; they occur at Luikonlahti, Outokumpu, Haukipudas, etc.; similar sulphide-graphite schists also form the

Table 1. Chemical composition of a recent clay and Precambrian sulphide schist.
Analyst: A. Heikkinen, Geological Survey of Finland.

1. Recent Littorina clay. Vähäkyrö, Vedenoja. Depth of 3.5 m.

Analysis		*Norm:*	
SiO_2	57.38		
TiO_2	0.84	Albite	18.29
Al_2O_3	17.16	Orthoclase	23.30
Fe_2O_3	3.23	Anorthite	8.34
FeO	4.17	Magnetite	4.64
MnO	0.09	Ilmenite	1.52
MgO	3.03	Apatite	0.67
CaO	1.71	$MgO \cdot SiO_2$	7.60
Na_2O	2.19	$FeO \cdot SiO_2$	3.70
K_2O	3.96	$Al_2O_3 \cdot SiO_2$	9.88
P_2O_5	0.28	Quartz	15.50
CO_2	0.00	Water	5.18
H_2O+	4.38	Graphite	0.73
H_2O-	0.80	SO_3	0.14
SO_3	0.14		100.09
C	0.73		
	100.09		

2. Sulphide schist. Kittilä, Kiistala.

Analysis		*Norm:*		*Mode:*		
SiO_2	58.86					
TiO_2	1.85	Albite	22.43	Albite	22.53	
Al_2O_3	16.05	Orthoclase	25.75	Magnetite	0.81	
Fe_2O_3	0.56	Anorthite	1.10	Ilmenite	3.57	
FeO	9.42	Magnetite	0.81	Muscovite	17.11	38.60
MnO	0.08	Ilmenite	3.57	Biotite	17.48	
MgO	2.00	Apatite	0.22	Phengite	4.01	
CaO	0.19	$MgO \cdot SiO_2$	5.00	Quartz	27.84	
Na_2O	2.64	$FeO \cdot SiO_2$	6.60	FeS	4.75	
K_2O	4.37	$Al_2O_3 \cdot SiO_2$	10.37	Graphite	0.83	
P_2O_5	0.07	$MnO \cdot SiO_2$	0.10	Residue	1.56	
CO_2	0.00	FeS	4.75		100.49	
H_2O+	2.55	Quartz	16.27			
H_2O-	0.07	Graphite	0.83			
C	0.83	V_2O_5	0.04			
S	1.75	Cu	0.03			
Cu	0.03	Water	2.62			
V_2O_5	0.04		100.49			
	101.36					
$-S = O$	0.87					
	100.49					

Table 2. Chemical analyses of the pelitic sulphide-graphite schists of Finland and Sweden

Oxide	1	2	3	4	5	6	7	8	9
SiO_2	49.97	67.31	53.21	57.31	51.56	55.60	52.82	69.40	59.45
TiO_2	0.44		0.50	1.02	0.45	2.68	0.86	0.59	4.60
Al_2O_3	5.58	13.05	14.90	19.32	19.61	12.90	14.43	4.42	13.23
Fe_2O_3		1.28	1.09	3.83	3.03	2.12	0.17	1.44	1.47
FeO	1.94	4.24	15.33	1.98	9.63	10.91	15.69	0.54	7.70
MnO		0.007	0.10	0.03	tr.	0.15	0.02		0.18
MgO	0.44	3.27	4.18	1.06	4.19	7.23	2.98	0.37	3.41
CaO	0.17	2.05	0.29	1.28	0.54	0.02	0.86	0.12	0.63
Na_2O	0.51	3.28	2.04	3.09	3.15	1.32	5.43	0.0	5.15
K_2O	2.92	1.84	1.94	4.16	2.22	1.12	1.04	2.20	2.42
P_2O_5		0.80	0.05	0.20	0.69	none	tr.		
CO_2				0.84					
H_2O+	1.73 (})		5.36	2.86	4.49	5.12	0.71	0.73	1.44
H_2O-						0.17	0.12		0.15
S	0.20	0.29	0.04	1.85			6.84		
C	35.92		0.55			0.99		$(H_2O-) + C = 20.54$	
Cu				1.30			0.04		
Ni							0.01		
Loss by ignition		2.93			0.95				
Total	99.82	100.347				100.33	102.02	100.35	99.83
	Graphite phyllite. Jynkkä. Analyst: Elsa Ståhlberg (Wilkman, 1938, p. 32).	Carbon phyllite. Puolanka. Analyst: A. Zilliacus (Väyrynen, 1928, p. 98).	Sulphide schist. Grythytta, Sweden. Analyst: G. Assarsson (Sundius, 1922, p. 53).	Alum shale. Stora Strand, Dalsland, Sweden. Analyst: G. Nyblom (Johansson, 1908, p. 26).	Sulphide-graphite schist. Petsamo, Kamminkivitunturi. Analyst: A. Zilliacus (Hausen, 1926 p,. 47).	Black schist. Sodankylä, Kersilö. Analyst: H. Lönnroth (E. Mikkola, 1941, p. 206).	Black schist. Sodankylä, Sattasköngäs. Analyst: Lauri Lokka (E. Mikkola, 1941, p. 208).	Carbonaceous schist. Veljakkajoki, Suistamo. Analyst: Elsa Ståhlberg (Hackman, 1933, p. 45).	Black schist. E of Lake Kuolajärvi, Kittilä. Analyst: L. Lokka (Hackman, 1927, p. 47).

basis of the sulphide gneisses of Hackman (as he termed the partly gneissose sulphide schists of Savo, including the Hiirola area to the north of Mikkeli.) But, in all the cases mentioned, there still and always occur intercalations of »marly sulphide-graphite schists»; and in very many cases, if the belt composed of sulphide schists is taken as the whole, there may be present both petrological groups — pelitic and calcareous — in equal quantities.

In Table 2, there are some more chemical analyses of the pelitic sulphide-graphite schists, both from Finland and Sweden.

SULPHIDE-GRAPHITE SCHISTS OF CALCAREOUS COMPOSITION

As a result of the sapropelic origin of the sulphide-graphite schists, various amounts of calcareous material may be inmixed in the pelitic material. Therefore, in the sulphide-graphite schists derived from the sapropels, all the intermediates between pelitic and marly sapropel are also to be expected. In the sulphide-graphite schists, the primary content in the calcareous material results in the formation of lime-bearing minerals, amphiboles and pyroxenes. Examples of such schists are given in Tables 3 and 4. In the analysis of Table 3, the normative anorthite exceeds 13 per cent, the respective value being in the pelitic sulphide-graphite schist only 1.1 per cent. But, still, also this schist is quite rich in potassium, the ratio K_3O : Na_3O being as much as 5. . Also other calcareous sulphide-graphite schists analyzed contain surprisingly large quantities of potassium

Table 3. Chemical composition of an amphibole-rich, and biotite-and feldspar-bearing sulphide schist. Nivala, Hitura. Analyst: A. Heikkinen.

	%	*Norm:*		*Mode*	%
SiO_2	46.79	Albite	5.24	$Na_2O \cdot 4CaO \cdot 8RO \cdot 3Al_2O_3 \cdot 12SiO_2 \cdot 2H_2O$	17.26
TiO_2	0.45	Anorthite	13.34	$2CaO \cdot 4RO \cdot Al_2O_3 \cdot 7SiO_2 \cdot H_2O$	18.69
Al_2O_3	9.64	Orthoclase	20.02	$2CaO \cdot 5RO \cdot 8SiO_2 \cdot 2H_2O$	2.68
Fe_2O_3	1.96	Magnetite	2.78	$K_2O \cdot 5RO \cdot 2Al_2O_3 \cdot 5SiO_2 \cdot 2H_2O$	5.40
FeO	16.20	Sphene	0.98	Orthoclase	16.68
MnO	0.16	Apatite	0.34	Magnetite	2.78
MgO	5.83	$FeO \cdot SiO_2$	12.54	Sphene	0.98
CaO	4.34	$MnO \cdot SiO_2$	0.36	Apatite	0.34
Na_2O	0.61	$MgO \cdot SiO_2$	14.60	Pyrite	10.32
K_2O	3.38	$CaO \cdot SiO_2$	2.55	Pyrrhotite	5.28
P_2O_5	0.16	Quartz	8.34	Chalcopyrite	0.27
CO_2	0.00	Pyrite	13.92	Graphite	2.83
H_2O+	3.34	Chalcopyrite	0.27	V_2O_5	0.52
H_2O-	0.25	V_2O_5	0.52	Water in excess	1.50
V_2O_5	0.52	Graphite	2.83		100.01
S	7.56		102.12		
C	2.83				
Cu	0.10				
	104.12				
$-O = S$	3.77				
	100.35				

Table 4. Chemical composition of calcareous sulphide-graphite schists of Pohjanmaa. Analyst: Aulis Heikkinen

1. Diopside-amphibole-sulphide-graphite schist. Kaustinen, Pieni Österneva.

		Norm:	
SiO_2	61.41	Ab	23.06
TiO_2	0.92	An	11.12
Al_2O_3	14.55	Or	14.46
Fe_2O_3	n.d.	$MgO \cdot SiO_2$	5.60
FeO	3.74	$Al_2O_3 \cdot SiO_2$	5.26
MnO	0.07	Sphene	2.55
MgO	2.23	Qz	27.03
CaO	2.83	FeS	1.58
Na_2O	2.73	FeS_2	4.08
K_2O	2.42	C	2.45
P_2O_5	0.12	Water	2.46
CO_2	0.00	MnO	0.07
H_2O+	2.20	P_2O_5	0.12
H_2O-	0.26	V_2O_5	0.09
C	2.45	Cu, Ni	0.05
S	2.76		99.98
V_2O_5	0.09		
Cu	0.02		
Ni	0.03		
	100.83		
—O = S	0.69		
Total	100.14		

n.d. = not determined.

2. Amphibole-bearing sulphide-graphite schist. Haapavesi.

		Norm:	
SiO_2	55.57	Ab	19.91
TiO_2	0.90	An	2.22
Al_2O_3	14.40	Or	25.57
Fe_2O_3	n.d.	$MgO \cdot SiO_2$	5.50
FeO	6.83	$Al_2O_3 \cdot SiO_2$	7.94
MnO	0.12	Sphene	2.55
MgO	2.20	Qz	17.46
CaO	1.07	FeS	4.40
Na_2O	2.34	FeS_2	4.08
K_2O	4.32	C	4.84
P_2O_5	0.20	Water	2.99
CO_2	0.00	MnO	0.12
H_2O+	2.92	P_2O_5	0.20
H_2O-	0.07	V_2O_5	0.17
C	4.84	Cu	0.03
S	4.46		99.30
V_2O_5	0.17		
Cu	0.03		
	100.44		
	1.11		
	99.33		

(see Table 4), the ratio mentioned being, however, in one analysis slightly below 1 (Anal. 1, Table 4). The last-mentioned schist is diopside-bearing. A very common value of this ratio approximates 2, as, for instance, in Anal. 2 of Table 4.

Comparing the analyses of Tables 3 to 4, a notable compositional variation appears, as may be observed in regard to the pelitic sulphide-graphite schists of Tables 1 to 2, as well. The ratio of Ab: An varies between the values of 0.4 (Nivala, Hitura) to 8.9 (Haapavesi); and the amount of the normative Or, from 14.46 (Österneva) to 25.57 (Haapavesi). On the other hand, all these variations in the chemical composition of the sulphide-graphite schists are quite to be expected because in all the samples so far examined, an intricate interbedding of thin bedlets very different in composition always occurs. In the diopside-bearing varieties of Kaustinen, for instance, bedlets of a pelitic and a marly sulphide-graphite schist may sometimes be seen at the same time in a single thin section. The alternation of diopside-rich, quartz-amphibole, amphibolite, mica-quartz and of the bedlets containing rounded grains of staurolite and garnet — the latter two minerals probably of a detrital origin — may be seen in the same hand specimen.

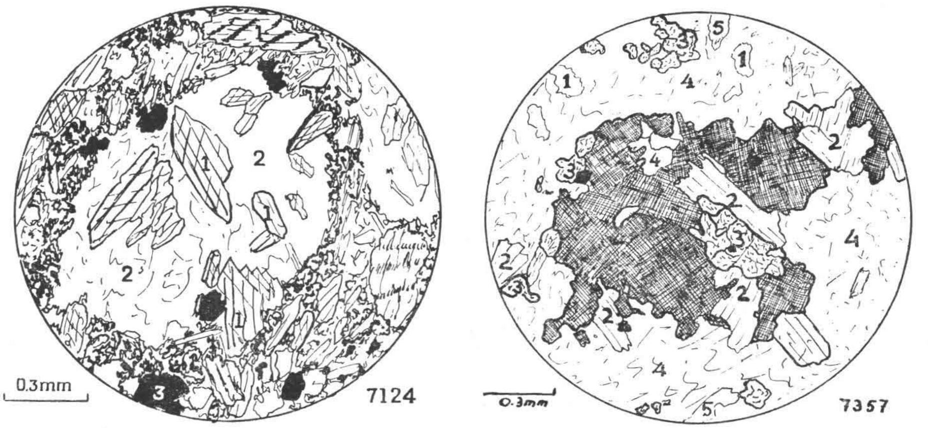

Fig. 7. 7 124: Quartzite pebble in an amphibole-sulphide schist. Kaustinen, N-end of Tammerpakka. 1 = amphibole; 2 = quartz; 3 = pyrrhotite.

7 357: Biotite-rich bedlet of an amphibole-sulphide schist. Kaustinen, Tastula. 1 = chlorite; 2 = biotite; 3 = sphene; 4 = quartz; 5 = plagioclase; 6 = pyrrhotite.

At Kaustinen, quartzite pebbles sometimes occur in the amphibolitic sulphide-graphite schist, and within these pebbles, and along their margins, there is to be seen a colourless amphibole, of distinctly later graoth than the other minerals (Fig. 7; 7 124). In some other cases, thin bedlets rich in biotite and sphene have been met with (Fig. 7; 7 357). All these observations indicate how mixed the material had actually been during its primary deposition.

In the foregoing, it has been mentioned several times that the calcareous sulphide-graphite schists are especially abundant within the zone of Pohjanmaa. But, they are always present also elsewhere, at least as thin bedlets intermixed with the pelitic schists (p. 28). In some cases they may form some thicker and coarser beds similar to ordinary carbon- and sulphide-bearing amphibolites. Such coarse beds are common and abundant at Nokia, as well, and still the sulphide schists of pelitic composition distinctly predominate there. Especially coarse may be the diopside-bearing varieties, resembling very closely the skarn, both in mineral composition and in texture. In actual fact, such beds have often been taken for skarn, as for instance at Nurmo (Southern Pohjanmaa). The resemblance may be still more evident in cases where these skarn-like portions are accompanied by the above-mentioned fine-grained and black bedlets of limestone, as has been observed at Nokia, as well as at the mine of Vihanti. That such portions are not, however, actual contact metamorphic skarns appears from cases in which the diopside-bearing bedlets are situated entirely enclosed by pelitic bedlets containing nothing but biotite and quartz, as extensively described by the present author in his report on Nokia (Marmo, 1957).

