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by Valto Veltheim

Geologinen tutkimuslaitos · Otaniemi 1969

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ON THE PRE-QUATERNARY GEOLOGY OF THE BOTHNIAN BAY AREA IN THE BALTIC SEA

BY

VALTO VELTHEIM

WITH 24 FIGURES AND ONE APPENDED PLATE

GEOLOGINEN TUTKIMUSLAITOS
OTANIEMI 1969

ABSTRACT

The paper is the second part of the author's study of the pre-Quaternary geology of the Gulf of Bothnia. The first part, dealing with the Bothnian Sea, was published in 1962. The same methods are used in both studies.

The base material for the study is the samples of drift collected from the sea bottom by means of a marine grab. The interpretation is based on evidence obtained on land showing that the glacial drift is to a large extent of local origin and reflects the quality of the bedrock on the spot.

An isolated post-Archean sandstone deposit is assumed to occur in the sea area about 17 nautical miles west of Raahe. Erratics indicate that the sandstone may in part be mineralized by pyrite, chalcopyrite, sphalerite, galena and safflorite.

The erratics of unusual rock quality such as feebly metamorphosed volcanic rock including vesicular lava, sandstone and phyllite showing fossile (?) features, conglomerate and tillite, found on the Finnish coast seem to indicate a provenance in the bottom of the Bothnian Bay.

The bedrock of the maritime sandy island of Hailuoto is shown to be composed of post-Archean sediments. The Hailuoto area is characterized by large-scale dislocations connecting it to the Muhos graben on the mainland.

Helsinki 1969. Valtion painatuskeskus

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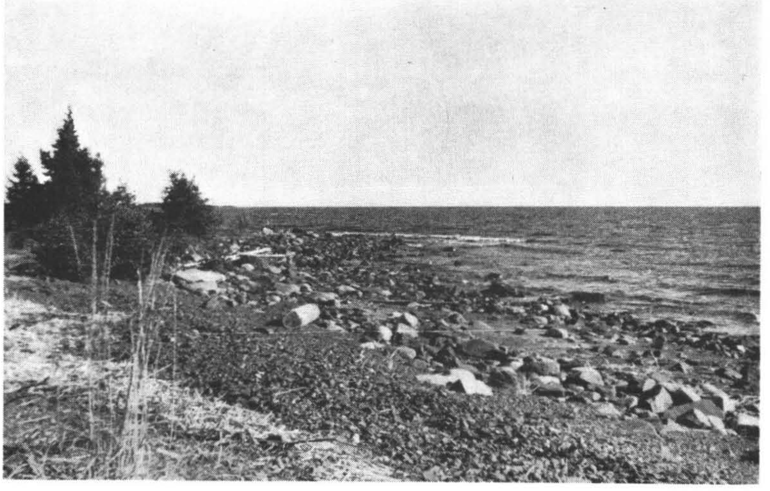

FIG. 1. Coastal scenery along the Bothnian Bay.

INTRODUCTION

The paper at hand forms the second part of an investigation in the pre-Quaternary geology of the bottom of the Gulf of Bothnia in the Baltic Sea, Fig. 2. The first part, dealing with the area of the Bothnian Sea, was published by the author in 1962. The author's interest in the submarine geology of the Gulf of Bothnia stems from the Bothnian Bay, where, on the shore north of Pyhäjoki, some sandstone blocks richly impregnated with sphalerite and galena, and apparently originating from the sea bottom, were found in 1953.

The bulk of the bottom samples, the P- and L-samples, of the Gulf of Bothnia was taken in 1958 and 1959. In view of the pioneering nature of the work it seemed advisable at the time to limit the interpretation and compilation work to the area of the Bothnian Sea as this seemed to include more easily localized Paleozoic deposits and could thus contribute towards a clarification of the relationship of the deposit *in situ* and the material found in the unconsolidated sediments.

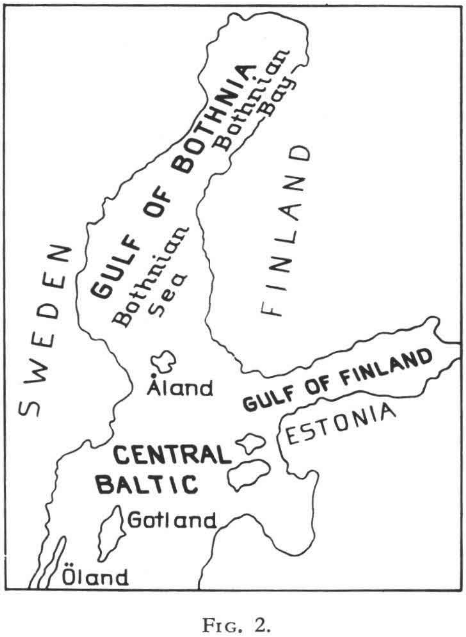

FIG. 2.

The method used in the taking of the bottom samples, their preliminary treatment on board, as well as their further treatment in the laboratory, have been described in the previous paper dealing with the investigation of the Bothnian Sea (Veltheim, 1962).

Earlier information on the pre-Quaternary geology of the Bothnian Bay is scanty. The only direct observations are the few drillings executed for prospecting purposes. In 1958 the Geological Survey of Finland drilled two holes outside the coast about 3 km to the west of Siniluoto. The rock of the drilling cores consisted of phyllite and mica schist analogous to the quality of the rock met with at the outcrops on the mainland (Nykänen, 1959).

In the winter of 1966, the mining company Otanmäki Oy carried out an investigation on the magnetic anomaly area north-east of the Nahkiainen beacon about 20 km to the west of the town of Raahe. Four holes were drilled within a distance of two kilometres. The bedrock here is composed of mica schist with an average strike of SW—NE and a dip of 70° to NW. Within the investigated area there lies a discontinuous interstratum about 50 metres thick and of a somewhat uncommon mineralogical composition characterized by iron-rich varieties of clinoamphibole, clinopyroxene and olivine, and including about 18 % magnetite and some quartz, calcite, mica and garnet. The upper part of the stratum to a depth of 40 metres has become transformed resulting in minerals like vermiculite and serpentine. The mineralogical composition and the alteration processes have been studied in detail by Hytönen (1968).

