GEOLOGINEN TUTKIMUSLAITOS

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N:o 176

GEOLOGY OF THE NOKIA REGION, SOUTHWEST FINLAND

BY
VLADI MARMO

WITH 16 FIGURES, 1 TABLE

HELSINKI 1957

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INTRODUCTION

Nokia is situated 18 km westsouthwest of the town of Tampere (Fig. 1), and the Nokia Region belongs geologically to the Tampere schist-belt, which became classical as a result of the works of Sederholm (1897, 1913, 1914, 1931, 1932). These schists belong to the Svecofennian formation but represent, according to Wahl (1936), a somewhat younger intraformational division.

More recently the Tampere area, or details of it, have been investigated by Stigzelius (1944), Saksela (1947), Simonen and Neuvonen (1947), Seitsaari (1951), and Simonen (1953).

The Nokia Region lies on the southern border of Tampere schist-belt, and owing to the strong geophysical anomalies observed there it drew the attention of geologists; the presence of these anomalies caused a detailed investigation of area to be made, but no economic ore was found.

The field work for the present study was carried out in 1948—1952, by the Geological Survey of Finland, the present author being the leader. During this period he was assisted by Mr. O. Nykänen in 1949, (geological mapping of the gorge of the Nokia River), and by Mr. O. Waldén in 1950 (geological mapping). Furthermore, the main part of the region has been investigated geophysically (magnetically and electrically) by the geophysicists of Geological Survey, and geo-and biogeochemically by Marmo (1953), and the most important anomalies obtained by the mentioned surveys were penetrated by diamond drilling.

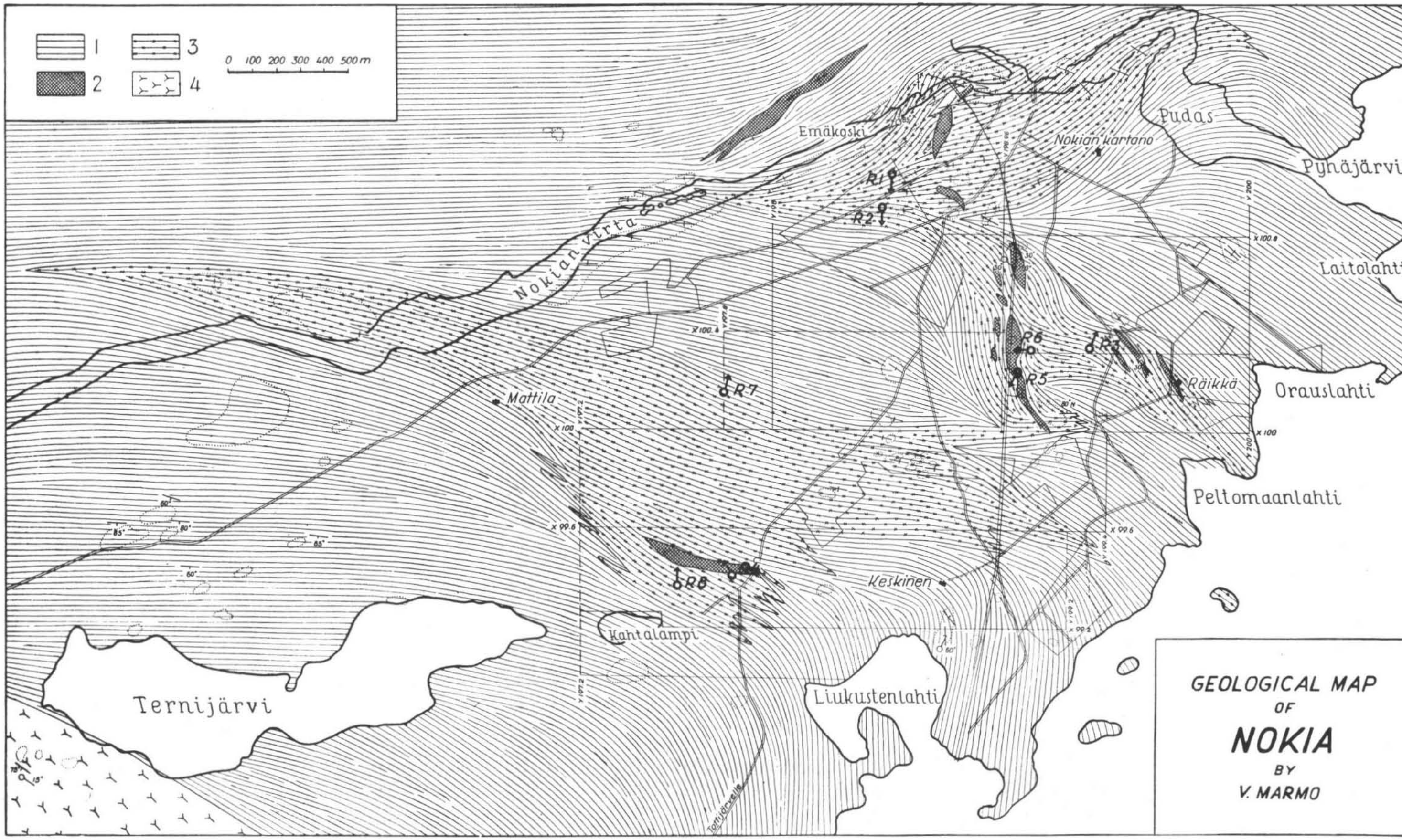

Fig. 1. Geological map of Nokia. 1 = phyllite; 2 = amphibolite, skarn, basic veins; 3 = sulphide schist; 4 = granite gneiss. R1—R8 = diamond drill holes. Koskenmäki, often referred to in the text, is around the Bore holes R 1 and R 2. The Lerunvuori Hill is just to the Southeast of R 5.

PART I: DESCRIPTION OF THE ROCKS

PHYLLITE ROCKS

PHYLLITE AND QUARTZITE

Phyllite is the predominant rock at Nokia (Fig. 1). It is not very homogeneous and especially the relation between biotite and quartz varies to such a degree that phyllite often grades into quartzite. The commonest type of phyllite consists of about 75 % quartz and 25 % biotite. The latter constituent is usually of dark brown common type. Sphene is sparse but present as an accessory in most slides examined; it is distinctly pleochroic (reddish → colourless) and forms rounded grains.

Such phyllite occurs in most parts of the area, but not in the vicinity of the sulphide-schists. Often, however, when approaching the sulphide-schists, it contains muscovite as well, and there the biotite is pale and less pleochroic than that of the common type of phyllite described above.

In some thin beds outcropping on the southern shore of the Nokia River tha albitic plagioclase is present as well, and the rock is then called albite-biotite gneiss, which also occurs as a thin bed in the diamond drill core N$^{\underline{o}}$R3 (Fig. 1).

South of Emäkoski, there are in the phyllite well rounded clusters with diameters of 5 to 20 cm (Fig. 2). Seitsaari (1951) has described similar,

Fig. 2. Basic clusters in the phyllite of Nokia, Koskenmäki.
Photo V. Marmo.

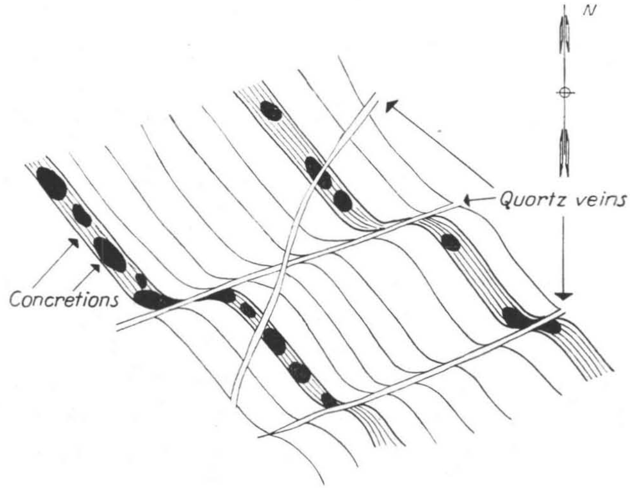

Fig. 3. Basic clusters occupy own layers, and they are cut by minor faults.

lime-bearing clusters from the eastern shore of the Lake Näsijärvi, likewise belonging to the Tampere schist-area. At Nokia, these clusters, interpreted as concretions, occur in distinct beds (Fig. 3), and often they are elongated to a size of about 20—30 cm in length and 3—5 cm in breadth. They may be cut by thin quartz veins, or in some instances (Fig. 3) penetrated by a small faultlet. According to Seitsaari (1951, p. 25), in the eastern part of the Tampere schist-belt, the composition of such clusters corresponds to that of marl. They are rich in usually chloritized amphibole ($c \Lambda \gamma = 19°$), which forms large crystals, often surrounded by a rim of fine-grained sphene. The green amphibole and the resorbed plagioclase are embedded in a mass of coarse quatz cemented by very fine-grained quartz.

PHYLLITE CONTAINING PALE BIOTITE

The common phyllite grades into the variety containing muscovite and, instead of dark brown biotite, a pale variety. Such phyllite often contains remainders of resorbed amphibole as well, and such rock is very fine-grained. When the amount of muscovite exceeds that of biotite, the name muscovite phyllite will be used. In such varieties the quartz grains are rather small and irregular in shape, and it seems that several grains have grown together, now forming an indistinctly grainy infilling between the scales of mica.