SULPHIDE-GRAPHITE SCHISTS OF SOUTHERN AND CENTRAL POHJANMAA

GNEISS-SCHIST BELT

The geological maps (1: 400 000) issued by the Geological Survey of Finland show a large gneiss-schist zone (Fig. 5) occurring in the westernmost part of Central Finland, along the eastern coast of the Gulf of Bothnia. This zone is bent in such a way as to resemble the letter »S», the middle part of which, between the settlement of Kannus in the north and the southern end of Lappajärvi Lake in the south, is comparatively straight. There the general strike of gneisses and schists averages S-N, but in places there are several strong deviations from this main direction.

To the south of Lappajärvi, a sudden change of the strike appears. To the west of the lake and within a short distance it turns almost 90° degrees. At Seinäjoki, the strike is east-westerly. Farther to the west, a new bend southwards occurs, and at the shore of the Gulf of Bothnia the strike is S-N again.

In the northern part of this belt, the changes of strike are more complicated (map of Fig. 5). There the gneiss-schist belt is strongly disturbed by several dislocations, which obviously caused the separation of this schist belt from the larger schistose zone occurring in the east, north of the commune of Kiuruvesi.

The sulphide-graphite schists of this part of Finland occur exclusively within the gneiss-schist belt here described. Outside this zone they are absent. Following the outcrops visible in the field, however, the sulphide-graphite schists can be traced only with much difficulty, because the outcrops are discontinuous and, excluding rather limited areas, comparatively few. Therefore, the geological maps of this area so far issued do not indicate the actual distribution of the sulphide-graphite schists; but most of amphibolites of the gneiss-schist belt here considered and indicated on the general geological maps of Pohjanmaa also include the sulphide-graphite schists.

The sulphide-graphite schists may be traced more succesfully by means of the aeromagnetic survey maps of the Geological Survey of Finland. The

Fig. 8. The aeromagnetic map of the gneiss zone of Pohjanmaa.

aeromagnetic anomalies obtained by this survey mainly indicate the presence of the sulphide-graphite schists. These anomalies are reproduced in Fig. 8[1]. The connection between the magnetic anomalies and the sulphide-graphite schists within the area here under consideration has been proved in the field. Therefore, from the data of Figs. 5 and 8, one may deduce that within the gneiss-schist belt here considered, the sulphide-graphite schists occupy a definite horizon which tends to be closer to the eastern and southern margins of the gneiss-schist belt than to the opposite sides. This zone, containig the sulphide-graphite schists is broken, however, at several places.

[1]) The discontinuity of the anomalies of this figure is because the aeromagnetic survey at the time of the writing of this paper was incomplete.

Within the areas around the settlement of Kaustinen, to the south of Lappajärvi, and to the west of the settlement of Seinäjoki, the sulphide-graphite schists are especially well developed. At the village of Teerijärvi, they are also fairly abundant.

GENERAL TECTONIC FEATURES

The drainage system of Pohjanmaa seems to portray the general tectonic of the area. The subparallelity of the streams of the area is striking, and at many places it could be proved that the drainage parallels the main tectonic directions. The abundant and widely distributed overburden makes, however, reconnaissance of this problem difficult and often also uncertain. Still it may be most appropriate to start with the general tectonics by describing the drainage pattern of the area.

Considering the whole of Finland south of Oulu, the rivers seem to portray two systems of tectonic features. The older direction runs approximately from north to south, and this is especially characteristic of the southwestern part of Finland. The great lakes of Päijänne and Näsijärvi follow this direction, as well as the flow direction of the rivers, to the south of Vaasa. In Central Finland it appears for instance, as the trend of the elongation of the Kivijärvi Lake. The E-W direction, which is, however, of much less importance than the south-northerly one, obviously belongs to the same system of tectonic events.

Northwards, however, the S-N trend becomes weaker and disappears. There it is obviously overlapped by a younger tectonic movement governed by the trend of NW by SE, and this direction seems to represent dislocations on a large scale. In general, the streams of Pohjanmaa follow precisely this direction; but especially clearly does this direction stand out in the elongation of the lakes of Central Finland. As one may see on the general geographical maps of this part of Finland, there is a wide and extensive zone that is thoroughly sheared in this direction. This zone diagonally traverses the whole of Finland from the Gulf of Bothnia in the north-west to Lake Ladoga in the southeast. This zone is rather broad. At the Gulf of Bothnia its width extends approximately from Kokkola to Raahe, and on the western side of the gulf, in Sweden, this zone continues further. In a most prominent way, this is marked there by the river Skellefte.

This zone of disturbances and dislocations may well have destroyed the continuity of the gneiss-schist belt of Pohjanmaa. Very possibly it is also responsible for the strong bending of this belt (to the northeast of Seinäjoki), as well as for the disturbances occurring N and NE of Kaustinen.

Under such circumstances, the sulphide-graphite schists of Pohjanmaa may be assumed to derive primarily from the same zone as those stretching along the belt beginning from Kuopio and continuing patch-wise up to Haukipudas in the northwest. At present, the last-mentioned zone is distinctly separated by the aforementioned large diagonal zone of disturbances from the sulphide-graphite schists of Pohjanmaa; but, within this zone, there still occur several minor relict patches of sulphide-graphite schists, and close to one of them, at Vihanti, there occurs an economic sulphide ore (p. 14).

Fractures trending SW-NE occur as well. Within the area here under consideration, however, this fracture direction is of minor importance only. Outside this area, this direction is portrayed by very strong dislocations, including the one probably responsible for the form and direction of the Gulf of Bothnia. In the southeast, Lake Puuruvesi, for instance, obviously represents this fracturing trend. The tectonic features which caused the fractures of this direction are probably younger than those portrayed by the NW-SE rupture zone.

There is much evidence to support the view that particularly the tectonic movements mentioned in the foregoing are those to which the »S» form of the gneiss-schist belt of Pohjanmaa is to be ascribed. Very possibly these tectonic features are also responsible for the separation of this belt, including the sulphide-graphite schists, from anorther very similar gneiss-schist belt, which also includes the sulphide-graphite schists, and which runs from the southeast through the Kuopio area and Kiuruvesi up to Haukipudas.

TECTONIC FEATURES OF THE KAUSTINEN AREA

The tectonics of the Kaustinen area are excellently elucidated by the aerogeophysical maps, on which the tectonic picture of Fig. 9 is mainly based. The electric anomalies (Fig. 10) reveal concentric curves clearly indicating a fold with a subvertical axis. The magnetic anomalies conform to the electrically obtained curves, as well. They are, however, somewhat less continuous. In the electric maps, the general fracture system of the area examined stands out clearly. The NW-SE trend appears as the most important one, just as it is within the whole region of which the area of Kaustinen is a part. In details, however, a direction perpendicular to the one mentioned is well represented, too, and it appears in the form of a step-wise displacement, and gives to the geological structure of the area a pattern composed of semirectangular blocks, very much in the same fashion as Tuominen (1957) has described for the area of Orijärvi, southwestern Finland. In addition, within the Kaustinen area, displacements according to N-S fracture also took place, and these displacements made the tectonics of this area very complicated. As a whole, however, one may say that

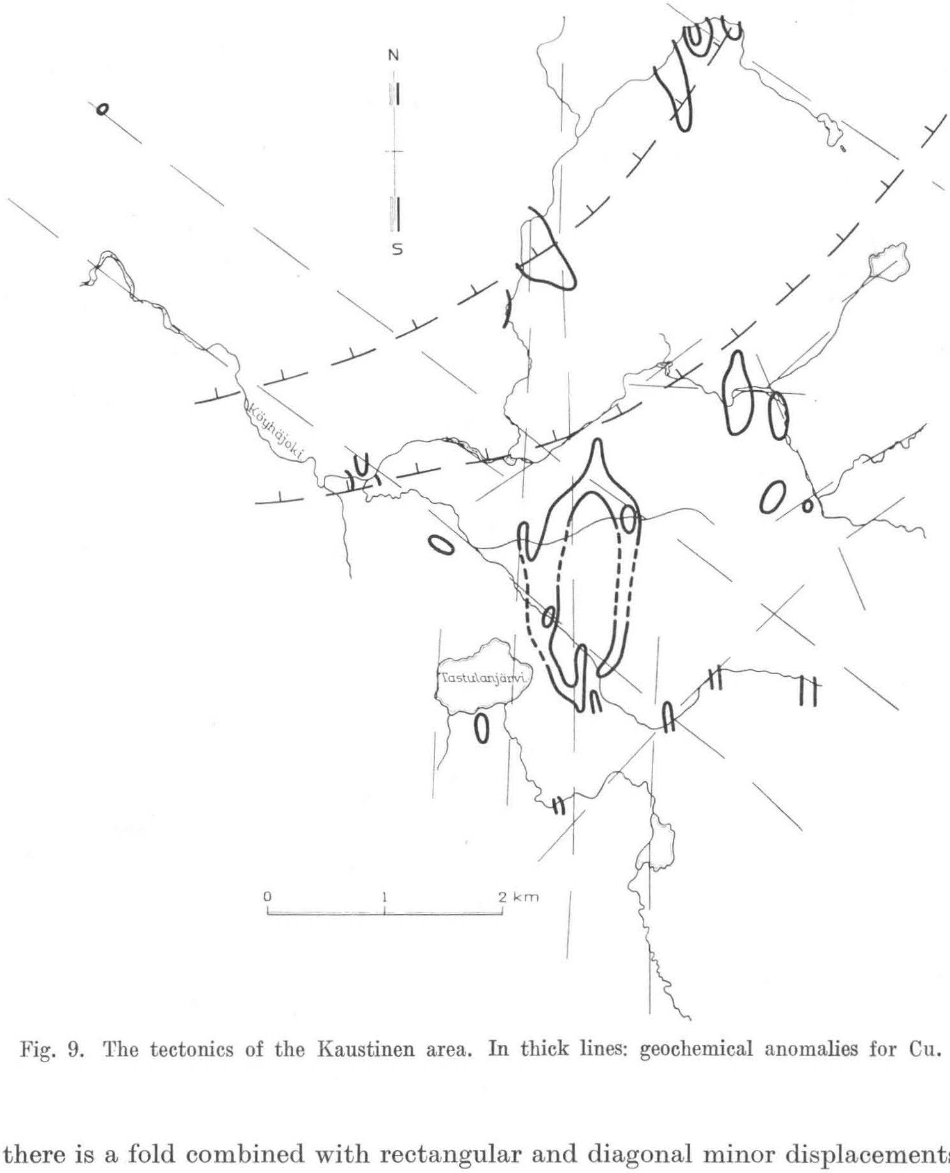

Fig. 9. The tectonics of the Kaustinen area. In thick lines: geochemical anomalies for Cu.

there is a fold combined with rectangular and diagonal minor displacements resulting in the formation of a block-wise, rigid deformation of the rocks.

To some extent, the displacements mentioned have been faults. Especially well exemplified is one such fault by the stream of Köyhäjoki, in which a distinct brecciation of the rocks may be seen, and this zone of brecciation further continues southeastwards. Another fault also well portrayed by the brecciation runs from south to north on the eastern side of Lake Tastula.

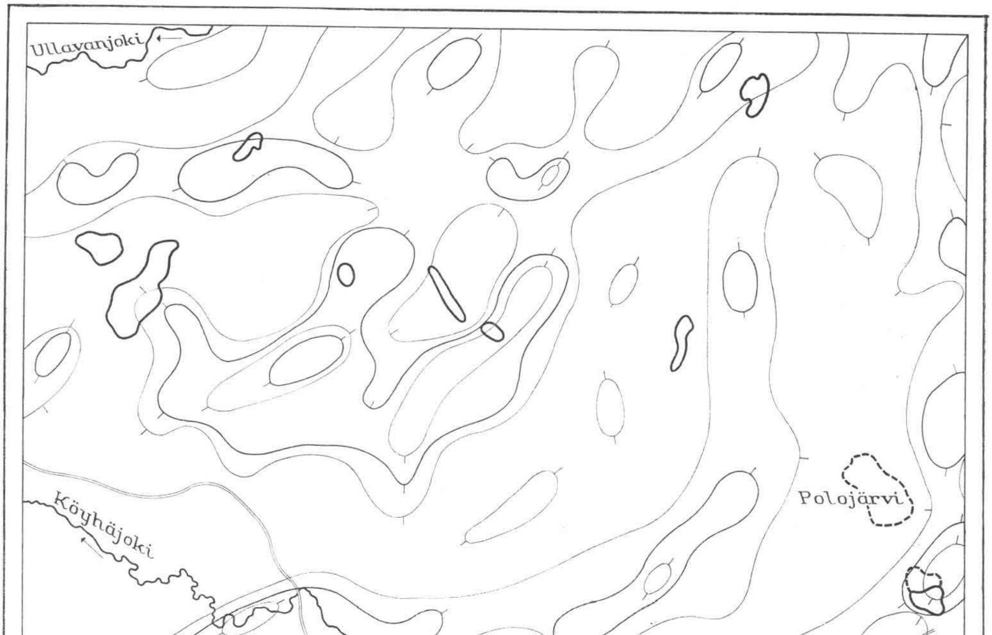

Fig. 10. The aeroelectric anomalies of the Kaustinen area.

It is here important to note that the flow directions of the streams and rivers of Pohjanmaa, but especially within the area of Kaustinen, very often represent the tectonic directions, too. Within the Kaustinen area, this fact could be proved aerogeophysically, as well.

As revealed by the map of Fig. 5, the area of Kaustinen is situated at the northern end of the most intensely folded, faulted and fractured part of the zone of the sulphide-graphite schists of Pohjanmaa. Furthermore, it is close to the western edge of the large zone of tectonic disturbances and dislocations extending from the Gulf of Bothnia southeastwards down to Lake Ladoga (see p. 34). The entire area of Kaustinen is intensely penetrated by huge pegmatite dykes. There are zones of brecciation and large folds. The eastward continuation of the aforementioned gneiss-schist belt of Pohjanmaa is broken up into pieces, and the strikes of the schists change there most turbulently from place to place.

It is quite likely that the tectonics of the sulphide-graphite schists of Pohjanmaa, and particularly within the Kaustinen area, are largely and predominantly dictated by the formation of the herein often-mentioned zone of fractures and dislocations, of the disturbance belt of Central Finland. Within this zone, the lateral shear movements must have been extremely strong, as one can see from the aerial photographs. Under such circumstances, the almost total splitting of the gneiss-schist belt, to the northeast of Kaustinen, is easily understandable, as is the formation of the block tectonics combined with the extensive folding met with within this area. Also the large-scale deformation of the entire gneiss-schist belt between Vaasa and Kaustinen, resulting in a huge »S» fold, is thus to be attributed to the same phenomena.