In the winter of 1968, the Otanmäki Oy also sank a drill hole at Lat. 64°59′ N, Long. 25°E, in the sea area between the Hailuoto island and the mainland. The present author understands that under a cover of unconsolidated sediments 65 metres thick, the drill core consisted of a sediment comparable to that of the Muhos graben and that this sediment continued beyond the depth of 163 metres where the drill hole came to an end.

The most significant of the indirect observations are those made by Okko (1949) in connection with his compilation of the Quaternary map of Kokkola (Sheet B 4). In his pebble counts Okko presented a group which includes four rock types: quartzite, dolomite, sandstone and shale, and diabase. These represent rocks not met with on the mainland thus pointing to the possibility of their source lying in the sea area. The distribution of these rock pebbles shows a maximal concentration between Raahe and the Kalajoki river. A secondary concentration is to be found in the vicinity of the town of Kokkola, while a third one, which is rather small, is situated near the Lohtaja church. The density of the sandstone and shale, which makes it of special interest to the present study, coincides with the distribution of the above groups. The average percentage of sandstone and shale pebbles in the first mentioned coastal strip is between 2 and 4. In a couple of instances it is as high as 7 %. The highest percentage figure in the Kokkola area is 2 and in Lohtaja 1. In addition to the aforementioned rock types, Okko paid attention to the finds of porphyry blocks, which likewise may have been transported from the sea area. As a possible explanation to the extensive sands on the coastal area, Okko suggests a friable sandstone deposit situated in the bottom of the Bothnian Bay.

Leiviskä (1905) in his comprehensive description of the geography of the coastal area refers to the limestone blocks that occur particularly on the northern part of the coast as being brought from the Swedish side. In ancient times these blocks have been collected by local people for domestic lime burning.

Discussing the source of the pyrite-bearing boulder found in Vihanti (35 km SE from Raahe), Hyyppä (1948) has come to the conclusion that the continental ice sheet has at first moved along the basin and may have started flowing eastward, i.e. towards the Finnish coast, only after it had been anchored to the bottom. Thus, in the »coastal regions there are to be expected only exceptionally such stones as have been transported from the Gulf of Bothnia» (Hyyppä, 1948, p. 119). The present author is prepared to agree with this supposition in so far as it applies to material deriving from the actual deep water basin or the area behind it.

Marmo and Laitakari (1952) have established that the two pyrite concretions found in the coastal region of the Bothnian Bay have been transported, among numerous similar ones found in south-west Finland, from the bottom of the Gulf of Bothnia. Kulonpalo (1957) has increased their number to five.

The existence of hematite-bearing boulders among the shore gravel around Raahe has long been known and their submarine provenance has been taken for granted. In 1955 similar boulders, some of them rich in iron, were found in Haapavesi, 65 km SE from Raahe. Subsequently Mr. P. Oivanen collected a total amount of nearly 300 samples from an area forming a broad belt extending to the shore at Lapaluoto, south of Raahe. From the report written by Oivanen (1960) the following points may be summarized: The size of the samples varies from 1 to 40 cm in diameter. A considerable proportion of the boulders is in a state of degradation. The mother rock varies greatly in quality. The biggest group is composed of green schist displaying the mineral assemblage cummingtonite, chlorite, quartz, kaolin?, and dolomite. Other rock qualities are dolomite, quartz-feldspar schist, skarn, chlorite schist, quartzite, and diabase. The hematite appears in a mode which clearly suggests its secondary origin, i.e. it mainly fills openings formed by disintegration.

Since the drift transport has been towards the sea on the western coast of the Bothnian Bay, geological observations based on loose material and directed to the sea bottom are scanty on the Swedish side. Some boulders found on the offshore islands have, however, pointed to their sub-aqueous source. Thus, kimberlite boulders have been found in the Kalix and Luleå archipelago. A map of the distribution of these boulders as well as of the occurrences of the kimberlite on the islands was compiled by Dr. Erik Åhman in 1955 (referred to by Ödman, 1957).

Åhman (1950) has described the conglomerate boulders found on the small island of Malören situated about 30 km from the Swedish coast, roughly 60 km due east from Luleå. The conglomerate is composed of semi-rounded balls consisting of fine-grained volcanic tuff, quartzite, sandstone, dolomite, schist and shale, cemented by brownish crystalline calcite with some quartz. Åhman suggests that the boulders are derived from the submarine gully extending some 20 km to the NW from Malören and correlates them with the Kieksi-conglomerate at Muhos. It may be mentioned here that also Brenner (1944), when outlining the northern border of the Muhos graben, approaches close to the Malören island and calls attention to the conglomerate boulders already known to occur on the island.

During the compilation of the results of the present work it appeared that one of the focal points of study was going to be the establishing of the post-Archean sediment succession in the region of the beacon of Nahkiainen, west of Raahe. In order to map out a more dense network of samples another trip was made in the summer of 1967 to this area. The samples collected are here called M-samples. In the same summer two further samples (W-samples) were taken with a dredge by Dr. Heikki Ignatius and Mr. Boris Winterhalter, Phil.Lic. These were also placed at the author's disposal.

A considerable part of this volume deals with the maritime island of Hailuoto where the quality of the bedrock had never been investigated. Thanks to the seismic measurements and the deep drilling carried out by the Geological Survey of Finland it has been possible for the present author to attempt an interpretation of the geology of the island.

ON INVESTIGATIONS CONTRIBUTING TO THE RESEARCH OF THE BEDROCK OF THE BOTTOM OF THE BOTHNIAN BAY

General depth conditions

In its general depth features the Bothnian Bay is comparable to the Bothnian Sea described in detail by Veltheim (1962). The Swedish side is characterized by a broken coast line, more steeply rising coastal banks and, especially to the south of Piteå, by relatively great depth variations quite close to the shore. The Finnish side, on the other hand, is characterized by flatness (see Fig. 1) to such an extent that the determination of the line between dry land and water in the topographical maps seems often to have been difficult. The same flatness very probably continues towards the open sea judging by the isobates, Fig. 3. This is definitely so in the northern part, outside Oulu and Kemi, where the 20 metre isobate runs about 50 km from the coast.