CHLORITE PHYLLITE

In the vicinity closest to the sulphide-schists the pale biotite is more or less chloritized, and in extreme cases the phyllite consists only of quartz and chlorite with accessory sphene and apatite (core of drill hole R5, Fig. 1). This kind of rock has been named chlorite phyllite.

MUSCOVITE QUARTZITE

As mentioned on p. 8, if the muscovite exceeds the amount of biotite, the normal phyllite grades into muscovite phyllite. Gradually the biotite disappears and muscovite decreases in amount, and the resulting rock is muscovite quartzite. In such rocks, at Nokia, there are two generations of quartz: 1) the older generation is represented by small, well-rounded grains always containing a pigment of pyrrhotite or of graphite; 2) the younger quartz which is pure and more coarse-grained.

Sphene and apatite are common but sparse accessories.

PHYLLITE CONTAINING ALUMINUM MINERALS

In the phyllites of Nokia, the aluminous minerals are occasional. In the core of drill hole R5 (Fig. 1) the muscovite phyllite containing a little chlorite and few resorbed grains of plagioclase, contains a small amount of cordierite as well. Fresh cordierite, however, has been seen in one slide only (at a depth of 36 m), in few additional slides, cordierite pseudomorphs, now occupyed by chlorite (chlorophyllite) and containing a few needles of rutile have been observed. Besides this muscovite-cordierite phyllite, andalusite-mica quartzite has also been met with at Nokia, but, likewise, in two thin sections only, both from the core of drill hole R6, at a depth of 172.90 m (Fig. 1). It consists mainly of fine-grained, well-rounded quartz, very pale, in part chloritized biotite, and contains evenly disseminated fine grains of andalusite.

ALBITE-BEARING PHYLLITE AND MICA GNEISS

The phyllite may also contain a little plagioclase. In some thin sections this feldspar is very fresh, and albitic, amounting in few slides to 5—10 % of the amount of quartz; such rock contains pale biotite, chlorite, and occasionally sphene and apatite as other constituents. The sulphides may be abudant. Such varieties of phyllite, however, are sparse, and they usually form thin beds, hardly more than 1 to 2 m thick, closely connected to the lime-rich beds, or they are interbedded in the sulphide-schists. According to their mineral composition such phyllites resemble adinole, and they will be discussed anew on p. 36.

In the diamond drill core N$^{\underline{o}}$R5, a piece of 90 cm in length has been met with containing albite in such an extend, that this kind of rock must be named mica gneiss. Its chief components are quartz, plagioclase, and pale, chloritized biotite; It contains, in addition, few small resorbed grains of colourless amphibole ($c \Lambda \gamma = 15°$), and a little sphene, the last-mentioned mineral being always closely accompanied by pyrrhotite.

GRAYWACKE

Often the phyllite contains pebbles of phyllite similar to that of the host rock, or also phyllite cobbles cemented by fine-grained quartz. Such beds are thin, usually thinner than 1 m, and they occur within the beds of phyllite or of muscovite-quartzite. Such rocks are interpreted as being graywacke sediments.

SULPHIDE-SCHIST

All rocks described above often contain pyrrhotite in varying amounts. In the schists characterized by the magnetic anomalies the percentage of pyrrhotite present is such that this sulphide is to be considered as a typical component of the rock. Pyrite occurs also, in conjunction with pyrrhotite, and often small amounts of sphalerite and chalcopyrite as well. The pyrrhotite is finely disseminated, and sometimes it occurs in close connection with graphite. Such rock is quite black, and was called by Marmo and Mikkola (1951) sulphide-schist.

The sulphide-schist is a fine-grained sedimentogeneous schist consisting of quartz and mica and containing pyrrhotite and/or pyrite in abundance, and usually also graphite (or shungite in the sulphide-schists of the Karelides).

The grading of the phyllite into sulphide-schist occurs through all transitional stages, and besides the phyllite, quartzite and muscovite quartzite can likewise grade into sulphide-schist. The »ground mass» of sulphide-schist consists of irregularly shaped quartz in conjunction with resorbed and often completely chloritized flakes of pale biotite and sericite. This mass is heavily impregnated by sulphides (often also by graphite), and therefore the identification of single minerals, or at least determination of their optical properties, is often impossible.

Fig. 4. A miniature fold in phyllite. Nokia. Thin sec. One Nicol, Mag. 30×.

At Koskenmäki the sulphide-schists are strongly disturbed by miniature folding (Fig. 4). Occasional grains of albitic plagioclase have been observed. Furthermore, the occurrence of coarse, sparse grains of colourless amphibole embedded in the mass of quartz and mica, is typical of the sulphide-schist of Nokia. This amphibole is considered to have derived from thin tuffic beds, also occurring at Nokia.

The pale biotite of the sulphide-schist is mostly heavily contaminated by pyrrhotite, and often surrounded by a rim of very pale sphene.

SCHISTOSE ROCKS RICH IN LIME

AMPHIBOLITE

East of the Lake of Kahtalampi (diamond drill core N$^{\underline{o}}$R4, Fig. 1) a rock mainly consisting of amphibole occurs, and it contains pyrrhotite between usually well preseved laths of amphibole. Similar rocks, in most cases distinctly schistose, have also been observed to the west of and at Räikkä. At the Kahtalampi Lake the rock is conspicuously rich in zinc (up to 0.27 % Zn) and contains copper (up to 0.015 % Cu). Thin calcite veins are there common. This amphibole-rock usually grades into amphibolite containing amphibole ($c \Lambda \gamma = 18—22°$), andesitic plagioclase, and small amounts of quartz. The amount of sulphides present is often such, that the rock contains up to 7 % sulphur, and then the name sulphide-amphibole schist seems to be appropriate.

More common than pure amphibolite are some metamorphic derivatives of it. Among them three main groups can be distinguished:

1. The amphibole is completely chloritized, and then the rock may contain a little muscovite, as well.

2. The amphibole is altered into biotite, and some of the amphibole (not biotitized) seems to derive from pyroxene (uralite). During the biotitization of the amphibole, the iron seems to have been released, and there are several instances, where the pyrrhotite grains clearly outline the form of an ancient amphibole crystal.

3. Large grains of amphibole lie in a groundmass which consists of very fine-grained, often indeterminable minerals, heavily impregnated by pyrrhotite and graphite. The groundmass is probably made of mica, chlorite, plagioclase, and quartz, consequently resembling some varieties of sulphide-schists. Amphibole is usually strongly resorbed and sometimes widely replaced by quartz.

PYROXENE-BEARING AMPHIBOLITE

Pyroxene-bearing amphibolite is rare at Nokia. Such rock contains predominantly amphibole (colourless hornbelnde), plagioclase, sulphides, and sparse grains of pyroxene ($c \Lambda \gamma = 38—40°$).

East of the Kahtalampi Lake an 1 meter thick bed of a rock was pierced by the drill hole R4 (Fig. 1), which rock is megascopically blistery, and mainly consists of diopside ($c \Lambda \gamma = 35—36°$), of sparse, basic plagioclase ($c \Lambda \gamma = 30°$), and of a small amount of pale greenish amphibole ($c \Lambda \gamma = 21°$). In cavities, prehnite of spherulitic structure, often in a serpentinized condition, has been observed. Biotite occurs in veinlets only, often together with serpentinized prehnite.

Similar bed, but only 1/2 meter thick, has also been pierced at Tyrkkölä (drill hole N$^{\underline{o}}$R5, Fig. 1).

SKARN-LIKE ROCK

A rock, usually schistose and composed of diopside, tremolite, plagioclase, quartz, and a little calcite, corresponds in its mineral composition to a skarn, and occurs, at Nokia, connected with limestone beds (see below). In drill hole R5, at a depth of 135.4 m (Fig. 1), such rock contained cummingtonite.

LIMESTONE

Limestone has been met with at Nokia only in diamond drill cores. In a pure condition it is there very rare, and actually it has been seen only in the core of drill hole N$^{\underline{o}}$R3 (Fig. 1) from a depth of 47.5 to 49.5 m, and this limestone mainly consists of calcite containing a little colourless chondrodite ($c \Lambda \gamma = 25—26°$); mica is sparse and very pale (lepidolite?), quartz forms minute drops in the calcite. Pyrrhotite and graphite form a thin dissemination in the limestone, and between the grains of calcite, veinlets of pyrrhotite often contain small drops and veinlets of chalcopyrite.

On both sides of the limestone bed of the drill hole N$^{\underline{o}}$R3, the diopside skarn-like rock occurs, and underneath the lower layer a bed (51.80—52.40 m), of much more impure limestone occurs. It is strongly schistose and contains ample diopside; hence it represents a part of the skarn itself. Furthermore it contains sphene and borders upon the muscovite quartzite.

In some cases the limestone of Nokia contains graphite in abundance. Drill hole N$^{\underline{o}}$R5 pierced two beds of limestone separated by a phyllite bed. The limestone beds are 4 m and 1 m thick, and the phyllite between them is of a thickness of 1.7 m. Here the graphite is particularly abudant, and it amounts to as much as about 1/4 of the amount of calcite.