GEOLOGY OF THE KAUSTINEN AREA

The outcrops within the greatest part of the Kaustinen area, and especially to the north of Köyhäjoki river, being very sparse, there is no sense in constructing any geological map on a large scale and on the basis of the geological field observations only. Geophysically, however, the strips of the sulphide schists of the area stand out clearly. Within the Kaustinen area, the sulphide schists are mainly surrounded by mica schists and mica gneisses; furthermore, they are cut by huge and abundant pegmatite dykes and veins, mainly composed of quartz, plagioclase, graphically intergrown microcline, biotite and muscovite, which usually forms radially grown patches (Fig. 11). To the west of the area of sulphide-graphite schists beryl-bearing pegmatites have been observed, as well. Tourmaline is likewise a common constituent of these pegmatites. The sulphide schists of the Kaustinen area, as well as of Pohjanmaa, in general, are predominantly calcareous. Mostly they consist of sulphide-graphite-amphibole-quartz schists, and the amount of amphibole may vary from very small to very large. The diopside-bearing varieties are common, and in some beds they may even predominate. Such portions may be several meters thick. Interbeds

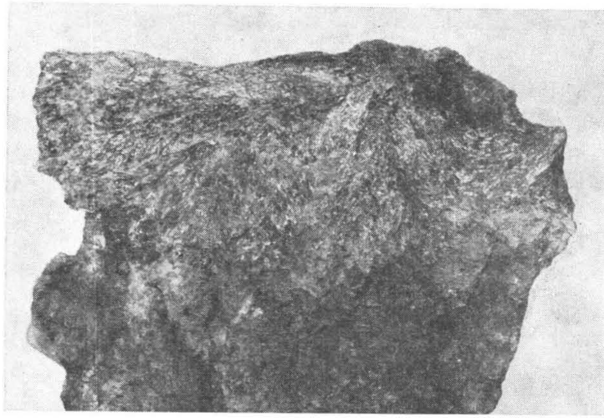

Fig. 11. A patch of the radially grown muscovite in pegmatite. Tastula.

of pelitic composition are always present too. In these bedlets, the biotite is always very pale, often almost colourless. In the embracing mica schists and mica gneisses, on the other hand, this mica is always dark brown.

The sulphide mineralization of the sulphide-graphite schists of the Kaustinen area is very simple: it consists predominantly of pyrrhotite, which, in places, may occur in the form of large, compact clusters, several cubic meters in size. They seem to be located along tectonically disturbed zones, and especially along the zone of brecciation which forms the continuation of the straight part of the flow of the Köyhäjoki. Furthermore, the places containing the pyrrhotite clusters mentioned are characterized by the presence of ample minor folds. In such clusters, chalcopyrite is conspicuously sparse. It occurs there as a coating of the fissures only. Sphalerite is there very occasionally found, and the content of nickel conspicuously low. The pyrrhotite of these clusters occurs in two generations (p. 50).

The sulphide minerals other than pyrrhotite being so sparse in the exposed sulphide-graphite schists of Kaustinen, perhaps the copper and zinc have been tectonically removed from the sulphide-graphite schists visible in the outcrops; in such a case they may have been redeposited somewhere else within or outside the zone of the sulphide-graphite schists. It was attempted to investigate this possible re-distribution of the heavy metals other than iron by geochemical means, as well. Thereby it was found that within the area to the north of the lakelet of Tastula, there is a distinct areal distribution of the geochemical anomalies for copper, nickel, and zinc. The occurrence of strong geophysical anomalies within the same area confirmed the possibility that the geochemical anomalies would reflect the geological distribution of the mentioned elements. As a matter of fact, it was found by digging, that at the spots of the strongest geophysical anomalies, the sulphide-graphite schist is distinctly richer in copper than alsewhere, and this was in agreement with the geochemical copper-anomalies of the same places.

To the east of the Tastula lakelet, comparatively high geochemical anomalies for zinc were obtained. Within the area of the mentioned geochemical anomalies mentioned, numerous sulphide-graphite schist boulders were collected, and all the local boulders examined contained microscopically easily detectable amounts of sphalerite, which is uncommon in the sulphide-graphite schists examined from the vicinity of the anomalies in question. It is almost absent in the afore-mentioned pyrrhotite clusters.

Comparison of the geochemical anomalies obtained with the tectonic map of the area (Fig. 9) clearly indicates that the mineralization, as portrayed by the geochemical anomalies and by the geophysical curves, strongly follows the tectonics of the area. The magnitude of the mineralization is, however, as yet unknown.

Along many tectonic directions, detected from the geophysical maps, brecciation zones have been found in the field. The Köyhäjoki, for instance, follows one such tectonic direction (see Fig. 10); and in the few outcrops visible the brecciation has also been observed. Furthermore, in the outcrops of Pieni Österneva, to the southeast of the village of Vintturi and near the sharp bend of the Köyhäjoki, there is a similar brecciation, accompanied by minor folding. At this place, the compact pyrrhotite cluster is well exposed. As mentioned in the foregoing this outcrop is probably situated in the same tectonic zone as that portrayed by the straight course of the Köyhäjoki (to the North of Tastula).

In the flow direction of the streamlet of Niittymaanoja, the S-N fracture trend is seen along which brecciation likewise occurs. Especially well is this evident on the eastern side of the road between the villages of Tastula and Vintturi, to the south of the school. This place is on the same line with the sharp bend in the Köyhäjoki, at the mouth of the streamlet of Niittymaanoja, and just to the west of the farm house of Viitala. Southwards along the same direction, there are streamlets to the south and north of the lakelet of Hyötyvesi.

SOME MINERALS TYPICAL OF THE SULPHIDE SCHISTS

BIOTITE

In most of the cases examined, the biotite of the sulphide and sulphide-graphite schists is characteristically pale. Often it is almost colourless and but very slightly pleochroic. Väyrynen (1928) was probably the first to describe the pale biotite of the »black schists» in some detail. For the sulphide- and graphite-bearing schists of Salmijärvi (the Kainuu region), he wrote (op. cit., p. 96, in translation): »Where the carbon material is present in minute amounts only, the mica is brown and the quartz forms clastic grains. With an increase in the amount of carbon, the mica loses its colour, and in the varieties richest in carbon, the other constituents, quartz and the almost colourless biotite, occur as thin strips between opaque bands.» This description includes the observation that in normal phyllites the biotite is always brown, but it is pale in the sulphide- and graphite-bearing schists.

From the bulk composition of the rock, Väyrynen has calculated the chemical composition of the pale biotite (Table 5, Anal. 2). This calculation reveals a remarkably high content of sodium.

Hackman and Wilkman (1929) likewise pay attention to the pale biotite occurring in the graphite-sulphide schists of Niluttijärvi Lake, in the Kuolajärvi region. In connection with the black schists of Sotkamo, the latter (Wilkman, 1931) gave a short microscopical description of the pale biotite, as well. According to him, this biotite is very pale (colourless to yellowish), and it is optically monoaxial. The birefringence is high: $\gamma - \alpha = 0.042$ —0.045. Furthermore, he reports the occurrence of muscovite lamellae within this biotite.

According to Vähätalo (1953), the biotite of the sulphide-graphite schists of Outokumpu is likewise only slightly pleochroic and almost colourless, pleochroic haloes being almost entirely lacking.

Marmo (1957) has described the pale biotite of the sulphide schists of Nokia. There, the axial angles, both of the pale biotite of the sulphide schists and of the brown biotite of the pelitic sediments, are, in general,

Table 5. The chemical composition of pale biotites of the graphite- and sulphide-bearing schists.

	1. Pale biotite. Mätäsvaara. Analyzed by Mr. Pentti Ojanperä, Geol. Surv. Finl.			2. Pale biotite. Salmijärvi. Calculated by H. Väyrynen (1928)	
	From purified biotite fraction Wt-%	Mol.	From a biotite fraction heavily contaminated by graphite Wt-%	Wt-%	Mol.
SiO_2	43.76	729		41.8	697
TiO_2	1.46	18.5			
Al_2O_3	17.71	174		26.0	255
Fe_2O_3	(Total Fe) 4.87			2.6	16
FeO		62		8.0	111
MnO	0.32	4		0.01	0
MgO	15.64	391		6.6	165
CaO	0.65	12		1.7	30
Na_2O		43	1.96	6.6	106
K_2O		51	3.53	3.7	39
H_2O-	0.02				
H_2O+				3.0	166
F	0.18				

Probable formula:

$(0.46\ Na_2O \cdot 0.54\ K_2O)\ (0.66\ FeO \cdot 4.16\ MgO \cdot 0.05\ MnO \cdot 0.13\ CaO)\ (1.85\ Al_2O_3 \cdot 0.2\ TiO_2) \cdot 5\ SiO_2 \cdot aq.$

about zero. Exceptionally, however, an axial angle of 16° has been measured, and this for a pale variety. At Nokia, the graphite is very much less abundant than it is in the sulphide-graphite schists of Pohjanmaa or of Karelia. Therefore no connection between the colour of biotite and the amount of graphite can be made, as Väyrynen did for his »black schists» of Kainuu.

In the case of Nokia, however, a close connection between the abundance of sulphides and the paleness of biotite may be readily detected. There, the pale, almost colourless biotite is very typical of the sulphide schists richest in pyrrhotite. It is to be noted that, despite the statement of Väyrynen concerning the connection between the colour of biotite and the abundance of graphite, in these schists described by him, the increase of sulphides is often parallel to the increasing amount of graphite. Thus also the parallelity between the abundance of sulphides and the colour of mica may be observed. This parallelity seems to support rather well the suggestion made by Karl (1952, p. 220) that the pale biotite may be a product of recrystallization of normal biotite under conditions where the iron was thereby transformed into other crystal forms. In the present case, particularly, this transformation may be due to the sulphur vapour pressure at the stage of recrystallization. The presence of sulphur, under these conditions, may then have facilitated the expulsion of iron from the biotite lattice to form independent crystals of pyrrhotite.

Analysis 1 of Table 5 elucidates the chemical composition of a pale biotite extracted from the sulphide-graphite schist of Mätäsvaara, eastern Finland. The schist mentioned consists mainly of quartz and very pale, almost colourless biotite, sometimes erroneously taken for muscovite. In addition, there is considerable graphite and iron sulphides, and a minor amount of albitic plagioclase. The mica forms very minute scales, heavily contaminated by graphite, which made the separation of material sufficiently pure for the analysis difficult. Therefore, the material of sufficient purity obtained sufficed for a partial analysis only. The determination of alkali metals was then made from a separate dose taken from the same material, but of inferior purity. In addition to mica, it contained graphite dust in abundance and a little quartz, but no plagioclase. Very probably the ratio of K_2O to Na_2O thereby obtained is sufficiently reliable to be used for the suggestion of the chemical composition of pale biotite, as done in Table 5. Qualitatively, a small chromium content was observed, too. The pale biotite analyzed was examined also by means of X-rays. Thereby it was ascertained that it is a trioctahedral mica of a biotite type with the following principal reflections:

3.36 Å (m)	2.63 Å (s)	2.45 Å (vw)
2.18 » (vw)	2.02 » (w)	1.68 » (w)
1.54 » (m)	1.37 » (w)	

s = strong; m = medium strong; w = weak; vw = very weak.

The F-content of the pale biotite of Mätäsvaara is low (0.18 %). Among the alkalies, in agreement with Väyrynen, sodium is well represented, but nevertheless in a much smaller amount than according to his calculations for the pale biotite of Salmijärvi (Table 5, Anal. 2). His calculation was probably much affected and invalidated by the sodium occurring in the original rock analysis used, which actually derived from plagioclase.

Concerning the iron content of the pale biotite represented by Anal. 1, the low value obtained confirms the view expressed by Marmo (1957) in regard to the sulphide schists of Nokia. He assumed, as mentioned, that the paleness of biotite is due to the expulsion of iron from biotite to form pyrrhotite, which, also in the sulphide-graphite schist of Mätäsvaara, is present in abundance, often occurring in closely association with the scales of pale biotite.

In many cases, the sulphide-graphite schists may contain biotite and muscovite, Both micas are also present at Nokia, the latter mica being sericitic. Especially often muscovite occurs in the sulphide-graphite schists of Lapland; and in those of Kiistala, in the commune of Kittilä, muscovite, accompanying a brownish biotite, is comparatively abundant. According to the chemical analysis of this schist (Table 1, Anal. 2), micas make up 38.6 per cent of the rock. From the analysis, the approximate composition of the micas may be calculated as follows:

44.3 % muscovite ($K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$)
45.3 » biotite ($K_2O \cdot 5(Mg,Fe)O \cdot 2Al_2O_3 \cdot 5SiO_2 \cdot 2H_2O$)
10.4 » phengite ($K_2O \cdot (Mg,Fe)O \cdot 2Al_2O_3 \cdot 7SiO_2 \cdot 2H_2O$).

The high water-content of the rock suggests, however, that the micas contain, on the average, more than $2H_2O$ water, because, after analysis, there remains 0.88 % H_2O in excess. Possibly the muscovite is also in this rock sericitic and consumes more than 2 H_2O.

PYROXENE AND AMPHIBOLE

As revealed by the description of the sulphide and sulphide- graphite schists (p. 8), portions rich in amphibole are always present, and some times such portions contain pyroxene, too, as is especially the case at Kaustinen (see p. 38). There, from the amphibole-quartz-sulphide-graphite schists, garnet and staurolite have been detected, as well.

Some of these minerals, and especially garnet and staurolite, are obviously of detrital origin. To such a conclusion leads the well-rounded form of some grains of the minerals mentioned.

The presence of amphibole and pyroxene, however, must be overwhelmingly attributed to the primary composition of the respective sediments, which, on rather good grounds has been suggested as having been that of a marl or a marly clay. The present writer agrees entirely with this view but, still, there are many arguments at hand which force us also to take the possibility into account that at least to some extent the amphibole and pyroxene may likewise there be of detrital origin. Especially in such sulphide-graphite schists as consist mainly of quartz and mica together with sulphides and graphite, but, in addition, contain minor amounts of rounded grains of amphibole and pyroxene, this possibility is quite evident. In such cases, the hornblende occurring as rounded grains is also mineralogically different from the amphibole which occurs as needles of a later origin in the same rock, or which form the bulk of the rock in the varieties richest in amphibole.

Furthermore, there are well-known instances of the presence of detrital amphibole and pyroxene in recent sediments, as well. Gorschkov (1957) has described the mineralogical composition of the recent sediments of the

Karskean Sea. He reports that in the fraction of the specific gravity of more than 2.8, there occur 0.8 to 11.8 per cent, of the total fraction, heavy minerals, among which, and especially in shallow water, up to 50 per cent may be represented by hornblende and pyroxene. In the sediments along the shores of the Novaja Zemlja, the fraction mentioned may contain 6 to 10 per cent hornblende and pyroxene, up to 22 per cent fragments of micas, 11 to 33 per cent epidote (in the main 1 to 7 %), ½ to 2 per cent garnet, and approximately 1 per cent staurolite.

According to Schtscherbakov (1958), the sediments of the Bering Sea near the shores and the Quaternary sediments of the coast, likewise invariably contain pyroxenes and amphiboles as well as garnet, staurolite, micas, etc. According to Petelin (1955), bluish-green hornblende is a common constituent of the sediments of the Ohota Sea.

From all the examples cited from the recent and Quaternary sediments, it may be deduced that also the schists derived from sapropelic sediments, including the sulphide-graphite schists, may contain, in addition to detrital garnet and staurolite, amphiboles and pyroxenes of similar origin, too — provided, however, that the metamorphism had not been too strong, because the last-mentioned minerals have an especially tendency to be completely recrystallized. In sulphide-graphite schists, the metamorphism is often comparatively weak. The clayey material has been recrystallized into biotite, which does not yet indicate any strong metamorphism, because this transformation is but a natural consequence of the expulsion of water from the clay minerals. Such minerals, on the other hand, as have been deposited »dry», like garnet and staurolite, and quartz, have often been seen in unaltered form. In these schists also the amphibole and pyroxene are usually products of the recrystallization of »soft» marly material; but, under similar conditions, detrital amphiboles and pyroxenes may still survive — and, to a very minor extent, they obviously also have survived.

In the following, however, only such amphiboles and pyroxenes will be considered as are not of detrital origin but are to be considered as the products of recrystallization under metamorphic conditions.