The entire sea area must be considered as a shallow basin, more than 90 % of the area being less than 100 metres in depth. A few exceptions can be found mainly in the southern part of the area, where, between Lat. 64°N and Lat. 64°50′N and between Long. 22°E and Long. 22°40′E, areas with depth figures up to 126 metres

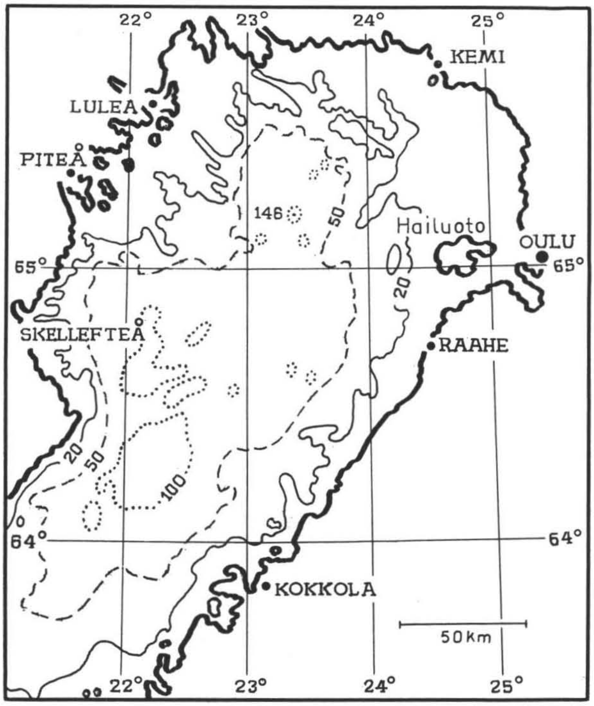

FIG. 3. General depth conditions in the Bothnian Bay area.

occur. The maximum depth, 146 metres, is, however, to be found on a small spot approximately in the middle of a line drawn from Oulu to Piteå.

Morphologically the bottom of the Bothnian Bay is likewise comparable to that of the Bothnian Sea. Flat areas, such as have been noted in the bottom of the Bothnian Sea and have been interpreted as paleozoic sediment banks (Veltheim, 1962), have not been established in the Bothnian Bay area, however.

Gravimetric measurements

The gravimetric map over Finland published by Honkasalo (1959) covers the entire Bothnian Bay area, Fig. 4. As a whole the area is gravimetrically rather flat. The negative anomaly area in the Oulu region may be connected with the existing, so-called Muhos graben, filled with shale (cf. p. 12). A rather strong, —35 mgal, anomaly belt, 30 km in width, extends from Pyhäjoki to the northwest close to the Swedish coast where it includes an oval shaped area indicating —40 mgal.

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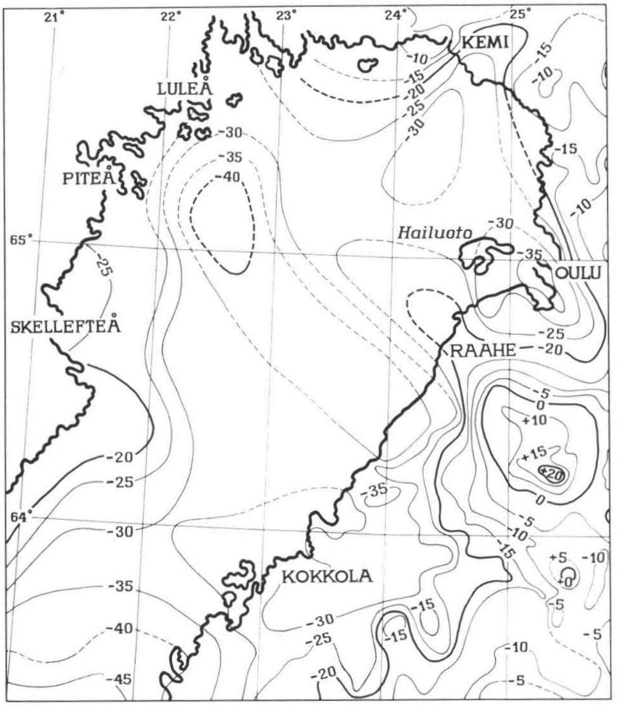

FIG. 4. Free air gravity anomalies in the Bothnian Bay area. Finnish Geodetic Institute, Honkasalo, 1959.

Aeromagnetic measurements

The aeromagnetic measurements executed by the Geological Survey of Finland cover the entire coastal region of the Bothnian Bay and a considerable sea area outside Oulu, where they include the Hailuoto island with its surroundings. These will be discussed in detail in connection with the compilation of the geology of the sea bottom.

On the geology of the coast of the Bothnian Bay

Excluding the so-called Muhos formation which will be described separately, and the Hailuoto island which was unexplored until recently, the entire Bothnian Bay coastal region is composed of Archean rocks. Following the general division outlined by Simonen (1960), the rocks on the Finnish side may be divided into a granite-gneiss complex, Svecofennidic and Karelidic schist belts, and an orogenic plutonic rock group.

The coastal area between Kemi and the Iijoki river is marked as granite-gneiss which is considered to be pre-Karelidic basement. In the map sheet of Oulu compiled by Enkovaara, Härme and Väyrynen (1952), the area is marked as consisting of a »mixture of gneissose and massive granites» thus indicating a complicated composition. According to the explanatory text to the map sheet (same authors, 1953), the area consists of ortho- and paragneisses including sedimentary and intrusive rocks showing lower metamorphism.

The Svecofennidic schist belt approaches the coast around Kokkola. According to the map compiled by Simonen (1960), it consists of migmatites with a supracrustal rock base.

Metamorphic orogenic plutonic rocks of varying composition occur on the large coastal regions to the north and to the south of the schist belt mentioned above (Simonen, 1960).

The Swedish side is for the most part marked as belonging to the Svecofennidic (in Sweden also called Svionian) complex. In the general map compiled by Magnusson (Magnusson, Granlund and Lundqvist, 1949), almost the entire southern coast area up to Piteå in the north, is classified as veined gneisses. A small area at Skellefteå and a bigger one at Luleå are depicted as »urgranit» (the very oldest granite). Narrow areas consisting of Svecofennian supracrustal rocks occur at Skellefteå and to the north of Luleå.