VEIN FORMING ROCKS

TREMOLITE-ACTINOLITE ROCK

At several places in the Nokia area, ultrabasic intrusive rocks occur, often in a strongly altered condition. From such places where the alteration has not proceeded to complete disintegration of the primary (?) mineral compositon, it seems that the rock has been a comparatively pure actinolite-tremolite rock, but usually the amphibolite has altered into chlorite and talc, resulting, in extreme cases, in a chlorite-talc rock containing no other components, or only small amounts of calcite, secondary quartz and sulphides.

Such rock forms at Nokia veins, which are usually narrow — from a few millimeters to about 1/2 meter thick, occasionally, however, much thicker, as is the case at the Lerunvuori Hill and at Koskenmäki, where diamond drill hole N⁰2 penetrated a 13.7 m thick-tremolite-actinolite vein.

The best preserved varieties may contain plagioclase as well, probably of albitc composition, and such varieties, which are exceptional at Nokia, contain small amounts of epidote.

The tremolite-actinolite rocks may, in places, be rich in sulphides, particularly in pyrrhotite. Sphalerite and chalcopyrite are often also present, but in smaller amount; sometimes, however, the zinc is rather abundant, and at Koskenmäki (drill core R5) it results in a content of up to 0.35 to 0.45 % zinc in the rock. At the same locality, the rock contains also nickel, up to 0.09 to 0.11 %.

DIABASE

Only one dyke of a diabasic character has been met with at Nokia; this, about 5 m wide dyke is on the southern shore of the Emäkoski rapids of the Nokia River, and it consists of resorbed amphibole and strongly saussuritized plagioclase.

Similar diabase has also been observed in the core of drill hole N⁰6 (Fig. 1), and there the probable thickness of the dyke is about 3 m.

THE MANNER OF THE OCCURRENCE OF THE ROCKS AT NOKIA

All beds are almost vertical, and only small deviations from this position have been observed. In the western part of the geological map of the region (Fig. 1), N of the Lake of Ternijärvi, the dip is 60—85° to the South or to the SSW. SW of this lake dip of 75 % towards SW has been measured.

From three miniature folds, the folding axis have been measured: about 1 km to the West of Ahovalkama (Fig. 5) the axis pitches 15° towards N 70° W and in the outcrop on the NE shore of the Liukostenlahti, 60° towards N 20° E; and SW of the Ternijärvi Lake: 15° towards S 70° E (Fig. 1). Judging from observations based on the direction of elongation of the prisms of hornblende, the axis at Emäkoski shows remarkable variations but seems to be on the average almost vertical. From the S shore of the Emäkoski Rapids an orientated specimen was studied, and the elongation of biotite and muscovite showed, that at the place of sampling the probable axis pitches less than 30° to the East. That is the most important exception observed.

In the W-part of the region, the strike is usually E-W or nearly so. Between Keskinen and Nokiankartano, however, a distinct curving to the South is observed, and there the bending of strata has been strongest. It seems to the present author, that the axis measured on the NE shore of the Liukostenlahti represent just this stage of folding, and it seems that this folding has occurred after the turning of the beds into a vertical position, or, at the earliest, contemporaneously with it. The turning of the beds into vertical position is characterized by the axis position of Ahonvalkama, which agrees well with the common strike of the beds in the western part of the Nokia Region. Likewise at the SW corner of the Ternijärvi Lake the observed elongation of hornblende pitches only 15° towards ESE, hence in good agrement with the pitch and strike of the axis measured

Fig. 5. Geological map of the southern part of the Nokia Region. 1 = granite; 2 = granite gneiss and gneiss; 3 = phyllite; 4 = sulphide-rich rocks, mainly sulphide schist; 5 = amphibolite; 6 = basic veins; 7 = magnetic anomaly.

at Ahonvalkama. If these two observations are considered together, a small depression results, evidently depending upon the effect of intruded granite. Beginning from the Liukostenlahti the S—N strike continues along the Luotosaari Island, across the Pyhäjärvi Lake, and bends anew to the Southeast and finally to the East (Fig. 5), during which distance the phyllite has become a migmatitic gneiss.

Magnetic anomalies have been met with at several points of Luotosaari, and in the Parish of Etelä-Pirkkala, to the NW of the Ania farm, is the southernmost end of magnetic anomalies. There, however, the sulphide-schist disappears, for the rock consists of a gneiss rich in pyrrhotite.

It seems to the present author, that, at Nokia, a fault like folding of phyllitic strata has taken place, and thus the axis of this bending is steep. The strongest folding has taken place at Koskenmäki, there causing ruptures and fracturing of the rocks. Along these opened cracks, basic intrusives (p. 13) have been intruded. Where the strike turns to the Southeast, S of Luotosaari, the cracks have been opened as well, and there basic veins also occur, not, however, in as conspicuous a manner as in the North. The main direction of fractures, between Koskenmäki, Liukostenlahti and the southern end of the Luotosaari, is N—S, or N 30° W and S 30° E, consequently in a good agreement with the ideas presented above.

The top of the sediments, at the Liukostenlahti, is towards the East (grading bedding). From the diamond drill core N:o 3 (Fig. 1) a piece, 15 cm long was taken, and a longitudial section of it examined microscopically, and found that there the base of the sediments is to the North, a result well supporting the findings obtained at the Liukostenlahti.

The sediment zone beginning at Nokia and crossing the Lake Pyhäjärvi is characterized by the presence of sulphide-schist, which it was possible to follow using magnetic anomalies. Limestone, not common at Nokia, occurs at Räikkä and at the Kahtalampi Lake (drill cores) closely connected with the sulphide-schists, and it also seems to occur at the southern end of the Luotosaari, there likewise in connection with the sulphide-schist. Such a conclusion has been reached due to the exceptional flora of this small area; the composition of the vegetation here distinctly differs from that of other parts of the entire Nokia Region. In the southern part of the Luotosaari, *Tilia*, *Cotoneaster*, *Primula*, *Viola mirabilis*, *Fragaria vesca*, *Ribes alpinum*, *Convallaria majalis*, abundat *Juniperus communis*, etc. occur, all these plants characteristic of a lime-rich substratum. As a result of the lack of outrops and diamond drilling in this part of the Nokia Region, it is difficult to decide if a pure limestone, or an exceptionally lime-rich skarn-like rock is in question, since Marmo (1950) has earlier concluded, that carbonate skarn is also characterized by similar trends in vegetation as are occurrences of pure limestone.

CONTACTS BETWEEN GRANITE AND PHYLLITE

An immediate contact between granite and phyllite has been met with to the West of Ahovalkama, SW of the Lake of Ternijärvi. At Naulalahti the exposures of granite and of phyllite are very near to each other, but the contact itself is covered by drift. The visible contact W of Ahovalkama is sharp, and it is well exposed in the yard of the Järvenpää farm. There the outcrop is predominantly of granite, but on the northern slope of the small hill phyllite occurs. Where in close proximity to the contact, the phyllite is strongly fractured, compact, and brecciated by the granite. The strike of the contact is N 70° W, and the dip is almost vertical. From the adjacent miniature fold in the phyllite the folding axis was measured, and its pitch has been found as being 15° towards N 70° W, and exactly the same pitch and direction was found for the elongation of the hornblende in the granite as well. This observation was made about 10 m to the S of the point of determination of the folding axis.

The granite of Ahovalkama is gneissose, and its strike is parallel to that of the phyllite. Similar granite occurs between Naulalahti and Kuusisto also; the boundary between granite and phyllite shown on the maps (Fig. 1 and 5) between Ahovalkama and the Ternijärvi Lake is based upon the statistical investigation of boulders in the area in question.

S of Rantala farm (Fig. 5) the phyllite is migmatitic, and on the SE shore of the Lake of Pyhäjärvi the phyllite grades into gneiss.

ON THE STRUCTURE OF SEDIMENTS OF THE NOKIA REGION

PHYLLITE

The megascopically homogeneous phyllite shows, under the microscope, considerable variations, and it grades into sulphide- and graphite-bearing schists. In the phyllite itself, fine- and coarse-grained varves are common. Sometimes, the contact between phyllite and sulphide schist may be rather sharp. In Fig. 6, a section from diamond drill core N$^{\underline{o}}$5, between 65 and 92 m, is shown. The pitch of this bore-hole is 20° towards S 25° W. The dip of the schists is probably vertical, and according to an observation made at the nearest outrop, situated about 50 m to the South of the point of drilling, the schists strike WSW.—ENE. The section in Fig. 6 begins with a bed of a phyllite rich in quartz, followed by the sulphide-schist (between 66 and 70 m), and the contact is there sharp. Also »beneath» the sulphide-schist the contact against coarse-grained phyllite is sharp, and the last-mentioned rock suddenly grades into a fine-grained variety; this, again, contains muscovite, and with the decrease of the amount of mica, a grading into phyllite rich in quartz takes place. Then follow the beds of

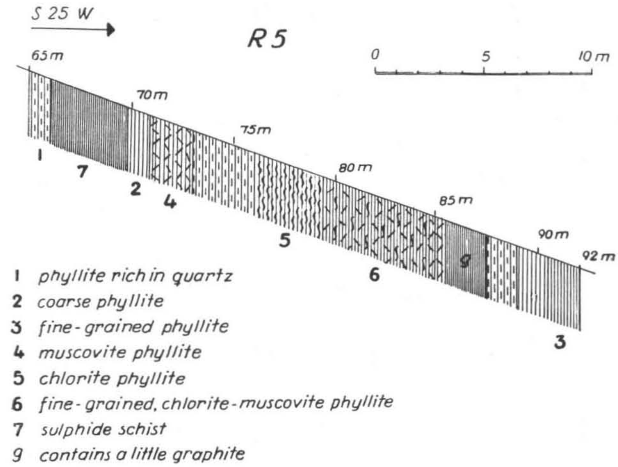

Fig. 6. Section along the drill core R5, between 65 and 92 m.

chlorite phyllite grading into fine-grained chlorite-muscovite phyllite, which occupies a bed between »depths» of 80 and 85 m, and with an increase of sulphides it grades into sulphide-schist containing small amounts of graphite. After the sulphide-schist follows phyllite rich in quartz, and the contact between both schists is again sharp. The phyllite rich in quartz grades by and by into a coarse-grained variety, and finally there a normal fine-grained phyllite occurs.