For a closer examination, amphibole from the sulphide-graphite schists of Kaustinen was extracted, and, thereby, an interval of specific gravity of 3.1 to 3.4 was used. The amphibole of Kaustinen is similar to the amphiboles of respective rocks of Pohjanmaa, in general. It is almost colourless and has the following optical properties:

$$\begin{aligned} \alpha &= 1.652 \\ \beta &= 1.641 \\ \gamma &= 1.629 \\ \alpha - \gamma &= 0.023 \end{aligned}$$

Table 6. Chemical composition of the amphibole of the sulphide-graphite schist. Kaustinen, Tastula. Analyst: P. Ojanperä, Geological Survey of Finland

SiO_2	50.44	841	
TiO_2	2.02	25	75
Al_2O_3	5.11	50	
Fe_2O_3	2.23	14	503 (+ 14 Fe_3O_4)
FeO	8.17	114	
MnO	0.40	6	
MgO	15.87	397	
CaO	11.92	213	
Na_2O	0.75	12	13
K_2O	0.13	1	
H_2O+	2.07	115	116
H_2O-	0.02		
F	0.03	1	
C	0.20	(impurity)	
Total	99.36		

$$\overbrace{[0.9\,Na_2O \cdot 0.1\,K_2O]}^{1} \cdot [16.4\,CaO] \cdot \overbrace{[30.5\,MgO \cdot 8\,FeO \cdot 0.5\,MnO]}^{39} \cdot \overbrace{[4\,Al_2O_3 \cdot 2\,TiO_2]}^{6} \cdot 65\,SiO_2 \cdot \overbrace{[8.9\,H_2O \cdot 0.1\,F]}^{9}$$

The refractive indices were determined, using the single variation method at a temperature of 24 to 25° C and sodium light, by Mr. A. Vorma of the Geological Survey of Finland.

In Table 6, the chemical composition of this amphibole is given. If the amphibole is taken to be a mixture of several more simply composed amphiboles, the following composition for the amphibole examined, in simple forms, may be calculated from the chemical analysis:

13 Mol. $(12/13\ Na,\ 1/13K)_2O \cdot 4CaO \cdot 8RO \cdot 3Al_2O_3 \cdot 12SiO_2 \cdot 2H_2O$
36 Mol. $2CaO \cdot 4RO \cdot (Al_2O_3,TiO_2) \cdot 7SiO_2 \cdot H_2O$
45 Mol. $2CaO \cdot 5RO \cdot 8SiO_2 \cdot H_2O$
5 Mol. $7RO \cdot 8SiO_2 \cdot H_2O$
14 Mol. $Fe_2O_3 \cdot FeO$ (taken as being present in the form of dust).

In the formulae given above, RO = (Mn, Fe, Mg)O, and the total ratio of Mn: Fe: Mg = 0.06 :1: 3.97.

By this calculation, there remain $33SiO_2$, $3H_2O$, anf IF in excess, 5RO being short. From this it may be dedused that in the amphibole TiO_2 probably does not replace only Al_2O_3, but, at least in the sodium-bearing component, it replaces RO, as well. In such case, this component would then consume the excessive SiO_2 also, as well as H_2O and F, thus balancing the distribution of RO between different components.

Qualitatively it has been found that the amphibole analyzed contains a little Cr, and, as impurities, some S and C.

Considering all the foregoing remarks, the formula of the amphibole of Kaustinen, the analysis of which is seen in Table 6, may be generalized into the following:

$$(Na, K)_2 \cdot 16.5\ CaO \cdot 39\,[(Mg, Fe, Mn)\ O,\ TiO_2] \cdot 6\,(Al_2O_3,\ TiO_2) \cdot 65\ SiO_2 \cdot 9\,(H_2O,\ F).$$

PYRRHOTITE

Marmo and Mikkola (1951) have published five analyses of pyrrhotites, extracted from the sulphide and sulphide-graphite schists. They concluded that the pyrrhotites examined by them have, in general, the formula: $Fe_{11}S_{12}$.

A more detailed study of the pyrrhotites of the sulphide-graphite schists, mainly carried out in connection with the present study, indicated, however, that even if $Fe_{11}S_{12}$ is an average composition of such pyrrhotites, there still appear, in details, variations in the composition of this sulphide.

In Table 7, twelve analyses of the pyrrhotites of the sulphide-graphite schists are given. Seven of these analyses are new ones. In this table, for each pyrrhotite, its composition Fe_mS_n is calculated. In addition, the new values of »S_A» are introduced. These values indicate how many per cent of the total sulphur of the sulphide is used for the formation of sulphides of Co, Ni, Cu, and Zn, present in the pyrrhotite analyzed.

The pyrrhotites analysed chemically were homogeneous, according to microscopical and in some cases X-ray examination and they did not contain any traces of pyrite, excepting the sample from Evijärvi (Anal. 5, Table 7, and Plate I, Fig. 2—3). This pyrrhotite contained very minute and sparse, concentrically grown secondary pyrite with small amounts of marcasite along the cracks. According to the planimetric estimation, the amount of the secondary pyrite remains, however, also in this specimen, less than 0.2 per cent. Thus it could hardly affect to any remarkable degree the ratio of Fe to S in this pyrrhotite.

According to the available analyses one may thus state that the composition of the pyrrhotites examined varies between the limits given by the formulae of $Fe_{11}S_{11.68}$ (Anal.3 of Table 7) and $Fe_{11}S_{12.9}$ (Anal. 12 of Table 7).

The lowest contents in sulphur ($S_{11.68}$ to $S_{11.96}$) occur in the pyrrhotites of the sulphide-graphite schists of Kaustinen, Tastula (Anal. 2 and 3 of Table 7); the highest in the pyrrhotites of the respective rocks of Rovaniemi and Ylistaro. Regionally, however, there does not seem to occur any regularity as far as the ratio of Fe: S is concerned.

The nickel and cobalt contents are characteristic of the pyrrhotites, in general. The ratio of Ni: Co, may however, attain any values between zero and infinity, and the largest variations, proportionally, are displayed by the Co-content. Nor any regional regularities in this respect could be observed; and still, according to Lange (1957) and to Hegemann (1943), in regard to the sulphide ores of Harz, these elements, if contained in pyrite, may serve as indicators of the original material of the ore, the sedimentogeneous pyrites having a more or less constant Ni: Co ratio,

Table 7. Chemical analyses of pyrrhotites of the sulphide-graphite schists. Analysts: for Fe, S, Ni, Cu, Zn, Ag, Au: P. Väyrynen (wet methods); for the rest: A. Löfgren (spectiographical methods).

No	Locality	Fe	S	Ni	Cr	Co	Cu	Zn	Mo	Ti	V	Ag g/ton	Au g/ton	Fe_n S_m	S_A %	unsolved
1	Kaustinen, Tastula (5264) ..	38.8	24.9	0.06		0.006	0.1	0.12				6.6	0.0	Fe_{11} $S_{12·35}$	0.578	
2	» (5264), dull	41.1	25.6	0.07		0.00	0.03	0.03						Fe_{11} $S_{11·96}$	0.256	
3	» (5264), bright ...	58.3	35.4	0.11		0.00	0.08	0.06						Fe_{11} $S_{11·68}$	0.396	
4	Vimpeli, Haapana (5268) ...	40.55	26.16	0.09	0.02	0.014	0.07	0.00	0.005	0.13	0.010	3.8	0.0	Fe_{11} $S_{12·3}$	0.325	
5	Evijärvi, Särkikylä (K/2292)	58.0	38.64	0.04	0.00	0.021	0.02	0.00	+	0.02	0.00			Fe_{11} $S_{12·78}$	0.323	1.32
6	Laihia (tectonized) (K/1098)	59.7	38.97	0.03	0.00	0.021	0.00	0.00	0.00	0.02	0.00			Fe_{11} $S_{12·52}$	0.295	0.54
7	Alajärvi, Hoisko [1])	59.50	38.40	0.05	0.01	0.002	<0.01		0.020	0.02	0.005			Fe_{11} $S_{12·42}$	0.1	
8	Ylistaro, Munakka [1])	58.10	39.0	0.08	<0.01	0.002	<0.01		0.003	0.02	0.006			Fe_{11} $S_{12·88}$	0.123	
9	Vihanti, Korvenkylä [1])	58.90	37.8	0.28		0.03								Fe_{11} $S_{12·35}$	0.419	
10	Juva, Ukkola [1])	60.50	38.6	0.15	0.04	0.05	0.04		0.005	0.01	0.003			Fe_{11} $S_{12·27}$	0.261	
11	Sotkamo, Tipasjärvi [1])	60.10	39.4	0.004	<0.01	0.000	0.10		0.003	0.03	0.004			Fe_{11} $S_{12·62}$	0.13	
12	Rovaniemi (K/361)	57.1	38.28	0.05	0.00	0.025	0.05	0.00	+	0.02	0.00			Fe_{11} $S_{12·9}$	0.148	2.62

[1]) Fe, S, Ni, and Co values taken from Marmo—Mikkola (1951), p. 35. The rest of the elements subsequently determined spectrographically by A. Löfgren using the orginal powdered samples.

but the hydrothermal pyrite displaying, in this respect, marked variations. According to Hegemann, the contents in Ni and Co of sedimentogeneous pyrites are there 0.02 and 0.001 per cent respectively. The magnitude of the respective contents in the pyrrhotites considered in the present paper are, however, in agreement with the data of Hegemann. That the ratio of Ni: Co is as variable as it is, is obviously due to the fact that in the sulphide-graphite schists of Finland the pyrrhotite is often displaced, hydrothermally mobilized (see pp. 17 and 39), and thereby the composition obtained different from the original one.

The value S_A (see above) indicates the amount of metals other than iron present in the pyrrhotites. In most cases, S_A is approximately 0.25 to 0.4. In this respect, there may be some tendency for particular areas to have a higher value of S_A than other areas. Anal. 1 to 6 (Table 7) represent samples all taken from a comparatively limited area and from occurrences which certainly belong geologically together. In all these cases, the value of S_A is more than 0.256 %. The maximum value observed is 0.578 %, and the mean of 6 pyrrhotites of this particular area is $S_A =$ 0.33 %.

Analyses 7 and 8 represent another area (see Fig. 7), which is to the south of the aforementioned one. This area corresponds to a separate concentration of the sulphide-graphite schists, while as a whole, still belonging, however, to the same schist belt. There $S_A = 0.1$ to 0.123 %.

Analysis 3 represents a sulphide-graphite schist from Savo. The S_A value of this pyrrhotite is of the same magnitude (0.261 %) as that of the pyrrhotites in the area of Kaustinen (Anal. 1 to 6). Anal. 11 and 12 correspond to the sulphide-graphite schists of the Karelidic zone, and the values of S_A for these specimens are 0.13 to 0.148 %.

Whether the regional variation in the S_A values, as revealed by the foregoing analyses, is real or imagined, is difficult to decide because the material available and analyzed is very limited. In any case, the pyrrhotites of the area of Kaustinen stand out clearly from the rest in being richer in Ni, Co, Cu, and Zn than the pyrrhotites of other areas considered in the present paper.

Marmo and Mikkola (1951) have pointed out that there are at least two generations of sulphides in the sulphide and sulphide-graphite schists (see plate I: 4). They also published a list (op. cit., p. 36) dealing with the nickel- and cobalt-contents of the younger and older generations of pyrrhotites. They found that the nickel is definitely enriched in the younger generation, being in all cases examined (10) more than 0.06 %, and in 8 cases out of 10 more than 0.10 %. In the older (primary) generation, the nickel-content of all the pyrrhotites analyzed (6) is less than 0.01 %, while in half the cases it is 0.000 %.

Fig. 12. Biotite-muscovite gneiss, Tastula. 1 = pyrrhotite; 2 = biotite; 3 = muscovite; 4 = quartz; 5 = plagioclase.

As regards the cobalt, however, the same could not be deduced. Also in this case, however, the younger generation tends, on the average, to be richer in cobalt (mean of 10 equals 0.098 %) than the older (primary) generation (mean of six equals 0.002 %).

In Norway, in the »vasskis» type of the pyrite concentrations, two sulphide generations likewise occur; but there are no available determinations of Ni and Co in the respective sulphides. However, the »gangkis» often clearly represents a still younger generation of the sulphides of the respective schists (compare p. 17), and the average Ni and Co contents of both »vasskis» and »gangkis» have often been determined, and many of the determinations have been published by Bjørlykke and Jarp (1950). According to the authors cited, the Co-content may vary considerably, even in different samples from the same deposit. On the average, however, the pyrites of »gang typus» contain 0.01 to 0.1 % Co; but the Heimtjernhø ore, which is supposed to be of sedimentary origin (= »vasskis»), contains only 0.004 % cobalt.

From the point of view of the different generations of pyrrhotite, the suplphide-graphide schists of Kaustinen are interesting. As one may see in Fig. 5 of Plate II, the »primary» and the »younger» generation are clearly visible there. Also in the gneiss met with at Kaustinen, pyrrhotite is often present, and it is obviously equivalent to the younger generation of pyrrhotite of the sulphide-graphite schists (Fig. 12). But, in Fig. 5 of Plate II, the »younger» generation is likewise split in two. Megascopically these »subgenerations» may be distinguished from each other, the older of the two appearing dull under the microscope, but the younger pyrrhotite very bright. The sample illustrated in this figure derives from an almost compact cluster of pyrrhotite measuring approximately 2 to 3 m in width and 10 m in length. Both generations have been separated and analyzed (Anal. 2 and 3, Table 7). The older, dull pyrrhotite contains a large amount of quartz and graphite inclusions, visible in many instances only under the strongest magnification. These inclusions appear in the pyrrhotite as a dust. According to the chemical analyses, they make up almost one third of the pyrrhotite. In the pyrrhotite of the younger, bright generation, such inclusions are either absent or only scantily present. This explains why one of the two pyrrhotites of different generations is dull but the other one bright.

Comparing the chemical compositions of these pyrrhotites, one obtains the following result:

	dull	bright
Formula	$Fe_{11}S_{11.96}$	$Fe_{11}S_{11.68}$
S_A	0.256	0.396
(Ni + Cu + Zn) %	0.13	0.25

The value of S_A indicates that the bright (younger) pyrrhotite is almost 50 per cent richer in Ni, Cu, and Zn than the dull (older) variety, and both generations are conspicuously poor (nil) in cobalt.

Analysis 1 of Table 7 illustrates the chemical composition of the pyrrhotite, which is also from Kaustinen. This specimen, however, derives from a part of the sulphide-graphite schists in which the sulphide has not been concentrated into large clusters but occurs as a dissemination. This pyrrhotite contains 0.1 % Cu, 0.12 % Zn, and 0.006 % Co, and $S_A = 0.578$. All these values clearly indicate that if the large sulphide clusters discussed in the foregoing have derived from the concentration of disseminated pyrrhotite, then the latter must have become largely »purified» during concentration.

Table 10 presents analyses of sulphide-graphite schists from Kaustinen. These analyses display a distinct irregularity in respect to the cobalt contents. The copper contents, however, are, on the average, comparatively high. Also this finding tends to prove the assumption that, during the formation of solid pyrrhotite clusters, the concentration of disseminated pyrrhotite had been connected with the removal of other metal sulphides from the pyrrhotite — probably simultaneously with the mobilization of the latter.