Karelidic supracrustal rocks reach the Bothnian Bay coast on the Finnish side in two main localities. The northern one, called the Peräpohja (Far North) schist area, occupies a wide triangular area north of the town Kemi and touches the coast at Kemi. The other locality, called the Pohjois-Pohjanmaa (North-Bothnian) schist area, approaches the coast from SE between Oulu and the Iijoki river. On the Swedish coast Karelidic supracrustal rocks appear to be rare occurring only in the area between Kalix and Piteå and in the archipelago of these localities. Among the authors who have investigated the different areas and who are referred to below, may be mentioned the following: Hausen (1936) and Härme (1949) the Peräpohja area, Mäkinen (1916) and Enkovaara (Enkovaara, Härme and Väyrynen, 1953) the Pohjois-Pohjanmaa area, Ödman (1957, referring to various authors) the Swedish side.

The Karelidic supracrustal rocks seem to present many similar aspects wherever they occur. A common feature is the satisfactory, in many cases first class state of preservation of the original structural features. Among the individual members of the sedimentary sequency may be mentioned conglomerates, arkoses, quartzites, black schists, phyllites, various volcanics including porphyries, dolomites, jaspilites and sedimentary iron ores.

For the purpose of the present work two rock types from the above group deserve closer consideration. Dolomites are frequently met with in the Peräpohja schist area as well as on the Swedish side. In the Pohjois-Pohjanmaa schist area they seem to occur only sporadically. The dolomite is generally of fine grain size showing stratification due to interlayers composed of dense, often silica-bearing matter. Typical colours are off-white and light yellow. The MgO—CaO ratio is fairly stable, averaging 0.66. Structural features that have been interpreted as pointing to algae (Geijer 1931, referred to by Ödman, 1957) are common in the Swedish dolomites. Similar organic manifestations have been reported from the Finnish side by Hausen (1936) and described in detail by Härme and Perttunen (1964).

Black schists and phyllites cover considerable areas in both the Finnish schist areas and are frequently met with also in the Kalix area in Sweden. They often appear to be graphite-bearing, and on the Swedish side the amount of graphite in black schists may exceed 50 % of the rock composition. In one case (at Säivis, west of Haparanda) concretion-like structures the size of a pidgeon's egg and composed of coal-bearing substance, have been observed (Ödman, 1957, p. 54).

The Muhos formation

A striking exception to the general geology of the Bothnian Bay coastal zone occurs at Oulu, where a shale deposit 50 km long and 20 km broad, approaches the shore in a NW—SE direction, Fig. 5. This is known as the Muhos formation and, after somewhat conflicting opinions, has been classified as Jotnian, two potassium-argon datings having given the ages of 1,280 Myr and 1,310 Myr (Simonen, 1960).

The shale deposit was discovered in 1938 in connection with the construction of the Pyhäkoski power station and it has been studied later on various occasions. When the Oulunjoki Oy Company carried out deep-drilling at Tupos in 1959, a thickness of 895 metres for the sedimentary stratum was established. Published data of the stratigraphy are available only previous to the drilling at Tupos. According to Brenner (1941), on top of the crystalline bedrock there is a layer of arcosic sandstone a few metres thick. Above this lies a thin layer of fine sandstone which may also occur as interlayers in the shale above. A noticeable feature is the intense red colour typical for most of the sedimentary succession. The shale may be devoid of carbonate or carbonate-bearing. In the latter case the carbonate may appear as calcite micro-crystals. Gypsum has been observed as fissure fillings and also as single grains. Pyrite may appear as idiomorphic crystals which may occur as accumulated clusters. The shale is stratified, individual layers averaging some millimetres in thickness. The dip varies from horizontal to about 20°. The mattress as a whole inclines, according to Brenner (op.cit.), to the south, the inclination degree being a couple of degrees.

Simonen (1955) emphasizes the immature nature of the Muhos sedimentary succession and concludes that, like the Jotnian sedimentary rocks elsewhere in Finland, it represents a tectonic accumulation of slightly decomposed detrital material. Thus, according to Simonen, the entire succession would suggest a floodplain deposit in the piedmont facies in postgeosynclinal basins.

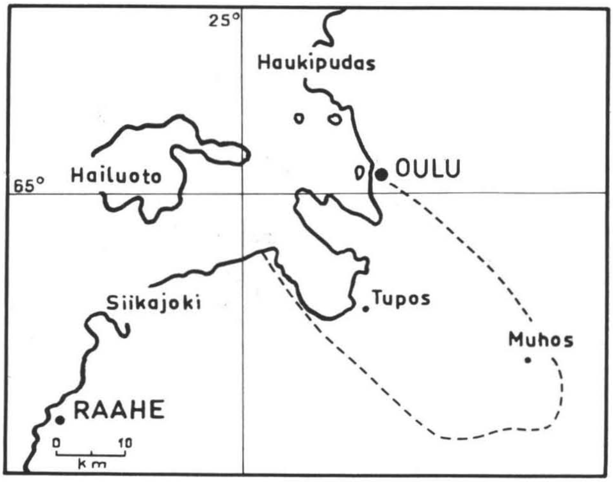

FIG. 5. The location of the Muhos formation.

In Kieksi, at Muhos, a conglomerate outcrop was found and described by Brenner (1944). According to Brenner, topographic features point to the likelihood of the conglomerate outcrop falling within the fault zone separating the crystalline basement from the Muhos sedimentary succession, the conglomerate, in consequence, representing a higher level in terms of the dislocation events. The thickness of the conglomerate stratum was estimated at 8—10 metres. The rock is stratified due to different degrees of coarseness. The pebbles are rounded as well as angular in shape, their size does not exceed that of a goose egg. The mechanical strength of the rock is small. The colour is rust to chocolate brown. The conglomerate is polymict the balls being for the most part granitic, gneissose, schist-like and of a basic rock quality. The cement consists of sandy and shaly matter. Brenner considers the »Kieksi conglomerate» a representation of a bottom formation (»Bodenbildung») of the Muhos sediments. In the conclusion, however, he expresses his unwillingness to pronounce upon any closer mutual relationship between the conglomerate and the sedimentary sequence proper — apparently because conglomerate similar in quality does not occur in the drill cores which have reached the basement complex below the sediment.

According to oral information given by Mr. Juha Kalla, the geologist in charge of the drilling operation at Tupos in 1959, the obtained cores show no principal differences in composition to those from other drillings in the area. Mr. Kalla notes that the sediment immediately on top of the basement complex is composed of exceptionally hard sandstone.

A study by Tynni and Siivola (1966) of the core samples of the Muhos siltstone (Tupos drilling) has revealed probable Precambrian microfossils which can be divided into algal colonies and spore-like structures.