The phyllite sediments of Nokia are characteristically similar to the geosynclinal sediments. In the section just discussed, the alternating of the rocks is such that the top of sedimentation is probably in the NNW (p. 15), and if so, this finding has bearings on the stratigraphical position of the sulphide-schists.

SULPHIDE-SCHIST

The main sulphide-schist zone of the Nokia Region is comparatively narrow, but long. It begins, in the North, at Haavisto, and continues through the Nokia Region to the island of Luotosaari, thence to the opposite shore of the Lake Pyhäjärvi. Altogether this strip is at least 8 km long. Owing to the fact, that the magnetic anomalies continue at least 2 km still further to the South over the sound of Kaivanto, the primary length of the bed of sulphide-schists is at least 10 km. Hence it seems, that the sulphide-schists represent at Nokia a distinct zone of sedimentation, indicating the exceptional conditions, which governed the deposition of sediments at some stage in the geosynclinal cycle.

As seen from the section in Fig. 6, the deposition of the sulphide-schists was not continuous, but it was interrupted by sedimentation of clays and sands. The sequence and contact relations of the same section suggest a possibility, that the materials which yielded in the regional metamorphism the sulphide-schists, took place under such conditions, in which the deposition of finest material likewise occurred.

The sulphide-schists of Nokia are similar to the »pyrite black schists» of Pettijohn (1949), which he explained as being of sapropelic origin. The sulhide-schists of Nokia contain, however, pyrrhotite as the main sulphide instead of pyrite in the schists described by Pettijohn.

Parallels for the conditions of sedimentation under which the iron-sulphide-rich sediments of the Nokia Region were laid down, can probably be found, for instance, in the Black Sea and other basins where stagnant water conditions prevail. The hydrology of the Black Sea is, according to Androussov (1897), as follows: Life is only possible to a depth of 100 meters beneath the surface of the sea. Below this level oxygen is deficient and the concentration of H_2S increases to an extend at which it is poisonous for life. Hence all dead organisms sinking below a depth of 100 meters are free to sink to the bottom of the sea and collect there as there are no other organisms below this depth to use such matter as food.

The concentration of H_2S in the water of the Black Sea increases rapidly at first. According to Androussov (op.cit.), it is nil on the surface; at a depth of 100 fathoms it is 33 cm^3/100 liter, at a depth of 200 fathoms 222 cm^3/100 liter, and at 300 fathoms already 570 cm^3/100 liter. Below this depth the H_2S concentration remains nearly constant.

Furthermore, according to Androussov (1897, p. 7), the presence of H_2S is due to anaerobic bacteria which catalyse the following reactions:

$$RSO_4 + 2\,C \rightarrow 2\,CO_2 + RS, \text{ and further:}$$

$$RS + CO_2 + H_2O \rightarrow H_2S + RCO_3.$$

The liberated H_2S reacts with iron compounds forming black, amorphous sulphide of iron, FeS. The mud sediment naturally always contains carbon as well.

According to Ström (1936) similar processes of sedimentation likewise occur at the bottom of the Norwegian fjords.

That similar conditions of sedimentation can be supposed for the sulphide-schists of Nokia also, seems to be clear. The composition of the sulphide-schists agrees well with that of the recent sapropels: quartz — mica — abundant pyrrhotite and often graphite. Furthermore it may be mentioned, that similar sulphide-schists have earlier been interpreted by Eskola (1932) as being of sapropelic origin. Marmo and Metzger (1953) have likewise interpreted the sulphide-schists of Hiirola as sapropels.

According to Pettijohn (1949, p. 457) the pyrite black schists (primarily sapropel) form a particular facies of sedimentation in exceptional circumstances (stagnant seas and fjords) of foreland sedimentation.

According to the explanation of the origin of mud sediments, quoted in the foregoing, it is rather difficult to imagine the origin of them without the presence of living organisms (Marmo, 1956). Hence if the sulphide-schists of Nokia are of sapropelic origin, then the life already existed during the laying down of the present sulphide-schist. Rankama (1948) examined the carbon of *Corycium enigmaticum*, presumed to be a fossil, from Tampere schist area, and he found that the relation of the carbon isotopes in the carbon in question distinctly indicates its organic origin. Rankama's investigation proved the organic origin of the carbon of *C. enigmaticum* independently of whether *C. enigmaticum* itself is a fossil (Sederholm, 1924, Rankama, 1948), or a tectonic form (Straaten, 1949). Because *C. enigmaticum*, the carbon of which has been studied by Rankama, is from beds of probably approximately the same age of sedimentation as the sulphide-schists of Nokia, the presence of living organisms under conditions of sedimentation of the present sulphide-schists seems to be evident.

According to Pettijohn (1949, p. 459) mud sediments usually contain vanadium up to 0.05 % and copper up to 0.01 %. The copper of the sulphide-schist of Nokia has been determined in several samples, and its content varies between 0.005 % and 0.025 %. The typical sulphide-schist of Koskenmäki contains 0.02 % Cu. Vanadium has been determined spectrographically (Mr. Oiva Joensuu, Chicago) from two diamond drill core samples (from the area NW of the Kahtalampi Lake), and both contained 0.1 % V. The copper content is evenly distributed thoroughout the beds of the sulphide-schists of Nokia.

The limestone met with in the diamond drill cores is always fine-grained, and usually black, owing to a fine dissemination of graphite. Similar limestone is typical of the saline facies of sedimentation, also often containing beds of mud sediments (Pettijohn 1949, p. 459), but limestone with a pigment of organic carbon can often belong to the sulphide-schist facies itself, since both facies depent upon similar conditions of sedimentation differing only in that the saline facies is characteristic of saline waters and high degree of evaporation (for example the Caspian Sea).

SEDIMENTS RICH IN LIME

The contact between phyllite and amphibolite is usually sharp, but there are instances where the transition from phyllite to amphibolite grades through an occurrence of amphibole-bearing phyllite. In diamond drill core N:o 2 (Fig. 1) hornblende-rich cobbles are embedded in a fine-grained mass of abundant quartz and mica — hence in a true phyllite. Such portions have been met with as thin portions only, and interpreted as being of tuffic origin.

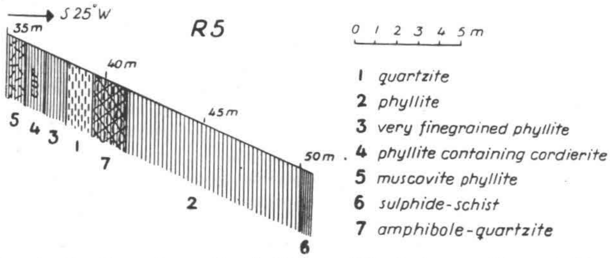

Fig. 7. Section along the drill core R5, between 35 and 50 m.

In Fig. 7, a short section of diamond drill core N:o 5 is seen. After a muscovite phyllite (35 to 36 m) follows the cordierite-bearing phyllite, which grades into very fine-grained phyllite and this in its turn into quartzite. Then follows a bed of amphibole quartzite, 2 m thick, and the contacts on both sides of the last-mentioned bed are sharp. Here the tuffic origin of the amphibole quartzite is probable. In Fig. 8, another mode of occur-

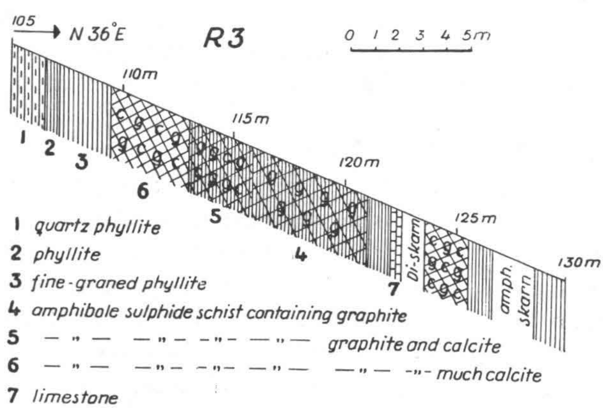

Fig. 9. Section along the drill core R3, between 105 and 130 m.

rence of amphibole-bearing rock is seen: the section begins with quartz-rich phyllite, which grades into a fine-grained and then into coarse-grained phyllite; then follows, after comparatively sharp contact, a bed of sulphide-schist, which is comparatively rich in calcite, graphite, and amphibole. This bed is 3 m thick, and its calcite content gradually diminishes so, that after 3 m no calcite is present, and a rock containing quartz and mica as the main minerals in conjunction with graphite, sulphides, and embedded grains of amphibole is in question. After a thin bed of phyllite, which separates the amphibole-bearing sulphide-schist from a bed of calcite followed by ordinary diopside skarn, there follows, succeeded by the amphibolebearing sulphide-schist, phyllite, amphibole-skarn, and again phyllite.