In Table 8 analyses of both the younger generation of pyrrhotite and the sulphide-graphite schist containing »primary» pyrrhotite are put together. These analyses reveal that in the pyrrhotite the nickel is 7 to 10 times as abundant as it is in the schist. The cobalt is entirely bound to the younger pyrrhotite. The copper, on the other hand, is much more abundant in the schist than in the extracted pyrrhotite.

Consequently, in such a case where the »younger generation» of pyrrhotite occurs only as a minute concentration, it is followed by the contents of nickel and cobalt, as well; if, however, the formation of the younger pyrrhotite results in a large-scale mobilization, the large solid sulphide clusters thereby formed are conspicuously poor in these elements. This nowise means, of course, any trend of differentiation, simply being a locally observed phenomenon. Nor does this observation invalidate the assumption that, in general, the younger generation of pyrrhotite has a tendency to be richer in nickel and cobalt than the older generation, because, in the opinion of the present writer, the compact pyrrhotite clusters of Kaustinen represent the »gangkis» type of the Norwegian authors, and not the younger generation of the »vasskis» type dealt with in the paper of Marmo and Mikkola (1951).

The results obtained and described in the foregoing for the pyrrhotites of the sulphide-graphite schists may be summarized as follows:

1. In the sulphide and sulphide-graphite schists, all the sulphides are more or less evenly distributed. They may have been locally mobilized and reappear, after a short-distance transport, as minor concentrations into blebs and veinlets, referred to as the »younger generation.»

2. The remobilization of pyrrhotite may have occurred on a large scale also, and then, probably under hydrothermal conditions, it caused the formation of compact pyrrhotite clusters of considerable size. These clusters are conspicuously poor in coloured metals.

3. During the formation of the large pyrrhotite clusters mentioned, the remobilized sulphide material obviously lost the coloured metals — nickel and cobalt as well as copper, all present in the sulphide-graphite schists. The fate of these metals remains, however, unsolved.

4. At Kaustinen, the pyrrhotites (both dull and bright) of the compact sulphide clusters are shorter in sulphur than are the pyrrhotites extracted from the sulphide-graphite schists of both the Kaustinen area and other localities considered in the present paper. From this observation it may be deduced that the remobilization of pyrrhotite, if resulting in the formation of large concentrations, was accompanied by a lower sulphur pressure than that which accompanied the formation of pyrrhotites of the sulphide-graphite schists outside the compact clusters.

In Table 9, there are additional analyses of the trace elements occurring in the pyrrhotites of the sulphide-graphite schists. These analyses are, of course, a contribution to the geochemistry of pyrrhotites, as well, but, having been carried out with impure material, they have not been considered in the foregoing discussion.

Table 8. Trace elements of sulphide-graphite schists (I) and of the respective pyrrhotites (II).

No	Locality	Ni		Co		Cu		Cr		Mo		V		Ti	
		I	II	I	II	I	II	I	II	I	II	I	II	I	II
1	Laihia	0.02—0.03	0.04	0.005—0.014	0.021	0.02—0.03	+	$<$0.01	0.00	+	0.00	0.006—0.015	0.00	0.04—0.10	0.02
2	Nokia	0.02—0.08	0.20	0.011	0.015	0.05	0.01	0.02	0.01	0.007	0.00	0.031	0.005	0.15	0.03
3	Rovaniemi	+	0.06	0.00	0.025	0.07	0.03	0.06	0.00	0.008	+	0.045	0.00	0.50	0.02
4	Kaustinen, Österneva	0.01	0.07—0.11	0.000	0.002	0.03—0.08	0.01	0.03	..	+	..	0.100	..	0.45	..
5	Vimpeli, Haapana ..	0.10	0.09	0.006	0.014	0.14	0.07		0.02		0.005		0.010		0.13

Table 9. Trace element contents of some impure pyrrhotites, extracted from sulphide and sulphide-graphite schists. Analyst: A. Löfgren.

No	Locality	Ni	Co	Cu	Cr	Mo	Ti	V	Ni: Co (Wgt-%)	
1	Leivonmäki	+	0.005	0.01	0.01	0.003	0.30	0.028	∼0	
2	Nokia, Koskenmäki	0.08	0.015	0.01	$<$0.01	0.007	0.03	0.005	5.3	
3	Ylitornio, Merivaara	0.40	0.002	0.05	$<$0.01	0.005	0.04	0.014	200	
4	Haukipudas, Putaankylä .	0.16	0.020	0.02	0.01	0.004	0.03	0.005	8	
5	Sotkamo, Kolmisopenjärvi .	0.04	0.010	0.05	0.02	0.004	0.03	0.006	40	
6	Nokia, Tyrkkölä	0.20	0.011	0.05	0.02	0.007	0.15	0.031	20	
7	Haukipudas, compact FeS	0.05	0.0	0.05		0.0		0.0		Ag, W, Sn, Pb = 0.0
8	» » »	0.08	0.1	0.13		0.0		0.0		Zn = 0.72; Au = tr.; Ag = 0.5; W,Sn, Pb = 0.0
9	Kuusamo, compact FeS ..	0.27	$<$0.01	0.03		$<$0.01				Zn, Ag, Sn, Bi, W, Pb, As, Cd =0.0; Mn = 0.01

THE MINOR CONSTITUENTS OF THE SULPHIDE-GRAPHITE SCHISTS

GOLD AND SILVER

G o l d. In 38 samples of the sulphide-graphite and sulphide schists, the gold content has also been determined (Tables 10_1 to 10_6). Only exceptionally, however, was there more than a trace of gold. There are 6 determinations for Kaustinen, 1 for Vimpeli, 1 for Alajärvi, 1 for Nivala, 1 for Nokia, 12 for Haapavesi, and 3 for Kiuruvesi, all containing 0.0 g/ton Au. In 3 specimens (2 of Haapavesi and 1 of Kiuruvesi), there are traces of gold, and in 1 single determination as much as 0.4 g/ton gold was observed. In addition, the following determinations of gold may be mentioned: A loose boulder from Haukipudas contained 0.9 g/ton Au; the sulphide-graphite schist of Paltamo, Melalahti, had traces of gold; a similar schist of Lohijärvi, Ylitornio contained 0.02 g/ton Au.

Such a situation is not quite according to expectations for the gold contents of the sulphide-graphite schists are supposed to have derived from sapropelic original material, because in the younger formations the respective schists usually contain more than traces of gold. In the »Alaunschiefern» from Thüringen, as a by-product of the fabrication of alum, a sludge is obtained, from which, at least at Saalfeld, Zeulenroda, and Mühlwald, gold has been recovered. According to Leutwein (1951), the sulphide-bearing schists of Thüringen, as determined from 4 different localities, contain 0.0 to 0.5 g/ton Au. However, 2 of 4 determinations indicate no gold. According to Hundt (1940), the alum slates of Hohenleuben contain, on the average, 0.2 g/ton Au. Furthermore, he could show that the gold of his alum slates was associated with the carbon. Leutwein (1951) also mentioned that if the carbon of the alum schists was separated into a concentrate, it was richer in gold than the primary schist. Thus, he concluded that the gold must be associated with the carbon.

Haber (1925) pointed out that in sea water, the gold occurs in an ion dispersed form to a minor extent only, but that it is mainly bound into materials floating in the water, most of which are built up of organic material. Therefore the accumulation of gold into the sapropelic mud

Table 10_1. The minor element contents of the sulphide-graphite schists

No	Locality	g/ton		Ni	Cr	Co	Cu	Zn	Mo	Ti	V
		Ag	Au								
1	Kaustinen, Niittykoski	2.0	0.0				0.28				
2	» »	1.6	0.0	0.04		0.0	0.23	0.0			
3	» »	2.0	0.0				0.25	0.0			
4	» Köyhäjoki S	0.8	0.0	0.0			0.06	0.0			
5	» » »	1.8	0.0	0.05		0.0	0.25	0.0			0.0
6	» » »	0.6	0.0	0.05			0.06	0.16			
7	» Pieni Österneva			0.01	0.03	0.02	0.01		+	0.45	0.100
8	» E of Tastula			+	<0.01	0.004	>0.5		0.0	0.12	0.026
9	» Niittykoski			0.08	<0.01	+	0.17		0.004	0.21	0.018
10	» Tastula			0.10	0.01	0.013	0.08		0.003	0.11	0.014
11	Vimpeli, Haapana	1.0	0.0	0.10		0.006	0.14	0.00			
12	Ullava (K/1500)			0.12	0.01	0.009	0.14		+	<0.5	0.050
13	Teerijärvi (ypunger)			0.17	0.01	0.005	0.03		0.008	0.15	0.013
14	» , Långviken (older generation)			0.004	<0.01	0.004	<0.01		0.005	0.25	0.008
15	» , K/1612			0.04	0.01	0.01	0.03		0.00	>0.5	0.011
16	Laihia, K/964			0.02	<0.01	0.008	+		0.00	0.03	+
17	» Miettylä K/722			0.03	<0.01	0.014	0.02		0.006	0.10	0.015
18	» K/2080			0.02	<0.01	0.005	0.03		0.00	0.04	0.006
19	Alajärvi, K/2318	0.0	0.0				0.05	0.10			
20	Nivala, 18/AJL/57			0.05	0.01	0.004	0.01		0.023	0.28	0.066
21	» »			0.11							0.35
22	» Pahkaperä			0.12			0.11				
23	» Maliskylä			0.12		0.01	0.12				
24	» Sarjankylä	6.6	0.0	0.05			0.14	0.65			
25	Pihtipudas, Virkapuro			0.02	0.00	0.070	0.02		0.00	0.21	0.00
26	Kalajoki, K/554			+	0.04	0.004	0.01		0.007	>0.5	0.110
27	Haukipudas, Ukkolanpää			+	0.01	0.00	0.03		0.00	>0.5	0.036
28	Rovaniemi, K/361			+	0.06	0.00	0.07		0.008	0.5	0.045
29	Kittilä, Kiistala			0.02	0.01	0.01	0.06		0.00	>0.5	0.024
30	Rantasalmi, Sallila			0.03	~0.01	0.004	0.01		0.007	0.5	0.110

would be expected. As a matter of fact, such an accumulation is also virtual, as shown by Leutwein (1951), who published analyses of the sapropelic muds from the Baltic Sea and from the Norwegian fjords. In the former case, the gold-contents of the mud were 0.5 g/ton (at Bornholm) and 0.7 g/ton (at Gotland). For the muds of the Norwegian coasts of the North Sea, Leutwein reported the gold-values of 1.7 g/ton (Nordfjord), 0.7 g/ton (Ulvesund), and 2.5 g/ton (Drontheim-fjord and Nord-Ranen).

Under such circumstances, the absence of gold would be well expected in such sulphide schists as contain graphite in only small quantities (i. g. Nokia), but it should occur in the sulphide-graphite schists of Pohjanmaa, which are always rich in carbon. In actual fact, however, as revealed by the foregoing trace element analyses, the gold content is practically nil there too.

Concerning the Karelian sulphide-graphite schists, which may contain shungite as well as graphite, and which may be very rich in carbon (Laita-

Table 10_2. Trace elements of the sulphide schists of the Nokia region

No	Specimen	g/ton Ag	g/ton Au	Ni	Cr	Co	Cu	Zn	Mo	Ti	V	S	S_A %
1	Räikkä	0.0	0.0	0.15									
2	R 3/ 44.75— 45.35			0.09									
3	R 3/ 36.13— 37.65			0.06			0.045	0.1					
4	R 4/115.9 —118.10						0.015	0.11				7.45	0.93
5	R 4/ 93.85— 96.9						0.02	0.13				6.0	1.16
6	R 4/ 27.8 — 31.6						0.01	0.13				6.05	1.105
7	R 8/ 61.1 — 62.8						0.005	0.12				5.8	1.105
8	R 8/ 62.8 — 64.6						0.01	0.2				6.2	1.6
9	R 8/ 64.6 — 65.95						0.005	0.19				6.35	1.515
10	R 8/ 80 — 82.04						0.01	0.12				4.65	1.45
11	R 8/ 82.04— 83.8						0.00	0.08				3.2	1.2
12	R 8/ 83.8 — 85.94						0.00	0.08				3.0	1.25
13	R 8/100 —101.3						0.01	0.18				5.0	2.00
14	R 8/101.3 —103						0.015	0.20				4.9	2.06
15	R 8/103 —105.1						0.01	0.27				5.5	2.47
16	R 8/105.1 —109.68						0.015	0.15				4.1	2.07
17	Mean of 10 determinations of bore hole R 8, listed above						0.008	0.159				4.87	1.64
18	Averages of the existing spectrographic determinations of trace elements for different varieties of sulphide schists occurring at Nokia:												
	Phyllite			0.02	+	+			+		+		
	Sulphide schist (mainly mica and quartz)	0.0	0.0	0.02	<0.01	+	0.015	0.126	+	>0.03	++	4.87	1.5
	Sulphide schist (contains tremolite)			0.03	+	+			0		+		
	Graphite amphibolite			0.03	+	+			0.01		0.01		
	Amphibolite phyllite			0.05	+	+			0.004		0.03		

kari, 1925), comparatively little data on their gold-content are available. Three of them are mentioned in the foregoing, the gold content being less than 0.02 g/ton, except for the sulphide-graphite schist of Haukipudas, with 0.9 g/ton Au.

S i l v e r. According to Leutwein (1951), the alum schist of Thüringen contains 1 to 30 g/ton Ag. The distribution of silver in this schist is, however, rather irregular. Some kind of parallelity between the gold and silver contents, according to Leutwein, still does exist. No data are available to indicate the silver-contents of the recent sapropelic muds.