FIG. 6. Protruding »cores» in decomposed rock caused by spheroidal parting intensified by subsequent weathering. On the right, detail showing spheroidal parting. Water channel, Merijärvi.

The old peneplain

The eastern coastal area of the Gulf of Bothnia has been regarded as an old peneplain (Sauramo, 1916; Veltheim, 1962). This assumption applies also to the coast of the Bothnian Bay and may even include a considerable bottom area outside the eastern mainland. Facts pointing to a close mutual relationship of the ancient degraded level and the present rock surface are indeed numerous in the Bothnian Bay coastal and maritime region. The disintegrated bedrock surface, generally considered as being caused by pre-Quaternary weathering, has been commonly noted by the geologists working in the area (cf. e.g. Okko, 1944). Weathering has also been observed in the upper part of the drill cores obtained at Nahkiainen (see p. 6), in Hailuoto (see p. 34), as well as in the numerous drill holes sunk in the course of prospecting at Pattijoki, east of Raahe.

Another occurrence found by the present author may be worth mentioning in this connection. It is to be found at a certain point in the channel blasted through the rock in the parish of Merijärvi, about 20 km from the sea coast. The bedrock here consists of massive diorite of medium grain size. The rock is, however, decomposed to the entire height, about 4 metres, of the channel walls. The decomposition is caused by spheroidal parting which is heavily intensified by subsequent weathering, Fig. 6.

Some phenomena pointing to metasomatism and substance circulation within the weathered rock crust have been recorded. The transformation of minerals in the upper part of the drill core from Nahkiainen, which has been described in detail by Hytönen (see p. 6) is indicative in this respect. The numerous basically weathered boulders which show secondary hematite injection (see p. 7) possibly derive from disintegrated rock crust where the circulating liquids have caused the mineralization. To the same cathegory may also be added the large amount of boulders, likewise decomposed, of different rock qualities impregnated with chalcocite. The first of these boulders was found in Oulainen in 1954 and it gave rise to intensive prospecting activity supervised by the present author. It appeared that chalcocite, when subsequently found in situ, was not connected to any special rock but occurred in rocks of varying composition within a relatively wide area in the region of Merijärvi. In most cases it existed as a filling of fractures in the bedrock. In some instances, however, chalcocite made up the impregnation of decomposed bedrock occurring in small depressions in the hard rock surface. It was evident that chalcocite was a secondary mineral in the rock and that it probably represented recrystallization accumulations due to copper-bearing liquids percolating through the weathered rock stratum which at one time had covered the present surface. The native copper observed as lamellae in the feldspar of the pegmatites in the area may be suggested as a possible original source of the metal in the chalcocite. (Reports by the present author in the Archives of the Geological Survey of Finland).[1]

On the movements of the continental ice sheet in the Bothnian Bay area

The directions of the glacial ice movements have been studied, among others, by Hyyppä (1948) and Okko (1949). Three main movement directions have been generally accepted. According to Okko (op.cit.) the oldest movement points to an arrival direction of the ice as being 285°—300°, the second being from 325°—340°, while the youngest ice movement has been from 345°—36°. The best preserved traces are those left by the oldest direction. The general transportation direction of the drift seems to be, according to Okko (op.cit.), from NW to SE. Among the observations by the same author on the subject should be mentioned the transportation direction of boulders derived from a small peridotite occurrence at Kunnari. Near the occurrence the transportation has been from 300°. Some distance away the fanning out of boulders becomes broader, the sides of the fan showing directions 289° and 310°.

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[1] The concentration of the various weathering occurrences into the region of Merijärvi could indicate that the phenomenon occurs within a larger area in the region. The weathering of the bedrock could explain the low topography of the area which includes, *inter alia*, the basins of the two drained lakes of Tähkijärvi and Merijärvi. The low topography manifests itself visibly in the course of the Pyhäjoki river, which, running from the SE fans out on approaching the Merijärvi area (about 2 km NW of Kalapudas) into several shallow-bedded rivulets, only to flow together again NW of Merijärvi (at Ilvessalo).

As the flooding melt waters have caused wide-spread damage in the district, an artificial channel has been dug to help the drainage. The weathering referred to in the text above, occurs close to the spot where the channel penetrates the »barrier» surrounding the low area.

BOTTOM SAMPLES

Taken as a whole, the samples from the Bothnian Bay area are quantitatively smaller and much poorer in quality than those from the Bothnian Sea. To a certain extent this may be due to the relative preponderance of fine and very fine material which covers the bottom of the Bay. In a number of cases, for some unknown reason, it was not possible to obtain any samples at all. The scantiness of the material explains the modified treatment of many samples. Thus e.g. the qualitative percentages have mostly been calculated from the entire material instead of a certain coarseness fraction. For the same reason no conclusions have been drawn regarding the Archean basement rock complex.

The classification of the sandstone proved difficult. Unlike the Bothnian Sea area, where a two-fold division into Jotnian and Cambrian types could easily be made, no pebbles that could have been suspected of being Cambrian were found in the bottom samples from the Bothnian Bay. Consequently, all the sandstone was considered to be Precambrian, and its classification, e.g. into different environmental facies, was in fact based on features observed in boulders found on the shore.

The location of the bottom samples is shown in the accompanying map, Fig. 7.

Sample P 7, Lat. 64°08,3'N, Long. 22°47,3'E, depth 35 metres. The bottom sample composed of fine sand including a few Archean rock pebbles.

Sample P 8, 64°19,0'N, 23°16,0'E, depth 33 metres. Fine sand including Archean rock pebbles.

Sample P 8 a, 64°21,3'N, 23°13,3'E, depth 34 metres. Fine sand.

Sample P 8 b, 64°22,0'N, 23°33,3'E, depth 25 metres. A few Archean rock pebbles.

Sample P 8 c, 64°23,0'N, 23°11,0'E, depth 46 metres. Fine sand and clay.

Sample P 9, eliminated.

Sample P 10, 64°39,0'N, 22°53,0'E, depth 68 metres. Fine sand.

Sample P 11, 64°48,0'N, 22°42,3'E, depth 68—88 metres. Ten pebbles the size of an egg, all of Archean rock composition.

Sample P 12, 65°01,0'N, 22°42,0'E, depth 18 metres. Fine sand.