Such thin beds of amphibole-bearing sulphide-schists are to be interpreted as to having derived from mud sediments rich in lime, a part of which, during metamorphism, has been altered into diopside skarn. The limestone bed occurring in the section shown in Fig. 8 is a remainder of a part of the primary mud sediment exceptionally rich in lime.

In Fig. 9 a section from the diamond drill core N$^{\underline{o}}$4 (Fig. 1) is seen. The borehole was drilled in the direction N 35° W, and the thickest bed of sediments rich in lime was traversed. If one begins from the NW (from the lower part of the section), there follows after the sulphide-schist (between 125 and 140 m) a bed about 28 m thick, mainly composed of amphibole-sulphide-schist containing only a few thin interbeds of phyllite or of sulphide-schist. Obviously this bed has primarily been a bed of lime-rich mud sediment. The amphibole-sulphide-schist contains 6 to 7.5 % iron bound to sulphide, 0.050 to 0.015 % Cu, and approximately 0.1 % Zn. After this lime-rich schist there follows a 5 m thick dyke of talc-actinolite-tremolite rock, not belonging to the sediments (p. 15), and veinlets composed of similar rock occur in other parts of the same section as well; between 25 and 90 m they penetrate a sedimentary rock mainly consisting of amphibole. Between 29 and 36 m graphite is conspicuously abundant, and between 71 and 74 m there is a limestone embedded in the afore-mentioned amphibole rock; thre are no marks of skarn on its contacts, but on its NW side, a bed of typical lava-rock with cavities containing prehnite (p. 12) occurs. The diopside-skarn is met with between 24 and 32 m.

Excepting the prehnite-bearing rock, this portions of schists may be of tuffic origin.

True lava beds are sparse at Nokia. Excepting the case described above, the agglomeratic bed at the Lerunvuori Hill may be mentioned. Some thin interbeds with agglomeratic structure occur at Koskenmäki.

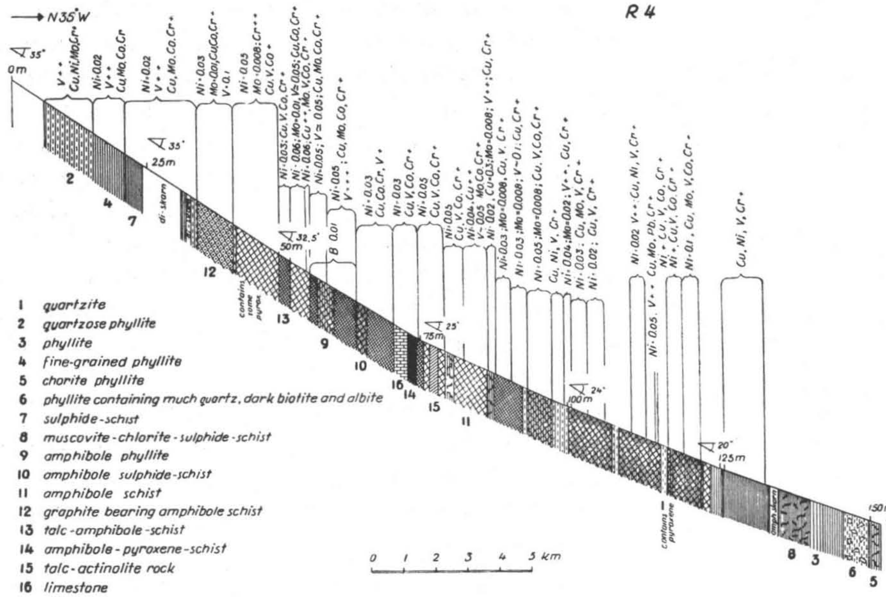

Fig. 9. Section along the drill core R4, between 0 and 150 m. Above the section the contents in trace elements are shown.

TRACE ELEMENTS OF THE SCHISTS OF NOKIA

The trace elements have been spectrographically determined (by Mr. Oiva Joensuu, Chicago) from diamond drill core N$^{\underline{o}}$4 only, and results are given in Fig. 9. The core has been examined for trace elements between 5 and 132,5 m and each analysis was made of a sample corresponding to as homogeneous kind of rock as possible. The regular distribution of vanadium is striking. In all analyses distinct line for vanadium (+) was abtained, and somewhat higher values (0.005 to 0.1 %) occur in some samples of graphite-bearing amphibolite. Nickel is evenly distributed (0.02 to 0.05 %) thorough all rocks excepting the amphibole-sulphide-schists connected with the rocks interpreted as being of lava origin. Molybdenum is also present in all rocks, but the highest value is reached (0.02 %) in an analysis of quartz-rich phyllite. Chromium is present in all analyses, but never more than enough for a distinct line. It may be mentioned here, that the tremolite-actinolite dykes contain, according to chemical analyses (p. 35), 0.13—0.25 % Cr_2O_3. In all samples distinct lines for B, Be, Sb, W, Te, Sn, La, and Sc were obtained, but only between 54.5 and 65.5 m B was present in larger amount (0.01 %). This part consists of tremolite-actinolite rock cutting as a vein a bed of amphibole-bearing phyllite.

CONCLUSIONS ON THE ROCKS OF NOKIA

According to the above description, the following conclusions can be made:

1. The sediments of Nokia belong to a sequence of geosynclinal deposition. The abundant occurrence of sulphide-schists points to the possibility that the marginal facies, and perhaps in part the foreland facies is present.
2. The sediments rich in lime, in most cases, probably have their origin connected with deposition of lime-rich materials together with mud, and the skarn-like rocks the metamorphic products of such materials.
3. A part of the lime-rich sediments, however, occur in close connection with rocks which bear preserved marks indicating an origin from lavas or from tuffs.
4. The primary sediments have been folded in connexion with the emplacement of granites (sediments S of Nokia), and the folding is characterized by the WNW—ESE axial direction. Then, a new folding, or it would be better to say »creasing», with an almost vertical axial direction occurred, and it caused, especially in the beds of sulphide-schists, numerous openings in a N—S direction. Such openings are most abundant along the line between Koskenmäki and Räikkä.
5. In the last stages of folding (or soon after the folding) the greenstone intrusions took place, and the openings in the sedimentary beds became filled by greenstone veins. The intrusion of sparsely occurring diabases may likewise be assumed to belong to the same stage of evolution of the rocks at Nokia.

PART II: METAMORPHISM

SOME MINERALS, USEFUL FOR THE INTERPRETATION OF THE METAMORPHISM AT NOKIA

QUARTZ

In quartzites and in phyllites the quartz usually forms rounded grains; in sulphide-schists and in the varieties of the above-mentioned rocks rich in sulphides the quartz is fine-grained, and the single grains have somewhat indefinite boundaries, due to sulphide contamination. Further, veins of quartz always occur, and they represent much younger quartz than the primary quartz of the schist itself. Perhaps more or less contemporaneous with the quartz veinlets is the quartz which forms drop like particles within the resorbed crystals of pyroxene and of amphibole.

BIOTITE

The normal, dark brown (in thin sections) biotite occurs only in pure phyllite and quartzite. When accompanied by sulphides and in all sulphide-schists the biotite is pale, somewhat yellowish, and it is weakly but distinctly pleochroic. The distribution of the pale biotite compared with that of dark biotite indicates that the kind of biotite met with depends upon the stage of metamorphism of the corresponding rocks. The co-occurence of the pale and dark varieties of biotite within some area has been observed earlier by several authors. According to Karl (1952, p. 220) the pale biotite is product of recrystallization of normal biotite the iron being transfered during re-crystallization into other crystal forms. Thus he explained the origin of a pale biotite examined by him from the graywacke sediments of Gerlostal in Tirol. Wyckoff (1952) has studied the biotite from the Wissaschickon schists of Pennysylvania, and observed, that a rock (hydrothermal metamorphic) rarely contains more than one type of biotite. She has noted specimens, where red or yellowish brown biotite shows borders of dull green biotite and this may be accompanied by epidote or sphene; the latter is perhaps more significant. She explains this phenomenon as follows (op. cit., p. 41): »during granitization TiO_2 appears to be released from biotite, re-crystallizing in sphene».

The liberation of titanium from biotite during metamorphism has also been described by Marmo and Metzger (1953) in the schists of Hiirola.

According to Hall (1941) the colour of biotite depends upon its chemical compositon, so, that red and orange-red and orange-brown varietites are richer in titanium than greenish varieties, and that dark varieties are richer in iron than the pale varieties, and the fact, that pale biotite very often is accompanied by sphene, indicates, that during recrystallization of the biotite, titanium was released and recrystallized in sphene; that the pale type occurs in sulphide-schists usually closely associated with pyrrhotite, indicates that iron was also released in the same process and recrystallized in the form of pyrrhotite.