As regards the sulphide and sulphide-graphite schists of Finland, as many determinations for silver as for gold are available. Because there is little or no gold, no parallel exists between the gold and the silver, as far as the sulphide-graphite schists of Finland are concerned. In the schists of the area of Kaustinen, the silver content varies from 0.6 to 2.0 g/ton

Table 10₃. Trace elements of the sulphide-graphite schists of the Haapavesi area

No	Specimen	g/ton		Cu	Ni	Zn	Co	V	
		Ag	Au						
1	Alasydänmaa, 136/AJL/55				0.08	0.18			
2	» 95c/AJL/55	7.6	0.4	0.58		0.26			
3	» 71/AJL/55				0.15	0.06			
4	» 99/AJL/55	1.8	tr.	0.06	0.03	0.03			
5	» 95/AJL/55	2.6	tr.		0.06	0.04			
6	» 165b/AJL/55			0.07		0.19			
7	» 95b/AJL/55	1.4	0.0	0.08	0.05	0.07			
8	» 165a/AJL/55			0.04	0.05	0.12			Pb = 0.0
9	» 96a/AJL/55	5.8	0.0	0.3	0.04	0.15			
10	» 118c/AJL/55	2.6	0.0	0.04		0.08	0.00		
11	» 128a/AJL/55	4.0	0.0	0.08	0.06	0.08	0.008		1)
12	» 123b/AJL/55	2.0	0.0	0.09	0.07	0.13	0.01		2)
13	» 124a/AJL/55	3.2	0.0	0.07		0.17	0.00		
14	» 140e/AJL/55	1.6	0.0	0.05	0.1	0.04			
15	» 140d/AJL/55	1.6	tr.	0.02	0.1	0.06			
16	» 112/AJL/55	5.6	tr.	0.51	0.06	0.30	0.001		3)
17	» 112b/AJL/55	3.2	0.0	0.18	0.12	0.2	0.008	0.07	4)
18	» 96b/AJL/55	2.4	0.0	0.08	0.02	0.21	0.001		5)

Spectrographically determined:

1) Sb = Cd = Bi = 0.0; Cr = 0.03; Pb = 0.005
2) Sb = Cd = Bi = 0.0; Cr = 0.02; Pb = 0.00
3) Sb = 0.0; Pb = 0.001; Mn = 0.05; Cr = 0.03; Ti = 0.3
4) Cr = 0.01; Ti = 0.12; Mo = 0.023
5) Sb = Cd = 0.0; Pb = 0.001; Mn = 0.5; Cr = 0.03; Ti = 0.7

Table 10₄. Trace elements of the sulphide-graphite schists of the area of Haapavesi having a composition resembling that of skarn

No	Specimen	g/ton		Cu	Ni	Zn	Co	V	
		Ag	Au						
1	69/IV/AJL/56			0.05		0.05			
2	85/IV/AJL/56			0.06		0.06			
3	56/IV/AJL/56			0.07		0.27			
4	26/22/AJL/56			0.06		0.0			
5	Suotuperä, 42/EV/56			0.09	0.03	0.15			
6	» 43/EV/56			0.16	0.02	0.18			
7	» 39/EV/56			0.02		0.48			Pb = 0.0
8	» 45/EV/56	0.0	0.0	0.07	0.0	0.35			Pb = 0.0
9	» 41/EV/56	4.0	0.0	0.09	0.05	0.40			Pb = 0.0
10	» 40/EV/56	0.2	0.0		0.01	0.08			
11	» 39/IV/AJL/56			0.0		0.02			
12	» 60/IV/AJL/56			0.03		0.12			
13	» 47/IV/AJL/56			0.05	0.04	0.02			
14	» 40/IV/AJL/56			0.0		0.01			
15	50/EV/56			>0.5	0.12		0.005	0.14	1)

1) Cr = 0.01; Ti = 0.13; Mo = 0.036.

Table 10_5. Trace element contents of a continuous section across the sulphide-graphite schists at Haapavesi

Specimen	g/ton		Cu	Ni	Zn	Co	S	S_A %
	Ag	Au						
2/ II/AJL/56	4.8	0.0	0.26	0.02	0.47			
2/ 17/AJL/56	1.4	0.0	0.08		0.03		6.7	0.71
1/ 25/AJL/56	0.0	tr.	0.06	0.03	0.03	0.01		
8/ 25/AJL/56	0.2	0.0	0.04	0.05	0.05	0.03	13.3	0.60
10/ 25/AJL/56			0.09	0.07	0.05	0.04	19.6	0.58
20/ 25/AJL/56			0.06	0.04	0.02	0.01	11.5	0.51
4/ 28/AJL/56	0.4	0.00	0.03	0.04	0.09		10.1	0.80
7/ 28/AJL/56			0.0	0.06	0.15		12.8	0.87
5/IV/AJL/56			0.03	0.05	0.12	0.00	8.95	1.12
Average of 9 determinations			0.05	0.044	0.112	0.018		0.741

Table 10_6. Trace element contents of the sulphide-graphite schists of scattered localities, and some means of these contents for certain areas.

	g/ton		Cu	Ni	Zn	Co	Cr	Mo	Ti	V	
	Ag	Au									
Haapavesi:											
skarn-like portion	2.7	0.0		0.03							
pelitic portion				0.055	0.15	0.007	0.02	0.03	0.125	0.10	
Kaustinen; average of tremolite-bearing schists	1.46	0.0		0.10		0.013	0.01	0.003	0.11	0.014	
Nivala: average of amphibole-bearing sulphide-graphite schists			0.12	0.10		0.01	0.01				
Haukipudas, 8/AMla/46	0.6	tr.		0.06		0.03					
Haukipudas, Putaankylä: the mean of 20 analyses				0.06		0.05				0.00	Bi=W=Sn=Pb=0.00
Haukipudas, Martinniemi: the mean of 5 analyses				0.086							
Jurva, M/2086	1.4	0.0		0.02							
Juva, Näärinki	0.6	tr.	0.06	0.03	0.03						
Sotkamo, Tiaislampi	1.0	0.0	0.1	tr.	0.11						
Sotkamo, Kolmisoppi	0.0	0.0									
Mikkeli, Hiirola	0.0	0.0									

(the mean of 6 analyses is 1.47 g/ton). The schists of Vimpeli (1 analysis) contain 1.0 g/ton Ag; those of Alajärvi (1 analysis) 0.0 g/ton; and of Nivala (1 analysis) 6.6 g/ton. The sulphide schists of Nokia (1 analyses) contain no silver. The silver contents of the schists of Kiuruvesi are 2.8 to 6.6 g/ton (the mean of four analyses is 4.6 g/ton Ag). The sulphide-graphite schists of Haapavesi contain 0.2 to 7.6 g/ton Ag (the mean of 12 determinations being 4.13 g/ton), and a boulder of Haukipudas contained 4.09 g/ton Ag.

For the Karelian sulphide schists the following determinations may be given: Melalahti, Paltamo — 2.2 g/ton; Ylitornio, Lohijärvi — 1.0 g/ton Ag.

Furthermore, as revealed by the chemical analyses of the sulphide-graphite schists of Pohjanmaa, there are indications that the silver is bound to the pyrrhotite rather than to the carbon. This may be deduced from those analyses of pyrrhotite where the silver was also determined (Table 7), because this element has been determined likewise from the sulphide-graphite schist from which the respective pyrrhotites were extracted (Table 8):

	Ag in schist	Ag in pyrrhotite
Kaustinen	0.6 to 2.0 g/ton	6.6 g/ton
Vimpeli	1.0 g/ton	3.8 g/ton

In these two cases, there can be no doubt that the pyrrhotite is the actual carrier of silver.

COPPER, NICKEL AND COBALT

The contents of copper, nickel and cobalt of the iron sulphides of the sulphide and sulphide-graphite schists have already been discussed in the foregoing pages (p. 49). An attempt will now be made to discuss the distribution of the mentioned elements in the sulphide-graphite schists themselves. This discussion is based on rather comprehensive analytical material presented in Tables 10_1 to 10_5.

Copper. In Table 10_1, analyses 1 to 23 represent the sulphide-graphite schists of Central Pohjanmaa. These schists are almost exclusively calcareous. This means that they contain amphibole and very often also pyroxene. In these schists the copper occurs in the form of chalcopyrite, and this is usually younger than the other minerals of the rock. Mostly it occurs as a coating or infilling of fissures, or along the grain boundaries of the silicatic minerals. As revealed by the discussion of pyrrhotite (p. 51), the copper occurs to some extent as a minor constituent of the pyrrhotites, as well.

As one may note in the list of the analyses, in all the cases examined copper is invariably present, but in very widely varying amounts, ranging from 0.01 to 0.5 %. In the opinion of the present writer, this variation is mainly due to a later remobilization of copper rather than to differences in the copper contents of the primary material. This assumption is proved by the fact that the chalcopyrite occurs mainly as minute veinlets or as a fissure coating, thus definitely indicating emplacement from mobilized conditions. The copper is probably syngenetic (see p. 11), but it has been locally mobilized and transported for a very short distance.

On the average, the amphibole-bearing sulphide-graphite schists of the area of Kaustinen contain 0.182 % Cu (12 analyses). If, however, the exceptionally high value of Analysis 8 (a chosen sample with more than 0.5 % Cu) is excluded, there is, on the average, 0.152 % Cu. The sulphide-graphite schists of the areas of Teerijärvi and Laihia (6 analyses) contain, on the average, 0.02 % Cu. In the Nivala area (4 analyses), the copper-content averages 0.095 %. The scattered samples of Analyses 24 to 28 contain, on the average, 0.036 % Cu. Consequently, there seems to be evidence of the Kaustinen area having sulphide-graphite schists richer in copper than the other similar schists considered in the present paper.

Table 10_2 presents the analyses of the sulphide schists of Nokia (Marmo, 1957). Ten analyses, all made from different parts of the same bore hole (R8), contain, on the average, 0.008 % Cu. The mean of all 14 determinations for Nokia makes up 0.012 % Cu.

Table 10_3 contains the analyses of the schists of the Haapavesi area. There, excluding the exceptionally high contents in copper of the samples chosen (95c/AJL/55 and 112/AJL/55), the mean of 26 determinations is 0.0735 % Cu.

This brief compilation gives the following results:

Sixty-seven analyses of sulphide and sulphide-graphite schists from 5 different areas indicate that the copper contents of such schists vary between 0.012 % (Nokia) and 0.152 % (Kaustinen).

Among the areas here discussed, Haapavesi (0.073 % Cu), Nivala (0.095 % Cu), nad Kaustinen (0.152 % Cu) belong to the same region characterized by a large distribution of the sulphide-graphite schists. Practically all the areas mentioned are equally rich in copper. The average of all the analyses for the schists of these areas is 0.11 % Cu. It is of interest to note that the Nokia region is much poorer in copper (0.012 %). Thus the sulphide-graphite schists of Pohjanmaa seem to be, also in general, definitely richer in copper than are the respective schists of other areas dealt with in the present study. It would be interesting discover whether this finding depends upon the petrological composition of the schists or not.

For the Haapavesi area, separate determinations for pelitic amphibole-sulphide-graphite schists (13 analyses), and for the skarn-like diopside-bearing sulphide-graphite schists (15 analyses) have been made. There the mean for the former group is (excluding, again, the exceptionally high values of the two samples chosen) 0.09 % Cu. For the skarn-like schists the respective mean is 0.05 % Cu.

In the case of the region of Nokia, there are likewise different determinations for different sulphide schists. For the pelitic composition (mica +

quartz + pyrrhotite), the copper-content averages 0.015 %, the tremolite-bearing varieties containing less than 0.005 % copper. Thus there appears a tendency similar to the case of Haapavesi: the pelitic composition is more suitable for the accumulation of copper than that approaching the composition of marls. This is the tendency in the case of different compositions in the same area; but it does not work for different areas, because the schists of Nokia are distinctly shorter on copper, on the average, than those of Haapavesi, and still at Nokia the pelitic sulphide schists are proportionally much more abundant than they are within the area of Haapavesi.

But there is another difference between the sulphide schists of Nokia and the sulphide-graphite schists of Pohjanmaa: the latter are richer in graphite, which is present at Nokia in much smaller quantities.

According to Degens *et allie* (1957), copper is the element which in the sediments is selectively enriched in the ash of the organic material of the shales. Hence, the fact of the copper contents of the sulphide schists of Nokia being lower than those of the schists of Haapavesi is in good agreement with the statements set forth by Degens. The other elements which behave similarly in the sediments containing organic material are silver, cobalt, nickel, lead, tin, vanadium, zinc and molybdenum. As will be seen later on in this paper, the sulphide schists of Nokia, being short in graphite, are, on the average, likewise shorter on nickel and cobalt than the sulphide-graphite schists of Pohjanmaa.

As mentioned, even if the average copper contents of the schists tend to be more or less of the same magnitude, there appear very marked variations in this respect within the same schist, from spot to spot. It has been attempted to elucidate how large these variations may be in actual fact by the set of analyses in Table 10_5, which contains the trace element determinations across the 20-meters wide zone of the sulphide-graphite schists. The sampling has been carried out at almost equal intervals. Excepting the highest value obtained (0.26 % Cu), the copper content varies from 0.00 to 0.09 %, averaging 0.05 % Cu. At this spot, the composition of the schists approaches that of a skarn.

Nickel. Using the same tables and regional considerations as in the case of copper, the distribution of nickel may be epitomized into the following values

Kaustinen (10 analyses): 0.051 % Ni (0.00 to 0.12 %)
Teerijärvi — Laihia (6 analyses) 0.047 % Ni
Nivala (5 analyses): 0.09 % Ni
Nokia (3 analyses) 0.02 to 0.03 % Ni. (There are, however, three samples of selected places with 0.06 to 0.15 % Ni).

Haapavesi:
skarn-like schists (13 analyses) 0.03 % Ni
pelitic, amphibole-bearing (7 analyses) 0.055 % Ni
Haukipudas, Putaankylä (20 analyses): 0.06 %Ni
Haukipudas, Martinniemi (5 analyses): 0.086 % Ni

(The analyses of the sulphide-graphite schists of Haukipudas are not included in Tables 10_1 to 10_5, but they are available in the Archives of the Geological Survey of Finland).

The values listed above hardly entitle us to draw any conclusions. It is only interesting to note the high value for the sulphide-graphite schists of Nivala, because the pentlandite-serpentinite ore used to be mined there. The analyses of the schists of Haapavesi may suggest, however, that the skarn-like sulphide-graphite schists are a less suitable environment not only for copper but also for nickel than are the schists approaching a pelitic composition. This assumption is, however, a very weakly supported one, because at Nokia no regularities of this kind could be detected.

C o b a l t. The average cobalt content in different areas is as follows:

Kaustinen area (6 analyses): 0.013 % Co (8 anal. : 0.005 % Co).
Teerijärvi—Laihia (6 analyses): 0.0076 % Co
Nivala area (2 analyses): 0.007 % Co
Haapavesi:
skarn-like schists (7 analyses): 0.005 % Co
pelitic amphibole schists (7 analyses): 0.007 % Co
Haukipudas (20 analyses): 0.005 % Co.

In the cross-section of Haapavesi (Table 10_5), the cobalt content varies in different samples from 0.00 to 0.04 %, and the mean of 9 determinations is 0.018 % Co. The Haukipudas area is likewise rich in cobalt. In Table 10_4, there is an analysis (8/AMla/46, Geol. Surv. of Finland) belonging to the Haukipudas area but not included in the mean value given above, which indicates 0.03 % Co.

VANADIUM, MOLYBDENUM, CHROMIUM, AND TITANIUM

In the alum shales and in the Kieselschiefern of Thüringen, Germany, according to Leutwein (1951), vanadium, molybdenum, and chromium are present in the following quantities: V = 700 g/ton; Mo = 250 g/ton; Cr = 30 g/ton. The respective contents of the recent sapropelic muds are of the same magnitude, and, as it will be shown in the following, more or less similar contents may be considered as typical of the sulphide and sulphide-graphite schists, as well.

V a n a d i u m. For different areas, the average vanadium contents are as follows:

Kaustinen area (5 analyses):		0.0416 % V
Teerijärvi—Laihia (6 analyses):		0.0088 % V
Nokia region (5 analyses):	approx.	0.01 % V
Haapavesi area (1 analysis):		0.007 % V
Haukipudas area (1 analysis):		0.140 % V
Haukipudas area (20 analyses):		0.00 % V

Consequently, the Kaustinen area appears to be richest in vanadium, too. The single sample from Haukipudas (Table 10_4) is the only one in which the V-content is higher than the mean for the Kaustinen area, where only one analysis is such that there is 0.00 % V. All the rest contain more than 0.014 % vanadium, and the highest value obtained is 0.1 % V.

M o l y b d e n u m. This metal is also present in most samples of the sulphide and sulphide-graphite schists analyzed, but, usually, in rather insignificant quantities only.