Sample P 13, 64°54,0'N, 23°05,0'E, depth 66 metres. Fine sand and clay.

Sample P 14, 64°49,3'N, 23°23,3'E, depth 62 metres. A few Archean rock pebbles.

Sample P 15, 64°48,0'N, 23°26,0'E, depth 76 metres. Fine sand and clay including a few Archean rock pebbles.

Sample P 16, 64°44,0'N, 23°45,0'E, depth 41 metres. Fine sand and clay including coarse material. An 8—16 mm grain size fraction contained 210 gr of material and gave the following qualitative division:

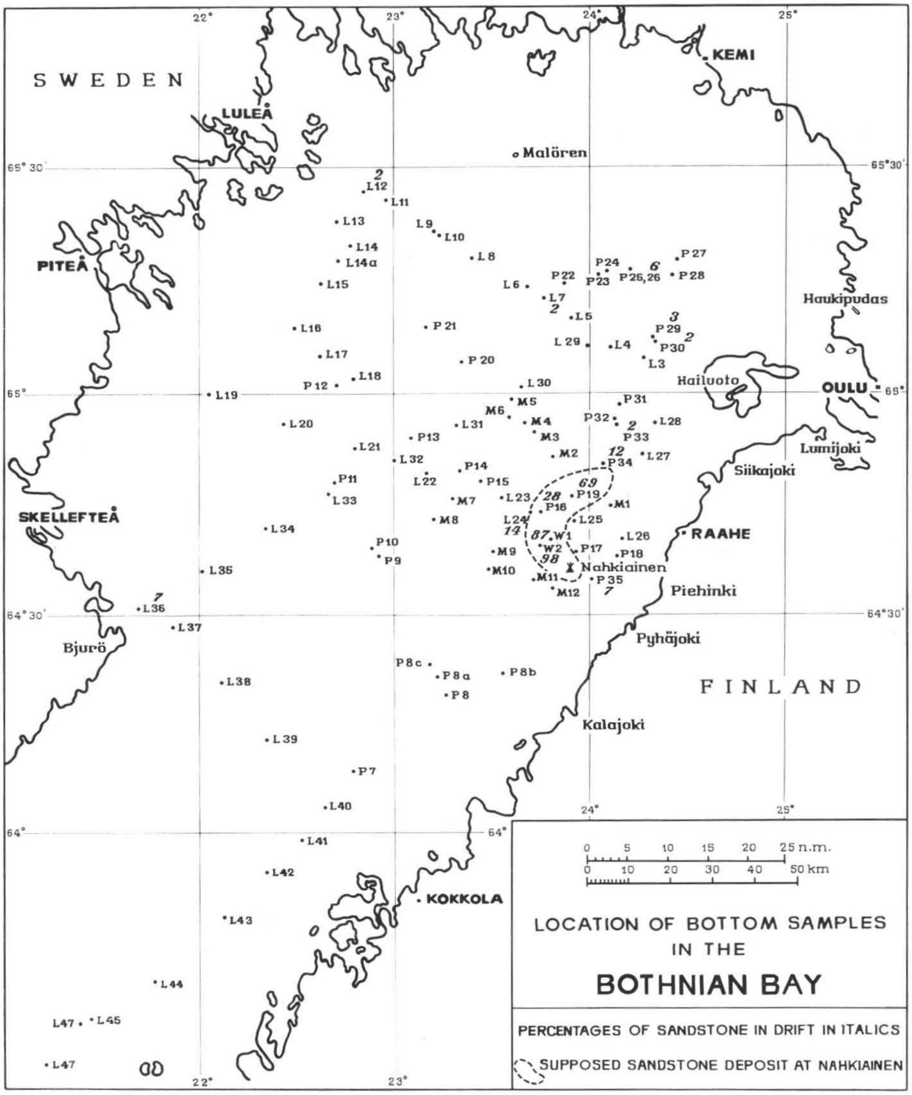

FIG. 7.

Archean rock	72 %	
Sandstone	13 %	28 %
Shale	15 »	

The sandstone was both of the grey and the reddish type. The shale included grey as well as purple red types.

Sample P 17, 64°38,4'N, 23°56,2'E, depth 17 metres. Sand including coarser material. The 4—8 mm grain size fraction separated by sieving contained 125 gr material which, except for one grey sandstone grain and two brownish shale grains, was entirely composed of Archean rock.

Sample P 18, 64°38,0'N, 24°08,1'E, depth 13 metres. Two Archean rock cobbles.

Sample P 19, 64°45,5'N, 23°53,5'E, depth 28—32 metres. The sample was composed of a small amount of gravel including a few cobble-size pieces. Classification of the entire material (550 gr) gave the following division:

Archean rock	31 %	
Sandstone	57 »	69 %
Shale	12 »	

The (weight) percentages may be somewhat misleading due to the fact that all the biggest pieces happened to be sandstone. The sandstone was of the hard greenish and the brittle greyish type. The shale included purple, red and yellowish types.

Sample P 20, 65°04,0'N, 23°21,0'E, depth 77 metres. Clay and limonite.

Sample P 21, 65°09,0'N, 23°12,0'E, depth 88 metres. Clay.

Sample P 22, 65°14,3'N, 23°52,0'E, depth 37—43 metres. Fine sand.

Sample P 23, 65°15,4'N, 24°02,0'E, depth 24—43 metres. Fine sand.

Sample P 24, 65°16,0'N, 24°05,0'E, depth 13 metres. Fine sand.

Sample P 25, 65°16,3'N, 24°12,0'E, depth 12 metres. Fine sand.

Sample P 26, 65°16,3'N, 24°12,0'E, depth 18 metres. Sand with somewhat coarser material. The 4—8 mm fraction, 107 gr in weight, gave the following division:

Archean rock	94 %
Sandstone	6 »

The sandstone was for the most part of the hard reddish type. The rest was of the grey brittle type.

Sample P 27, 65°17,4'N, 24°26,3'E, depth 13 meters. Fine sand.

Sample P 28, 65°15,5'N, 24°25,0'E, depth 23 metres. Fine sand.

Sample P 29, 65°07,2'N, 24°19,1'E, depth 16 metres. Clay including sand and gravel. The 4—8 mm grain size fraction, 76 gr, gave the following division:

Archean rock	97 %
Sandstone	3 »

The sandstone was of the grey type.