After heating biotite to 1 000°C Kozu and Joshiki (1929, cited by Winchell 1951, p. 376) reported that its properties do change so that the axial angle increases and the FeO content diminishes, and the colour becomes paler.

Mrs. Toini Mikkola determined $2V_\alpha$ for the dark and pale biotite of Nokia, and she found, that in both types of biotite the axial angle is about zero, for the pale variety of biotite, typical of the sulphide-schists, she found, however, in one case as great value as $2V_\alpha = 16°$.

The biotite is often chloritized along its margins. In some cases this alteration has been complete. The relations of the rocks containing dark or pale type of biotite is seen in Fig. 10. There a section from diamond drill core N$^{\underline{o}}$3 (between 25 and 35 m) is taken. At the NE end of the section, after the fine-grained phyllite with pale biotite, a coarse-grained variety containing dark biotite occurs. The bed of the »dark-biotite phyllite» is about 2 m thick, and it is followed by an albite-biotite schist containing a pale variety of biotite. The lastmentioned schist grades into phyllite containing pale biotite and little or no albite.

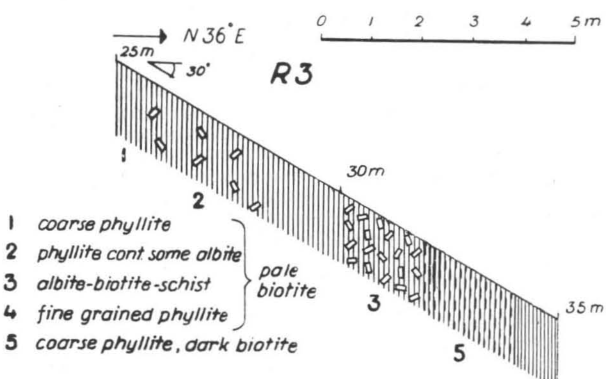

Fig. 10. Section along the drill core R3, between 25 and 35 m.

MUSCOVITE AND SERICITE

These minerals are abundant (p. 9) in many varieties of the schists of Nokia. The muscovite occurs either alone or, more frequently, together with pale biotite, and usually accompanied by chlorite. In Fig. 6 muscovite phyllite occurs (between 71 and 73 m) between the phyllite and the quartz phyllite. Between 80 and 85 m of the same section, chlorite besides muscovite is remarkably abundant.

GARPHITE

Since the sulphide-schists of Nokia are of sapropelic origin (p. 18) their graphite content is easily explained ,and it is moreover surprising that the graphite does not occur more abundantly at Nokia. Also the graphite present in the limestone of Nokia, as a fine dissemination, can be explained as being organic.

At Nokia, graphite occurs in another manner also, and then it is connected to basic rocks, or occurs as coating of cracks and fissures in amphibolite, in skarn-like rocks, and in sulphide-rich pelitic rocks as well. When Laitakari (1925) discussed the origin of Finnish graphites, he explained the graphite of skarns and limestone contacts (op. cit. p. 86) as being dependent upon the reduction of carbon dioxide. The transport of the carbon into the fissures may be supposed to have taken place in the form of CO_2 and after reduction of the gas carbon would have deposited as a coating of the fissures. The carbon (shungite) met with in the cavities of the volcanics of Suoju was likewise explained by Marmo (1949) to have originated through the reduction of carbon dioxide.

There are, however, certain difficulties which hamper one from accepting this explanation in the case of Nokia. What one may say with security is that carbon now coating the fissures must have come from its original source in the form of some compound. If this compound was carbon dioxide, then one must ask, which factors have caused the reduction of that gas to such a degree that free carbon has resulted? Can this reduction reaction be caused by hydrogen? In organic chemistry the reduction of the oxygen compounds of carbon is well known and usually they ara katalyzed by different kinds of finely dispersed metals. For the reduction of carbon dioxide, however, there does not seem to exist any convenient methods, and therefore there is as likely as no definite way for the explanation of the reduction of carbon dioxide in nature either. In the sapropels the presence of hydrocarbons is quite possible, and the oxidation of hydrocarbons is quite possible, and the oxidation of hydrocarbons, if incomplete, will release free carbon. According to Rankama (1948), Eskola has in a personal communication to him explained the origin of shungite of Shunga in Russian Karelia as being dependent upon the break down of certain hydrocarbons (see also Marmo 1953 a).

In connection with the black slates, which are much younger than the sapropels of Nokia, the occurrence of hydrocarbons is a common feature. Evidently the primary sapropel of Nokia contained hydrocarbon as well, and during metamorphism these compounds have been transfered into cracks, fissures and pores (the carbon of amphibolites), and there they have been dehydrated, the free carbon was produced, and it crystallized in the metamorphism as graphite. The most suitable temperature range for a dehydration of hydrocarbons is that between 350° and 600°C, or, as will be shown later (p. 32), just such temperatures at which the main metamorphism took place within the Nokia Region.

SULPHIDES

The sulphides of the schists of Nokia have been preliminarily described by Marmo and Mikkola (1951, p. 8—10); they showed also that the black colour of the sulphide-schists of Nokia often depends upon a very fine and abundant dissemination of pyrrhotite, and there are many samples of sulphide-schists of Nokia, which ackording to microscopical study, do not contain any graphite. On the other hand, there also such schists occur, which may contain up to 3.8 % C.

Pyrrhotite, the main sulphide at Nokia, evidently occurs corresponding at least to two generations. The older, »primary» generation is represented by small thin lamellae occurring in the interstices of other minerals, and it is foliated concordant with the schistosity of the schists. When graphite

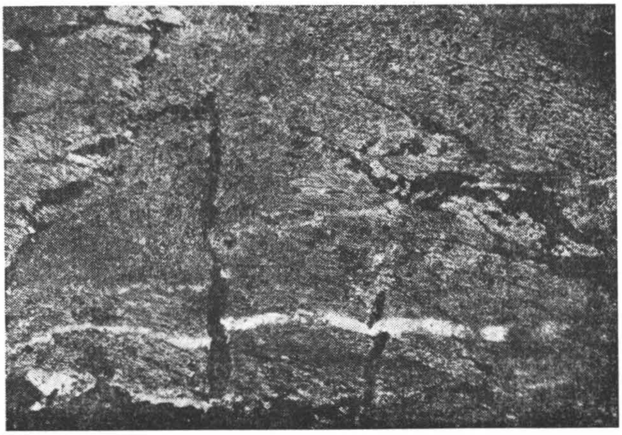

Fig. 11. The calcite veinlet (white) cutting, and itself is cut by, a pyrrhotite veinlet (black). Nokia. Thin section. One Nicol, Mag. 40×.

is also present, it occurs closely connected with this older generation of pyrrhotite (compare Marmo and Metzger, 1953), and this generation is probably derived from the primary iron sulphides of the ancient mud sediments. But pyrrhotite also occurs in the form of veinlets penetrating other constituents, and of a distinctly younger origin than the first-mentioned pyrrhotite. In Fig. 11 a photograph of a thin section of sulphide-schist is seen. There the schist is penetrated both by calcite and by pyrrhotite veinlets. The pyrrhotite veinlet (black) cuts the calcite veinlet but to the right of that instance the pyrrhotite veinlet is in turn cut by the calcite veinlet (white). Consequently both veinlets seem to be more or less contemporaneous.

Fig. 12. Amphibolite containing concordant lamellae of pyrrhotite. Nokia. Thin section. One Nicol. Mag. 80×.

The pyrrhotite also occurs in the form of grains of variable size and in close connection with pale biotite and amphibole. In Fig. 12 the pyrrhotite occurs as »concordant» lamellae between the laths of a pale amphibole, and the origin of such pyrrhotite is probably a result of the reaction between H_2S and the iron, primarily bound up in the biotite or amphibole.

The pyrrhotite connected with the mica and amphibole has evidently originated during the stage of metamorphism characterized by the recrystallization of pale biotite. The veinlets of pyrrhotite, which seem to be concomitant with the calcite veins, are probably of still younger origin, and their pyrrhotite can be derived from that connected with mica and amphibole. From the microscopical examination of the pyrrhotite of Nokia, the following conclusions may be drawn: 1. the iron sulphides of the primary sapropel have been altered at an early stage of metamorphism into pyrrhotite (in part also into pyrite); 2. during the evolution of metamorphism and depending upon the action of H_2S biotite and amphibole have lost a part of their iron, which has crystallized in the form of pyrrhotite; 3. during folding and related movements a part of both pre-existing pyrrhotites has became mobile and formed veinlets.

S p h a l e r i t e also occurs in different generations, the earlier of which is connected with the primary pyrrhotite, and the latter forms veinlets penetrating the youngest pyrrhotite. Marmo and Mikkola (1951, p. 9) explained the older generation as sedimentogeneous and to be of the same age as the primary pyrrhotite. The younger generation has evidently originated as a result of the mobilization of the primary sphalerite. Usually the sphalerite veinlets are younger than the youngest pyrrhotite, but there are also instances, where the pyrrhotite veinlets are cutting sphalerite grains. This may mean that there is not any great difference between the ages of younger sphalerite and the youngest pyrrhotite generation.