Kaustinen area (5 analyses):	0.0015 % Mo
Teerijärvi—Laihia (6 analyses):	0.003 % Mo
Nokia region (5 analyses):	0.003 % Mo

These means, however, are losing much of their importance owing to the large variations in the Mo-contents. Within the Kaustinen area, for instance, three specimens out of five contained but traces of molybdenum. For Teerijärvi—Laihia, 50 per cent of the analyses contain 0.00 % Mo. For Nokia, three analyses indicate no Mo or only traces of it; in one case there is 0.004 % Mo, and in another case as much as 0.01 %. Thus the distribution of molybdenum, if taken in detail, is quite irregular. Regionally, however, the presence of this metal, too, seems to be characteristic of the sulphide and sulphide-graphite schists. The mode of occurrence of molybdenum is not quite clear. In general, molybdenite has not been seen microscopically in the sulphide schists excepting in one case: Within the Kaustinen area, approximately 5 km to the north of Köyhäjoki River, a small boulder of sulphide-graphite schist containing megascopically visible scales of molybdenite has been collected. Consequently, at least if molybdenum is present in some larger quantities, molybdenite may be formed. Therefore it is highly possible that also in other cases where molybdenum is present, molybdenite is formed but in such minute particles that when occurring together with graphite it may be very easily overlooked.

According to the most recent work published by Leutwein (1957), both vanadium and molybdenum are particularly characteristic of sapropels, but, it is very important to stress in this connection, among the »Kieselschiefer» of Germany, two facies are actually present: sapropels proper and the »Gytja»-facies (in the sense of Krejci-Graf). The former facies, has been formed entirely under water containig H_2S; the latter facies, on the contrary, may have had oxygen (and especially carbon dioxide, as pointed out Pustovalov, 1952) in the water under which the sedimentation took place. The sedimentation itself, however, must have occurred in the presence of prevalent H_2S-pressure. According to Leutwein, these two facies may be distinguished from each other also geochemically: the sapropels proper are usually enriched in vanadium and molybdenum; nickel, on the other hand, prefers the »gyttja»-facies of compositionally very similar carbon- and sulphide-bearing quartzitic as pelitic schists.

The molybdenum- and vanadium-contents of the sulphide and sulphide-graphite schists of Finland may thus indicate that most of them have been deposited as sapropels proper. In many cases, however, and perticularly at Nokia, Teerijärvi and Haukipudas, representatives of the »gyttja»-facies are obviously likewise always present.

Chromium. At least in traces, this element seems to be a regular minor constituent of the sulphide-graphite schists:

Kaustinen area (5 analyses)	0.014 % Cr
Teerijärvi—Laihia area (6 analyses) less than	0.01 % Cr
Nivala area (1 analysis)	0.01 % Cr
Nokia region (5 analyses) less than	0.01 % Cr
Haapavesi area (5 analyses)	0.02 % Cr
Haukipudas (2 analyses)	0.01 % Cr

Furthermore, there are single determinations for chromium of the sulphide-graphite schists of Kittilä and Rantasalmi (0.01 % Cr in both cases), and of Pihtipudas (0.0 % Cr). In addition, there are two analyses indicating an unusually high cromium content: Rovaniemi — 0.06 % Cr, and Kalajoki — 0.04 % Cr.

From the values listed, it may be deduced that for the sulphide and sulphide-graphite schists of Finland a Cr-content of about 0.01 % may be taken as normal. This is definitely higher than are the average Cr-contents of the alum shales reported — averaging approximately 0.003 %.

T i t a n i u m. In general, titanium is a conspicuous minor constituent of the sulphide-graphite schists. In some cases, the amount even exceeds the Ti-contents of the common Precambrian rocks.

Kaustinen area (5 analyses)		0.29 % Ti
Teerijärvi (3 analyses)		0.30 % Ti
Laihia (3 analyses)		0.06 % Ti
Nivala area (1 analysis)		0.28 % Ti
Nokia region (1 analysis)	well over	0.03 % Ti
Haapavesi area (3 analyses)		0.37 % Ti
Haukipudas (1 analysis)		0.13 % Ti

In addition, there are some single determinations for Ti of other areas than those listed above: Rantasalmi, Kalajoki, Rovaniemi, and Kittilä — more than 0.5 % Ti; Pihtipudas (Virkapuro) — 0.21 % Ti.

From the values listed above it may be concluded that for the sulphide-graphite schists of Pohjanmaa, on the average, a Ti-content of 0.30 % is more or less regular. There are, however, several single values which are much higher than this mean: At Haapavesi (96b/AJL/55, Alasydänmaa), the sulphide-graphite schists contains as much as 0.70 % Ti. Also the schist of Ullava contains more than 0.5 % titanium, but, not far from the sampling point of this specimen, a deposit of ilmenite associating anorthosite was recently discovered.

OTHER MINOR CONSTITUENTS

ZINC, LEAD, ANTIMONY, CADMIUM AND BISMUTH

Z i n c. Sphalerite is a comparatively common mineral of the sulphide and sulphide-graphite schists. It is less common, however, than often observed by microscopy because, during rapid work, limonite has sometimes been erroneously taken for sphalerite. Such errors have then been corrected by more careful microscopic examination, or detected after the chemical analysis has been performed. This has sometimes happened to the present writer, too.

In the following list of the average zinc contents, those analyses which indicate unusually high contents have been omitted.

Kaustinen area (6 analyses): In 5 cases 0.00 %, in 1 case 0.16 % Zn

Alajärvi (1 analysis)	0.10 % Zn
Nokia region (14 analyses)	0.147 % Zn
Haapavesi area (32 analyses)	0.15 % Zn
Sotkamo (1 analysis)	0.11 % Zn
Juva, Näärinki (1 analysis)	0.03 % Zn

Despite the mean values, which indicate that the characteristic zinc-contents of the sulphide-graphite schists average approximately 0.1 % or even more, in actual fact the mean is probably below this value, because there are always notably more indications of contents less than 0.1 % than of higher contents. In Table 10_5, in the section across the sulphide-graphite schist at Haapavesi, the mean of 9 determinations is 0.11 %; but, this mean is considerably affected by the single high value (0.47 % Zn) of this set of analyses. If this exceptionally high value is overlooked, then the mean of 8 determinations will drop down to 0.07 % Zn only. This statement is, of course, made with many a reservation, because in these schists the zinc has obviously moved very easily. Therefore it is to be expected that if there appeared, during or after crystallization, any opportunities for mobilization, the zinc would certainly have moved and become concentrated in places more suitable for its deposition than those from which it was transported. And still, as far as its origin is concerned, it is certainly always syngenetic.

As a matter of fact, there seems to be a plausible explanation for the tendency of zinc to move as easily as it seems to do in the schists of sapropelic origin. In the opinion of the present writer, this explanation can be based on the experimental work of Barnes (1958), who studied the system of ZnS-H_2S-H_2O, and thereby found out that in H_2S-saturated water, at 75° C and 300 psi, the solubility of ZnS exceeds 10 mg/liter. Thereby, complex ions of the type of $ZnS \cdot xH_2S$ will be formed. These complex ions will remain stable at low temperatures and pressures. If such ions are formed before the precipitation of ZnS, they certainly may be responsible for the easy transportation of zinc in the sediments here concerned.

Zinc being easily mobilized it is also understandable why a large set of analyses of the same sulphide schist deposit always contains one or several analyses indicating considerably higher zinc-contents than the mean of the set would actually allow. Examples:

Kaustinen area: four analyses with 0.0 % Zn, one analyses with 0.16 %
Nokia region: average — 0.147 % Zn, the highest value 0.75 %
Haapavesi area: average — 0.15 % Zn, the highest value 0.48 %.

Hence one may conclude that the zinc is much more capable of being concentrated locally in the sulphide-graphite schists than are the other metals here considered. At Kaustinen, where the majority of the sulphide-graphite schists contain, on the average, but traces of zinc, there still occur appreciable geochemical zinc-anomalies in the soils; and being close to such a geochemical anomaly, the sample with 0.16 % Zn was taken. In addition, several loose boulders containing megascopically visible patches

Table 11. The trace element contents of the sulphide-graphite schists of Lapland, according to Sahama (1945, p. 36).

No	V_2O_5	ZrO_2	MnO	BaO	SrO	La_2O_3	CeO_2	Nd_2O_3	Y_2O_3	Sc_2O_3	B_2O_3	Rb_2O	Li_2O	Cr_2O	NiO	CoO
1	0.01	0.0	0.15	0.03	0.0	0.001	0.004	0.003	0.0	0.001	0.006	0.05	0.005	0.1	0.001	< 0.001
2	0.01	0.0	0.02	0.07	0.003	0.001	0.0	0.0	0.0	0.001	0.1	0.03	0.003	0.1	0.01	0.003
3	0.006	0.01	0.18	0.05	0.006	0.006	0.003	0.003	0.003	0.006	0.01	0.08	0.003	0.03	0.003	0.003

1. Ilmenite- and carbonate-bearing black schist, Kersilö, Sodankylä
2. Black schist bedlet between layers rich in pyrite. Sattasköngäs, Sodankylä
3. Black phyllite. Kuolajärvi, Kittilä

of sphalerite have been collected from a geochemically anomalous area. Such a tendency of zinc is, of course, rather promising from the point of view of ore prospecting, too, and especially as far as geochemical prospecting is concerned.

L e a d. The presence of lead does not seem to be characteristic of the sulphide-graphite schists. It may occur in these rocks, as well, but very irregularly or even sporadically distributed. Unfortunately, there are no determinations of lead available for the areas of Kaustinen and Nokia. For the Haapavesi area, however, 8 analyses including lead exist, five of the samples analyzed containing 0.00 %, one 0.001 % and one 0.005 % Pb. For the sulphide-graphite schists of the area of Haukipudas, lead determinations were made in connection with several analyses without being detected. For Hiirola, the one lead determination indicated 0.00 % Pb, but, still, within the same zone of the sulphide-graphite schists, only 3 km away from the sampling point of the analyzed specimen, an easily distinguishable but as yet unexamined geochemical lead-anomaly has been encountered.

C a d m i u m, a n t i m o n y, b i s m u t h. Determinations of these elements have only seldom been made, and the available analytical data are too few to allow drawing any conclusions. In actual fact, the only analyses indicating these elements, are those for some sulphide-graphite schists of the areas of Haukipudas and Haapavesi. In all these determinations, the elements in question appeared to be lacking.

THE MINOR CONSTITUENTS OF THE SULPHIDE-GRAPHITE SCHISTS OF FINNISH LAPLAND

For the present study, no other elements besides those listed in the tables and discussed in the foregoing have been determined. By completing the picture of the composition of the sulphide-graphite schists, the other minor constituents may also be considered, and, therefore, the careful study of the trace elements of such schists carried out by Sahama (1945), will here be referred to. According to his determinations (spectrographically), the sulphide-graphite schists of Finnish Lapland contain different trace elements in the quantities indicated in Table 11, according to Sahama (1945).

THE DISTRIBUTION OF THE TRACE ELEMENTS BETWEEN THE SULPHIDE-GRAPHITE SCHISTS AND GOSSAN OR OVERBURDEN

The distribution of the minor constituents of the sulphide and sulphide-graphite schists between the schists themselves and the gossan or any weathered portion of these schists, is highly important from the point of view of the geochemical prospecting carried out within the areas consisting of such schists. Its importance lies in the fact that all the constituents of the sulphide-graphite schists removed from them during the processes of weathering will pass into solution and into the overburden through these primary weathering products. In the form of sulphates, they may then enter ground waters (Marmo, 1958a), which will cause the geochemical anomalies in the area.

The pairs of analyses in Table 12 elucidate such a distribution. In Anal. 1, an amphibole-bearing sulphide-graphite schist and the respective gossan taken directly from the surface of the analyzed schist specimen are represented. Nickel and cobalt seem to be absent from the gossan; but there is comparatively much copper — though in smaller quantities than it is present in the unweathered sulphide-graphite schist. Cr, V, and Ti, on the other hand, have been definitely enriched in the gossan. Such a distribution of different minor constituents is quite understandable. As

Table 12. The distribution of the minor constituents between the sulphide-graphite schists (from which they derive) and the respective gossan or immediately overlying morainic soil.

	Ni	Co	Cu	Mo	Cr	V	Ti	Zn
1 Laihia, sulphide schist	0.02	0.005	0.03	0.0	<0.01	0.006	0.04	
» gossan	+	0.000	0.02	0.0	0.01	0.011	0.06	
2 Nivala, Sarjankylä, schist	0.05		0.14					0.65
» » soil	0.05		0.23					0.95
3 Haapavesi, Suotuperä, schist ..	0.08							0.18
» » soil	0.02	0.00	0.04					0.04

previously described by the present author (Marmo, 1953a), the pyrrhotite of the sulphide schists is transformed, in the process of weathering, into iron sulphate. Consequently, the nickel and cobalt of the pyrrhotite will thereby be likewise dissolved and transported away with the waters. Obviously, these elements will not become precipitated together with that portion of iron which forms the iron hydroxides of the gosan. The presence of copper in the gossan, on the other hand, may well depend upon the fact that chalcopyrite is less soluble than pyrrhotite. Chromium, vanadium and titanium occur in the schists forming oxide minerals, or they may occur as minor constituents of certain silicates. Therefore, these metals will necessarily be enriched in the gossan, as it also has teken place in the gossan of Analysis 1.

Analyses 2 and 3 of the same table have been made from sulphide-graphite schists and for the soils immediately overlying the respective schists. Therefore, these soil samples contained ample gossan material, as well. Also in these cases, the sulphide-graphite schists analyzed contained much amphibole. In the samples of Nivala, the nickel is equally abundant in the schists and in the covering soils. In the sample of Haapavesi, on the other hand, the amount of nickel is much reduced from the content in the schist. In the samples of Nivala, both copper and zinc are distinctly enriched in the soil; in the Haapavesi sample, on the other hard, the zinc is reduced in the soil. Why do these two samples behave, in this respect, differently? There does not seem to be any indubitable explanation for this fact, but it may depend upon the difference in the composition of the respective soils. Perhaps the soils of Nivala are richer in clayey particles, which act as absorbers of cations of the heavy metals better than do the constituents of the soils of Haapavesi. One thing, however, is here of real importance: the overburden, if taken directly from the surface of the sulphide-graphite schists, seems to be more suitable for geochemical prospecting work than the pure gossan. Compared with the primary metal contents in the schists, the respective elements are surprisingly abundant in the soils. This, of course, is valid exclusively for such soils as derive from the immediate vicinity of the schists.

SOME ORE GEOLOGICAL ASPECTS

As revealed by the descriptions in the foregoing pages of the sulphide and sulphide-graphite schists in Finland, these schists occur along belts and zones composed of different schists and gneisses. These zones tend to embrace more massif cores of quartz diorites, granodiorites and granites. In these zones, the sulphide-graphite schists obviously occupy places that have been characterized during the stage of sedimentation, by conditions particularly suitable for the sedimentation of mud and sapropelic sediments, because, as appears to be the most probable explanation, the sulphide and sulphide-graphite schists have derived from sapropelic and »gytja» sediments, subjected to regional metamorphism. The original sapropelic sediments obviously had a rather varying composition, ranging from that of carbonaceous and sulphide-bearing pelites to marls and calcareous muds, likewise rich both in iron sulphides and in organic material. Such an origin explains why these schists contain, on the average, appreciable amounts of copper, nickel, cobalt, zinc, vanadium, molybdenum and chromium — all typical minor constituents of the sapropels, as well. The average contents in the sulphide-graphite schists of Finland of the elements mentioned are listed in Table 13.