Sample P 30, 65°06,5'N, 24°20,0'E, depth 11—17 metres. The sample, 60 kg in all, was composed of sand and coarse material. The 8—16 mm grain size chosen for classification weighed 1 kg and gave the following division:

Archean rock	98 %
Sandstone	2 »

The majority of the sandstone was of the grey brittle type, the rest being of the hard red type.

Sample P 31, 64°58,2'N, 24°09,0'E, depth 17 metres. Fine sand.

Sample P 32, 64°56,3'N, 24°07,4'E, depth 26 metres. Fine sand and clay.

Sample P 33, 64°56,0'N, 24°08,0'E, depth 16 metres. Archean boulders and cobbles with small amounts of gravel. The 8—16 mm fraction weighed 244 gr and gave the following division:

Archean rock	98 %
Sandstone	2 »

The sandstone included both grey, brittle, and red, hard types.

Sample P 34, 64°50,3'N, 24°04,0'E, depth 21 metres. Sand and gravel. The 8—16 mm grain size fraction weighed 666 gr and gave the following division:

Archean rock	88 %	
Sandstone	10 »	12 %
Shale	2 »	

The sandstone included equal amounts of grey, brittle and red, hard types. The sample contained some wind-worn quartz grains. Some shale pieces were purple-red, some were grey.

Sample P 35, 64°35,0'N, 24°00,3'E, depth 14 metres. Clay, sand, gravel and stones. The 8—16 mm grain size fraction weighed 642 gr and gave the following division:

Archean rock	93 %	
Sandstone	5 »	7 %
Shale	2 »	

The sandstone was mainly of the grey type. The shale included grey, greenish and purple-red slabs.

Sample L 1, 65°36,3'N, 24°28,4'E, depth 9 metres. Fine sand including a few Archean rock pebbles.

Sample L 2, 65°27,2'N, 24°16,0'E, depth 16 metres. Fine sand.

Sample L 3, 65°04,3'N, 24°17,0'E, depth 17 metres. Sand including pebbles of Archean rock.

Sample L 4, 65°07,0'N, 24°07,0'E, depth 18 metres. Fine sand.

Sample L 5, 65°10,0'N, 23°54,0'E, depth 20 metres. Gravel composed entirely of Archean rock.

Sample L 6, 65°14,0'N, 23°41,0'E, depth 58 metres. Clay and limonite.

Sample L 7, 65°12,3'N, 23°46,0'E, depth 34 metres. Coarse sand. The 4—8 mm grain size fraction gave the following qualitative division:

Archean rock	97 %
Sandstone	3 »

Three-fourths of the sandstone was of the hard, red type, the rest being of the grey, brittle type.

Sample L 8, 65°18,0'N, 23°24,0'E, depth 80 metres. Limonite.

Sample L 9, 65°21,3'N, 23°12,0'E, depth 108 metres. Fine sand and clay.

Sample L 10, 65°21,0'N, 23°14,0'E, depth 62 metres. Clay from which it was possible to separate a few hundred coarse sand grains. One sandstone grain was found.

Sample L 11, 65°25,3'N, 22°57,3'E, depth 87 metres. Fine sand.

Sample L 12, 65°27,3'N, 22°49,5'E, depth 28 metres. Clay mixed with sand and gravel. The classification based on the 4—8 mm grain size fraction gave the following result:

Archean rock	98 %
Sandstone	2 »

The sandstone was of the red, hard type.

Sample L 13, 65°23,0'N, 22°42,2'E, depth 35 metres. Clay mixed with gravel of Archean rock.

Sample L 14, 65°19,5'N, 22°46,0'E, depth 22 metres. Sand including some coarser material of Archean rock and one sandstone grain.

Sample L 14 a, 65°17,4'N, 22°42,3'E, depth 13 metres. Sand with some coarser material of Archean rock.

Sample L 15, 65°14,3'N, 22°37,3'E, depth 9—12 metres. Sand and gravel of Archean rock.

Sample L 16, 65°08,2'N, 22°29,2'E, depth 12 metres. Fine sand from which a small amount of coarser material could be separated all of it of Archean rock.

Sample L 17, 65°05,0'N, 22°37,3'E, depth 15 metres. Sand with some coarser material of Archean rock.

Sample L 18, 65°02,0'N, 21°47,3'E, depth 31 metres. Twelve Archean rock cobbles.

Sample L 19, 64°59,5'N, 22°03,0'E, depth 30—40 metres. No sample obtained.

Sample L 20, 64°56,0'N, 22°26,0'E, depth 66 metres. Clay and limonite.

Sample L 21, 64°52,5'N, 22°48,0'E, depth 72 metres. No sample obtained.

Sample L 22, 64°49,3'N, 23°10,0'E, depth 74 metres. Limonite.

Sample L 23, 64°46,0'N, 23°33,0'E, depth 72 metres. Clay.

Sample L 24, 64°44,0'N, 23°42,0'E, depth 43 metres. Clay and limonite. From the clay 14 grains were separated, two of these were sandstone.

Sample L 25, 64°43,0'N, 23°55,0'E, depth 28 metres. A score of Archean rock pebbles.

Sample L 26, 64°40,3'N, 24°09,5'E, depth 25 metres. Clay.

Sample L 27, 64°51,4'N, 24°16,5'E, depth 16 metres. Fine sand.

Sample L 28, 64°56,0′N, 24°20,0′E, depth 20 metres. Clay and fine sand.

Sample L 29, 65°06,2′N, 23°59,0′E, depth 20 metres. Gravel. From a random sample two sandstone grains were found.

Sample L 30, 65°01,0′N, 23°39,0′E, depth 68 metres. Clay.

Sample L 31, 64°56,0′N, 23°19,0′E, depth 101 metres. Clay.

Sample L 32, 64°51,0′N, 22°59,5′E, depth 79 metres. Clay and limonite.

Sample L 33, 64°46,3′N, 22°40,0′E, depth 92 metres. Clay.

Sample L 34, 64°42,0′N, 22°20,3′E, depth not determined. Fine sand.

Sample L 35, 64°36,0′N, 22°01,0′E, depth 102 metres. Mud.

Sample L 36, 64°30,5′N, 21°41,2′E, depth 38 metres. Clay and limonite mixed with rock material. The 8—16 mm size fraction weighed 164 gr and gave the following division:

Archean rock	93 %
Sandstone	7 »

The sandstone was of the hard, red type.