C h a l c o p y r i t e usually occurs in conjunction with the pyrrhotite and sphalerite of later origin, and forms narrow veinlets, or also occurs as small ex-soluted particles in sphalerite. The mode of occurrence of chalcopyrite is of interest here, since it can be used for interpretation of some of the metamorphic features discussed later on.

Chalcopyrite ex-soluted from the pyrrhotite has been observed as well, but very seldom. An especial case is illustrated in Fig. 13. There the chalcopyrite »brecciates» the pyrrhotite. No ex-solution is there in question, but obviously a replacement of pyrrhotite by chalcopyrite, a phenomenon also described by Laitakari (1931) from ore of Pitkäranta.

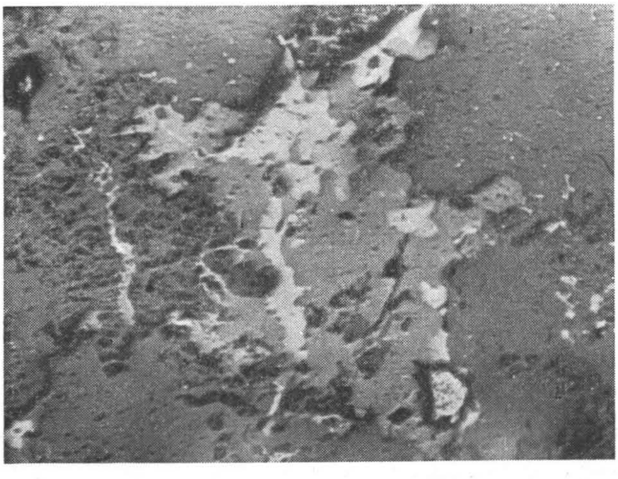

Fig. 13. Pyrrhotite (grey) brecciated by chalcopyrite veinlets (light gray). Nokia, diamond drill core R4, 75 m. Polished section. One Nicol. Mag. 350×.

P y r i t e in the schists of Nokia is common but not abundant. Usually it occurs as strongly corroded grains of distinctly earlier origin than other sulphides. There are, however, also instances, where the pyrite is renewed. In Fig. 14 in the lower left-hand corner pyrite is seen, and it is older than the pyrrhotite visible in the same figure. There are, however, narrow veinlets of pyrite as well, and these penetrate the pyrrhotite. A similar phenomenon is likewise to see in such cases, where the youngest pyrite cuts the »bird's eye», also of comparatively late origin. This case has been described by Marmo (1953 b) in another connection.

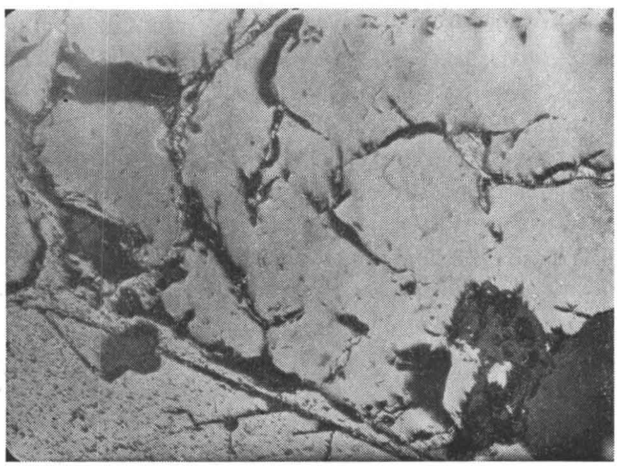

Fig. 14. Two generations of pyrite. In the lower left corner is pyrite older than pyrrhotite (gray) which is the main mineral of the figure. Pyrrhotite is, in turn, penetrated by veinlets of pyrite of other generation, which, consequently, is younger than the pyrrhotite. Nokia, R4. Polished section. One Nicol. Mag. 60×.

N i c k e l m i n e r a l s have been seen at Nokia only occasionally. Marmo and Mikkola (1951) described linneite. In addition, flame-like bodies, very similar to those described by Ramdohr (1950) for pentlandite, have been seen in pyrrhotite, and it may be, that here also pentlandite is in question. The presence of this mineral, however, cannot be stated, since the material of the flames could not be separated for a careful examination. Vähätalo (1951) has separated similar flames from the pyrrhotite of the Outokumpu Mine and observed, that it is linneite and not pentlandite which at Outokumpu is in question; hence also in the case of Nokia the identity of the material of the flames is not without doubt.

ON THE STAGE OF METAMORPHISM

Simonen and Neuvonen (1947), and Seitsaari (1951) have discussed the metamorphism of different parts of the Tampere schist-area, and they have established, that the main recrystallization of rocks occurred under conditions of the amphibolite facies, and according to Simonen and Neuvonen (1947), the conditions of a lower stage of metamorphism have been characteristic of areas containing ore minerals in abundance.

These observations are valid for the Nokia Region as well.

AMPHIBOLITE AND SAUSSURITE FACIES

The highest stage of metamorphism, which can be distinctly observed at Nokia, is that of amphibolite facies characterized by the mineral assemblage (in phyllitic rocks): normal, dark biotite — quartz. In some cases plagioclase is present too. The plagioclase is, however, albitic, but this property is perhaps not a result of metamorphism, but it may be the primary composition of plagioclase. In the lime-rich sediments the most typical assemblage of the same facies is amphibole — plagioclase — biotite.

In a few cases the phyllite of Nokia contains andalusite as well (p. 9). In such cases andalusite belongs, at Nokia, to a mineral association biotite (dark) — anadalusite — quartz, and the muscovite is absent. According to Turner (1950, p. 77), in the amphibolite facies andalusite and potash feldspar are unstable together, if sufficient amount of water is present, because mentioned minerals react in such conditions forming muscovite. Furthermore, if the pelite is rich in aluminum and corresponds to the pyroxene-hornfels facies (Turner, op. cit. p. 71), the aluminum crystallizes in andalusite, and biotite is the only mica. According to Ogniben (1952, p. 84) the assemblage andalusite — biotite — quartz belongs to the amphibolite facies, but there are, at Nokia, in andalusite-bearing rocks also pseudomorphs both after andalusite and after cordierite (p. 9), and such porphyroblasts Ogniben (op. cit.) has described from the pelites of Adamello (Monte Sabioni), and according to him they represent the lowermost stage of the amphibolite facies.

Within the phyllites rich in sulphides, pale biotite occurs instead of dark variety (p. 24), and it is often accompanied by small amounts of muscovite. Owing to the lack of plagioclase, the determination of the facies of a mineral combination, pale biotite — muscovite — quartz, is difficult, because the dark biotite and muscovite may occur together both in the amphibolite and in the epidote-amphibolite facies.

On p. 25 it was mentioned, that the origin of pale biotite may be a result of leaching away of iron from the biotite during its recrystallization into the pale form. The loss of iron may be dependant upon H_2S, which reacts with the iron of biotite and forms iron sulphide, and a contemporaneous release of titanium from mica may hereby be assumed (formation of sphene, which seems often to be, at Nokia, of comparatively late origin). This means that either the H_2S occurred in some stage of the metamorphism as a supplementory factor, or that H_2S has always been present, but the reaction between H_2S and the iron of mica first became possible when the PT-conditions reached some definite stage in the mineral evolution of the schists. The first alternative means a recrystallization under unchanged PT-conditions, the second alternative implies the change of temperature, perhaps also of pressure.

Since there are materials of sapropelic origin in question, the iron sulphides are there present in abundance, and obviously also a surplus of H_2S to react with the iron of mica. Hence the second alternative seems to be more probable. The conditions governing such a reaction may be determined, and the means for such determination are perhaps available from the study of ore minerals.

In the sulphide schists, besides pyrrhotite, chalcopyrite and sphalerite occur. In several instances chalcopyrite occurs as small ex-soluted particles in the sphalerite (Fig. 15). According to Borchert (1934) such an ex-solution occurs at 350°—400°C, hence within the temperatures of the epidote-amphibolite (or saussurite facies of Rosenqvist, 1952) facies. From observations under the microscope, the occurrence of such ex-solutions is seen to be closely connected with the rocks containing pale biotite, and, consequently, the mineral association pale biotite — muscovite — quartz most likely corresponds to the epidote-amphibolite (or saussurite) facies.

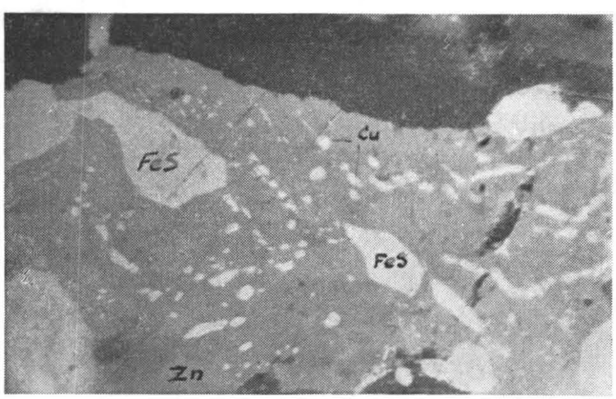

Fig. 15. Chalcopyrite (Cu and all small particles) exsoluted from the sphalerite (Zn), which contains larger blebbs of pyrrhotite (FeS) as well. Nokia, Koskenmäki Polished Section. One Nicol. Mag. 60×.