Table 13. The heavy-metal contents of the sulphide schists of the Nokia region, and of the sulphide-graphite schists of Pohjanmaa

	Average of all schists	Sulphide schists, Nokia		Sulphide-graphite schists, Pohjanmaa	
		Average	Maximum (this paper)	Average	Maximum (this paper)
Cu	0.065	0.012	0.045	0.110	>0.5
Ni	0.051	0.025	0.15	0.056	0.17
Co	0.007	..	..	0.007	0.07
Zn	0.104	0.147	0.27	0.093	0.65
V	0.015	~0.01	0.03	0.016	0.14
Mo	0.0025	0.003	0.01	0.002	0.023
Cr	~0.01	<0.01	<0.01	0.012	0.06

From these values it is to be seen that, for the sulphide-graphite schists of Pohjanmaa, a tenfold enrichment of the heavy metals of the respective sulphide-graphite schists would be required to produce a concentration approaching a semi-economic ore of copper(1.1 %), nickel (0.5 %), and zinc (0.9 %). For the schists of Nokia, however, the zinc content alone would, at a tenfold enrichment, be of some economic interest (1.47 %). In fact, a tenfold enrichment of the heavy metals of a schist may be comparatively easily attained: if the sulphides of a portion of the sulphide schists measuring 1 000 X 100 X 10 m were to become mobilized (for instance, by a joint of tectonical stress and hot solutions) towards the ends of this portion, a tenfold enrichment would be reached within a portion of 100 X 100 X 10 m, at the end of the sulphide schist body. Under such circumstances, this enrichment would result in an ore body of semi-economic quality, approximately 400 000 tons in size and containing 1.1 % Cu, 0.5 % Ni, and 0.9 % Zn. Such a concentration is quite possible; and, consequently, under very suitable conditions and in an appropriate tectonical environment, the sulphide and sulphide-graphite schists may really give materials sufficient to form ore bodies of economic quality and size.

The factors giving rise to such a concentration of the minor constituents of the sulphide-graphite schists — or, primarily, of sapropels and marly muds — are, probably, predominantly of a tectonical character, and one must then particularly keep in mind features like compression, fracturing, and folding. When the original sapropels begin to be largely recrystallized — this takes place, of course, mainly under the conditions of regional metamorphism — the compression is probably the only tectonic factor operating. This factor reduces the volume of the recrystallizing sapropelic sediment, largely connected with the expulsion of water from the material. At this stage of evolution, the temperature may be greatly elevated, and, therefore, the water expelled would act under such circumstances very much in the same way as the hydrothermal solutions are supposed to act. Therefore, at least copper and zinc, but very likely also nickel may thereby be transported by these waters (Marmo, 1960). Tectonical activities of this kind are certainly insufficient to produce any ore bodies, but it may well explain the microscopical observation that, chalcopyrite and sphalerite mainly occur in the sulphide-graphite schists as a coating over the fissures, or as a filling in minute veinlets, cracks and fractures in the rock. In other words, these sulphides almost invariably occur, in these schists as the youngest of the sulphides. The presence of the younger generation of pyrrhotite in the sulphide-graphite schists may likewise be explained in the same manner. Also the »replacement» phenomena of the sulphides of the schists mentioned, may, in most cases, be explained as produced by simple brecciation rather than by actual replacement (see, for instance, Laitakari, 1931). Consequently, the cracks and fissures occurring, say, in a pyrite crystal, may be filled up by hydrothermally remobilized chalcopyrite and sphalerite; and the breaking up of pyrite may be caused by the compression under which the metamorphism of the schists is taken place.

The formation of minor folds, often met with in the sulphide and sulphide-graphite schists, may likewise be attributed to the same stage of the metamorphic evolution of the rocks.

If the recrystallization of the schists is accompanied by features producing faults, then the opening fractures may give way to the hot, hydrothermal-like solutions carrying copper, nickel, and zinc, to propagate in larger quantities, and even escape from the original environment of the heavy metals. If these fractures are regular and uniform, the deposition of the heavy metals takes place along these fractures. Under such circumstances, however, a sufficiently large accumulation of these metals to form ores is unlikely. In the field, minor accumulations of copper and zinc sulphides along fractures has often been observed, mostly, however, in economically insignificant quantities only. Samples taken from such fractures may contain solid and very attractive chalcopyrite; all the »ore», however, is thus contained in this fracture — a few mm thick. Such fissures and fractures filled with chalcopyrite occur in especial abundance in the sulphide-graphite schists of Kiuruvesi, Central Finland.

The place of deposition of actual ores of economic size may be provided by folding or by large-scale cross-fracturing of sufficient power to open in the schists large geometrical spaces, either within the schists themselves, or outside but close to them. Therefore, from the point of view of ore prospecting, the sulphide or sulphide-graphite schists would be especially promising in localities where faulting has produced cross-fractures or folding has been strong, or where both phenomena have considerably affected the structure of the schists.

Recently, Gray (1958) strongly supported the view that such a concentration of ore-forming material is especially common. Furthermore, in his opinion, sediments are, in general, the most appropriate sources of materials for the formation of large ore deposits. Gray considered the water derived from the sediments themselves as the most important factor in the transportation of ore-forming material from the sediments, where it appears in a very dispersed form, into the large accumulations forming the ores. He gave a similar explanation for the rich deposits of the Copper-Belt in Rhodesia, with which ores Gray is especially familiar. In regard to the deposits of Witwatersrand, he likewise assumed that the widely dispersed metallic constituents of the original sediments became concentrated into the ores, during or after the folding, by solutions which facilitated the metamorphism, as well. Gray extended similar ideas on the origin of the ore deposits, to include many vein-ores, too, as, for instance, those of Kipuchi, or of the Balkans, and of northern England.

The zones consisting of the sulphide or sulphide-graphite schists are unfortunately, however, mostly rather extensive; and these rocks being plastic (see for instance Oftedahl, 1955), they tend to undergo folding. Therefore, there may not always be possibilities and space for sulphides to accumulate in sufficiently large quantities to form an ore. The sulphide-graphite schists may be folded and bent but still remain unbroken. But apprepriate spaces may be opened in the less plastic surrounding rocks. Under such circumstances, the mobilized sulphides may accumulate there and form an ore outside their original environment.

All these factors bring it about, as far as the ores connected with the sulphide-graphite schists are concerned, that tracing the most appropriate locii for the ore deposition may, and usually really is, a very tedious task, which is additionally hampered by the omnipresence of iron sulphides. The considerable presence of pyrrhotite or pyrite everywhere within the zone of the said schists causes strong geophysical anomalies, which completely mask the usually much weaker anomalies reflecting the occurrence of actual economic sulphide ores.

The question arises, whether the average content of the heavy metals in the sulphide-graphite schists could possibly serve as a useful guide to an ore prospector. If, say copper, zinc, or nickel would be transported away from these schists to form the ore elsewhere, then, naturally, the schists themselves would be impoverished in regard to the respective elements. Consequently, sulphide and sulphide-graphite schists containing comparatively small percentages of copper, or zinc, or nickel, etc., would be more promising from the point of view of ore prospecting, than those rich in the respective metals (Marmo 1958 b). But even then the question is posed whether they might not be poor in these elements already from the time of sedimentation. In such a case, the sulphide-graphite schists rich in these heavy metals would indicate an environment richer in them than schists elsewhere, and thus they would tend more to produce an ore. It is quite likely that schists where mobilized sulphides have been accumulated to form an ore are, after this process, impoverished in the respective sulphides, but certainly does this not mean that every sulphide schist poor in these metals has this shortage as result of removal of heavy metals.

On the other hand, copper, zine and nickel probably have quite a different capacity for mobilization as well as a different behaviour during transportation. Therefore these elements would be accumulated in different locii. This possibility was set forth by Mr. Heikki Paarma during a discussion following the reading of some papers on geochemical prospecting in 1958 (see also: Paarma, 1958). In this discussion, he proposed that for this particular reason when working in geochemical prospecting on sulphide-graphite schists, geochemical anomalies simultaneously rich in several cations of heavy metals should be neglected, while only such should be chosen for further investigation as indicate an increase in the contents of one or, at most, two elements. The geochemical examination carried out at Kaustinen (p. 39) may actually give some support to Paarma's idea, because the zinc seems to dominate in particular places, where neither copper nor nickel has shown any signs of concentration.

The present paper is an account of all the investigations of sulphide and sulphide-graphite schists carried out to date by the present writer. In the last chapter of this paper, some ideas have been presented that may be considered as hypothetical. These ideas may, however, well serve as working hypotheses in further continuatien of this field of investigation.

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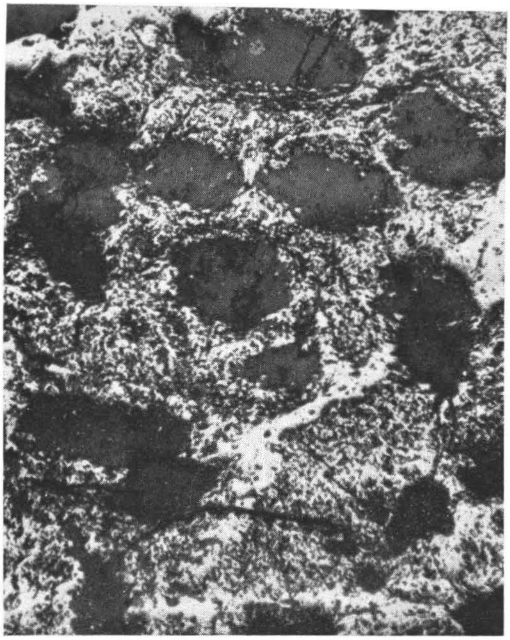

Fig. 1. A clastic structure of a pelitic sulphide schist. Rounded grains are quartz, and the light cement consists largely of pyrrhotite. A boulder collected from Kaustinen, Tastula, N //, 40 x.

Fig. 2. Pyrrhotite of an amphibole-sulphide schist of Evijärvi. In the pyrrhotite there are narrow cracks filled by concentrically grown pyrite and marcasite. N //, 40 x. See the next Figure.

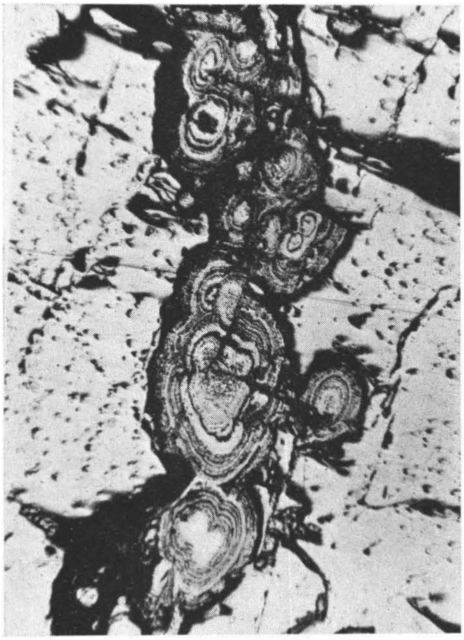

Fig. 3. »Bird eyes». Concentrically grawn pyrite occurring along narrow fissures of pyrrhotite illustrated in the foregoing figure. N //, 300 x.

Fig. 4. Two generations of pyrrhotite in the amphibole-sulphide schist of Kaustinen, Österneva. The older generation occurs as a fine impregnation, the younger one as minute veinlets. Pyrrhotite is light. Dark areas are composed of silicates. N //, 40 x.

Fig. 5. Three generations of pyrrhotite in the sulphide schist of Kaustinen, Tastula. The oldest generation: thin dissemination; the second generation: gray strips near the edges of figure, consisting of dull pyrrhotite, third generation: bright patches in the center of figure. Ordinary light. 2 x.

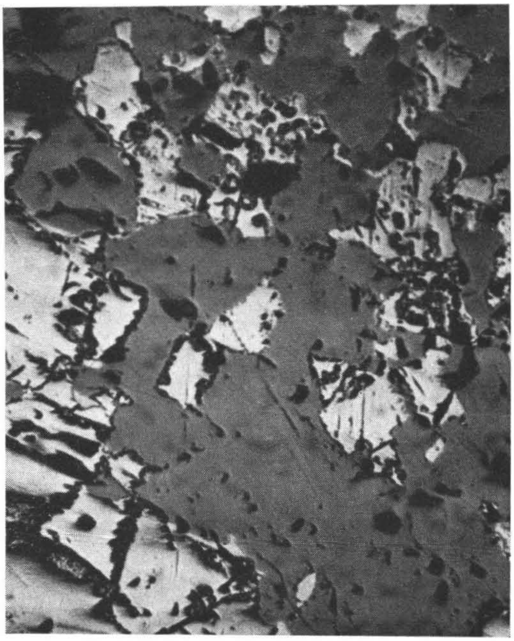

Fig. 6. Sphalerite (gray) patch containing pyrrhotite (light) in a boulder of sulphide schist. Kaustinen, Tastula, N //, 40 x.

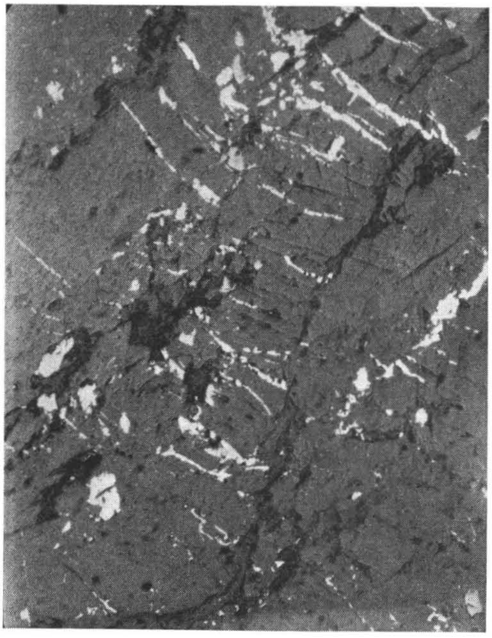

Fig. 7. Pyrrhotite occurs in the cracks of pyroxene. Nokia. N // x 60.

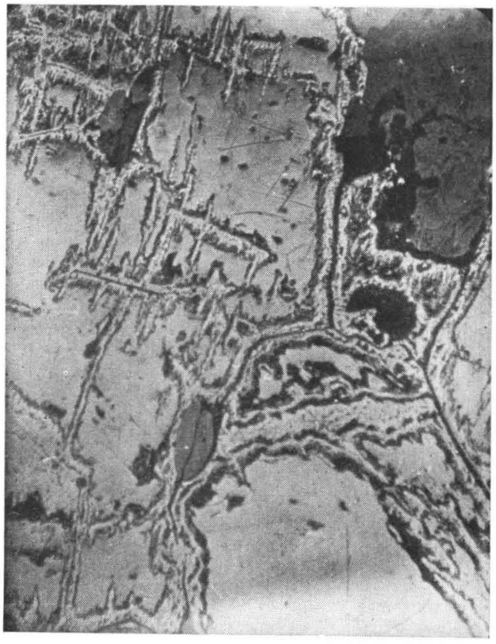

Fig. 8. Marcasite in pyrrhotite. Sulphide-graphite schist. Jalasjärvi. N // x 200.

Fig. 9. A mixture of marcasite and fine-grained pyrite around the grains of pyrrhotite. Sulphide-graphite schist Tipasjärvi, Vuoriniemi. N // x 60.