GREENSCHIST FACIES

Cholorite phyllite and chlorite-sulphide schist are probably the pelitic representatives of the greenschist facies among the rocks of Nokia. These schists are always closely related to the sulphide-schists, which relationship indicates that during the lowering of the facies of metamorphism below the conditions of saussurite facies, only a part of the schists was able to attain the mineral association corresponding to the new PT-conditions. Such a restricting factor may have been the unequal distribution of water in the sedimentary beds; only in such beds, where water was present in a sufficient amount, biotite could be chloritized. In regard to the chlorite-bearing schists, however, certain comments are to be made.

According to Yoder (1952), chlorite is stable in amphibolite facies, as well, and, consequently, its presence does not mean any criterion of low grade of metamorphism. At Nokia these rocks are considered as belonging to lower facies than those containing pale biotite, because under the microscope one can see frequently the chloritization of pale biotite in an environment of a retrogressive metamorphism. But it should still be hold in mind, that the chloritization of biotite is not bound only to addition of water, but there also potassium of biotite will be removed, which fact makes the consideration of metamorphic stage of chlorite-bearing schists of Nokia still more difficult, and, unfortunately, there do not seem to exist any means, at Nokia, to determine the probable temperature at which the chloritization of the pale biotite took place.

The tremolite-actinolite veins, on the contrary, definitely correspond to the greenschist facies, but even there the stage of metamorphism seems to be different in different parts of the vein.

In Fig. 16 two drill cores through such veins are shown.

In the section taken from diamond drill core N:o 5, between 130 and 163 m the basic vein has been pierced, and the vein is in sharp contacts with the penetrated sulphide-schists. In the marginal parts of the vein there the tremolite-actinolite laths are in a well preserved condition, and embedded in a ground-mass consisting of chlorite, serpentine and talc. In the middle part of the vein the large amphibole crystals are, on the contrary, completely altered into talc and chlorite, and the rock contains narrow calcite veinlets, and in one slide graphite veinlet in conjunction with calcite occurs.

In the section of drill core N:o 2 (Fig. 16) 14 meters of similar rock occur, and here it is on both sides likewise in a sharp contact with sulphide-schist. The narrow magrinal zones of the vein contain fresh tremolite-actinolite and a little fresh albite. Inwards the plagioclase gets turbid, as is the case in the middlemost part of the vein as well. Between the zones containing

5 1521—57/2,43

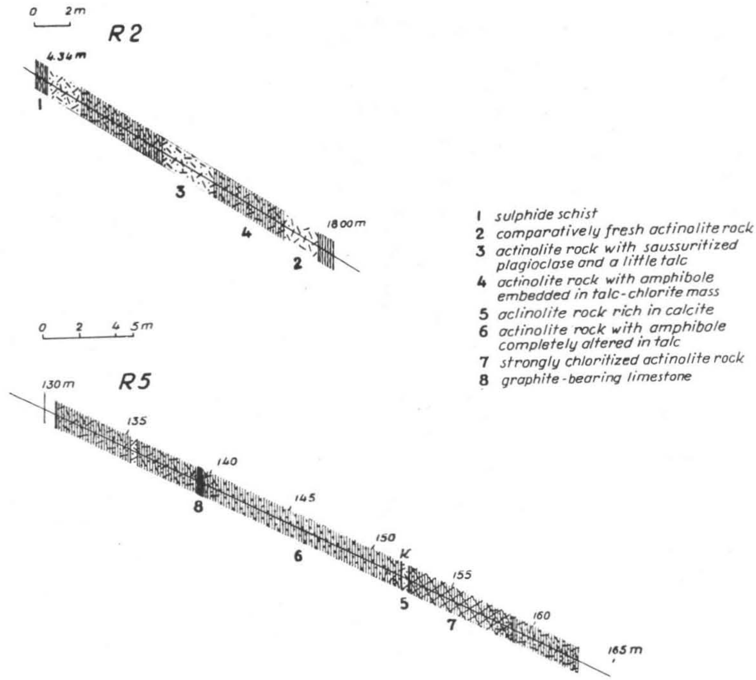

Fig. 16. Section along the drill core R2 (between 4.34 and 1.8 m.) and R5 (between 130 and 165 m.).

turbid plagioclase, however, there are broad zones mainly consisting of talc and chlorite only.

In table I two analyses of tremolite-actinolite vein rock are given. Anal. 1 is made of a sample containing mainly somewhat serpentinized tremolite-actinolite embedded in a groundmass consisting of talc, chlorite, serpentine, and alittle albite, sphene, apatite, and pyrite. The modal composition was calculated so that after the calculation of apatite, sphene, chromite, pyrite, albite, and potash feldspar, the aluminium surplus was used for the formation of chlorite ($2MgO \cdot Al_2O_3 \cdot 2H_2O \cdot SiO_2$); because the plagioclase of the rock is albite, anorthite was not calculated, but the calcium-content was used for the formation of amphibole ($2CaO$. $5 (Mg, Fe) O \cdot 8SiO_2 \cdot H_2O$), and it is thereby observed that MgO and FeO were enough for 3.6 MgO · 1.42 FeO. No quartz remained.

Anal. 2 was made from a sample containing microscopic grains of amphibole embedded in a main mass of talc and chlorite. The calculation of the modal composition was carried out in similar way as in Anal. 1, but after calculating the amphibole according to the relation between MgO and FeO obtained from the Anal. 1, MgO, SiO_2, and H_2O remained, which were used for formation of talc ($3MgO \cdot 4SiO_2 \cdot H_2O$).

Table I: The chemical analyses of the basic vein of Nokia.
Analyst Dr. H. Wiik (Geological Survey of Finland).

	2	1
SiO_2	46.48 %	47.75 %
TiO_2	0.66	0.55
Al_2O_3	6.37	4.44
Fe_2O_3	3.96	4.48
FeO	7.56	6.19
MnO	0.29	0.21
MgO	21.24	19.04
CaO	6.15	11.49
Na_2O	0.36	0.40
K_2O	0.51	0.32
P_2O_5	0.04	0.49
H_2O+	2.65	1.63
H_2O-	0.19	0.00
Cr_2O_3	0.25	0.13
S	3.51	3.78
	100.42 %	100.90 %
—O = S	0.87	0.94
	99.55 %	99.96 %

Apatite	0.00 %	1.34 %
Sphene	1.67	1.27
Albite	3.14	3.14
Orthoclase	2.78	1.70
Chlorite	14.37	4.51
Talc	26.43	0.00
Amphibole	44.14	81.27

Both analyses are made from the same vein, Anal. 1 from its marginal part, Anal. 2 from its middle part.

The alteration of the material of the marginal zone into that of the central part of the vein is characterized by an introduction of water and by leaching away of calcium. Consequently the water content in the middle of the vein must have been considerably greater than in the marginal parts, or, if the content of water in the whole vein has been the same, the conditions in the central part have been more favourable for metamorphic changes than those in the marginal parts. This can depend upon the more sudden cooling in the marginal parts of the vein than in its inner parts, and this prevented the alteration of amphibole in the marginal parts of the vein. In the inner part of the vein the lowering of the temperature was slower, and the reaction between water and amphibole, and contemporaneous leaching away of calcium could take place. Since the veins are comparatively narrow, and the reactions in question are slow, such an alteration corresponds to a very low range of metamorphism, which consideration agrees well with what is known about the conditions of the greenschist facies.

THE FINE-GRAINED ALBITE-BIOTITE GNEISS

Albite-biotite gneiss has been met with at Tyrkkölä in diamond drill cores (p. 9). The rock consists of coarse quartz and albite grains embedded in a fine-grained groundmass consisting of the same minerals, and of sparse pale biotite. In addition there may occur coarse and strongly resorbed laths of amphibole, and the sulphide of the rock is pyrrhotite. In diamond drill core N:o 6 (Fig. 1) similar rock contains plagioclase in the form of long, narrow laths, which give to the rock its habit resembling that of ophitic structure. The plagioclase is andesine ($c \Lambda \gamma = 18°$). Occasionally there may occur chloritic clots, which may be remainders of vesicles. It seems, that there an intermediate lava rock is in question, but because this rock occurs embedded in a phyllite and forms comparatively narrow beds (1 to 2 m thick), it is more likely a dyke rock.

CONCLUSIONS

Concerning the metamorphism of the schists of Nokia the following conclusions can be drawn:

1. The main metamorphism of the Nokia schists took place under the conditions of the amphibolite facies;

2. In the parts of the schists rich in sulphides the saussurite facies predominates, and the mineral association: pale biotite — muscovite — quartz, typical of the sulphide-schists, corresponds to the conditions of this facies. The chlorite-bearing sulphide-schists may correspond to a lower facies, since their chlorite is a result of chloritization of biotite, but chlorite being stable under the conditions of amphibolite facies as well, such a statement could not be proved;

3. The young ultrabasic veins have been metamorphosed under the conditions of the greenschist facies. The veins are more altered in their central parts than along margins, which phenomenon is explained as depending upon more sudden cooling of the marginal parts of the veins than of their interiors.

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