Sample L 37, 64°28,3′N, 21°52,0′E, depth 80 metres. Limonite.

Sample L 38, 64°20,4′N, 22°07,0′E, depth 102 metres. Clay.

Sample L 39, 64°13,0′N, 22°21,0′E, depth 88 metres. Clay.

Sample L 40, 64°03,3′N, 22°39,0′E, depth 48 metres. Clay and fine sand including a small amount of rock material among which one sandstone grain was found.

Sample L 41, 63°59,0′N, 22°32,0′E, depth 32 metres. Fine sand including a few bigger grains of Archean rock composition.

Sample L 42, 63°54,3′N, 22°21,0′E, depth 38 metres. Fine sand.

Sample L 43, 63°48,1′N, 22°08,0′E, depth 29 metres. Fine sand including a few bigger grains of Archean rock.

Sample L 44, 63°39,0′N, 21°47,0′E, depth 38 metres. Fine sand.

Sample L 45, 63°33,4′N, 21°27,0′E, depth 45 metres. Fine sand and clay.

Sample L 46, 63°33,0′N, 21°24,0′E, depth 37 metres. Clay, sand and gravel. Among the gravel one sandstone grain was found.

Sample L 47, 63°28,3′N, 21°13,3′E, depth 25 metres. Fine sand.

Sample M 1, 64°45,3′N, 24°06,0′E, depth 26 metres. Fine sand including two pebbles the size of a lump of sugar, one sandstone and one garnet-rich gneiss.

Sample M 2, 64°51,3′N, 23°46,0′E, depth 36 metres. The sample was composed of four pebbles the size of an egg, two of which were sandstone.

Sample M 3, 64°55,0′N, 23°43,0′E, depth 45 metres. Clay.

Sample M 4, 64°56,1′N, 23°40,2′E, depth 45 metres. Fine sand from which a small fraction of coarser material could be separated. This contained 5 per cent sandstone.

Sample M 5, 64°59,2′N, 23°35,3′E, depth 70 metres. Clay, including a small amount of gravel and a sandstone pebble the size of a plum. The gravel contained 3 per cent sandstone.

Sample M 6, 64°57,1′N, 23°36,0′E, depth 66 metres. Clay.

Sample M 7, 64°46,0′N, 23°18,0′E, depth 62 metres. Clay.

Sample M 8, 64°42,4′N, 23°18,3′E, depth 67 metres. Fine sand.

Sample M 9, 64°38,4′N, 23°31,0′E, depth 72 metres. Mud.

Sample M 10, 64°36,2′N, 23°29,0′E, depth 67 metres. Fine sand.

Sample M 11, 64°34,4′N, 23°42,3′E, depth 25 metres. Sand. One per cent of the coarser grains were sandstone.

Sample M 12, 64°33,4′N, 23°48,3′E, depth 21 metres. Sand.

Sample W 1, 64°40,4′N, 23°48,0′E, depth 32—45 metres. Apparently due to the dredge used for the sampling, very little fine material was caught. The sample obtained weighed about 6 kg and consisted of coarse gravel, pebbles and one (sandstone) boulder the size of a coconut. The pebble size material was composed solely of sandstone. A size fraction of 0.8—3.2 mm was separated. It weighed 1.640 gr and gave the following qualitative division:

Archean rock	13 %	
Sandstone	85 »	87 %
Shale	2 »	

The sandstone presented a great variety of rock types. Fine-grained, dark brick-red sandstone mostly in the shape of slabs appeared in abundance. The shale included both dark red and light grey types.

Sample W 2, 64°39,6′N, 23°45,4′E, depth 34—42 metres. All the conditions were the same as with the previous sample. The 0.8—3.2 mm size fraction weighed 528 gr and gave the following qualitative division:

Archean rock	2 %	
Sandstone	97 »	98 %
Shale	1 »	

With the exception of the last two bottom samples (W 1 and W 2), all the samples were taken with the van Veen type marine-grab. Samples W 1 and W 2 were obtained with a modified dredge and as they proved to be excellent as far as the quantity of the material was concerned, the possible superiority of the instrument for this purpose seems worth serious consideration.

SHORE OBSERVATIONS

As the glacial drift transportation has been to the southeast, the material found on the Finnish coast may yield information on the rock quality of the sea bottom. The author has examined, partly at random, the shore from Kemi to Kokkola, and most of the open sea islands in front of the Finnish coast. The conditions have in general been satisfactory for pebble observation. Places unfavourable for study have been the sands, cliffs and the flat shore meadows.

As anticipated, the major part of the drift is composed of material which can be easily recognized as belonging to Archean bedrock. The mixture of many different rock qualities which characterizes the basement complex on the mainland is mirrored also in the drift material. Broadly speaking, it indicates the similarity of the bedrock in the sea bottom and on the mainland. However, among the drift some easily defined rock types, e.g. dolomites, have been considered worth reporting since they may prove the maritime extension of certain mainland rock occurrences.

In practice the work developed mainly into a research of feebly metamorphosed »strange» rock types which might indicate the existence of hitherto unknown and unanticipated rock deposits in the sea bottom. In most cases one had to be satisfied only with an assumption of the existence of a certain rock quality in the sea area while leaving its further localization open.

The quality in terms of the degree of metamorphism proved highly significant and was finally adopted as the criterion in classifying the samples into known, as well as unknown, rock groups. Thus, e.g. among the sandstone, the very hard as well as the quartzitic varieties were generally considered Karelian while the feebly metamorphosed varieties were taken to be younger and were further classified according to the characteristic features observed in the sandstone itself and the petrographical resemblance to known rock types. Pebble counts were executed only when certain rock types existed in a quantity likely to contribute to the localization of their provenance.

For geological observation two localities stand out as exceptionally revealing: the Hailuoto island, and the shore to the north of Piehinki about 10 km to the south of Raahe. Hailuoto stands out as a locality of special interest owing to the results of the executed deep drillings. Both localities will be separately discussed in the following.

The Hailuoto island

Pebble observations

The Hailuoto island is composed entirely of sand which includes stones of varying sizes. Some block and boulder concentrations observed mainly on the beaches may be considered results of wave and/or ice activity. The colour of the sand is

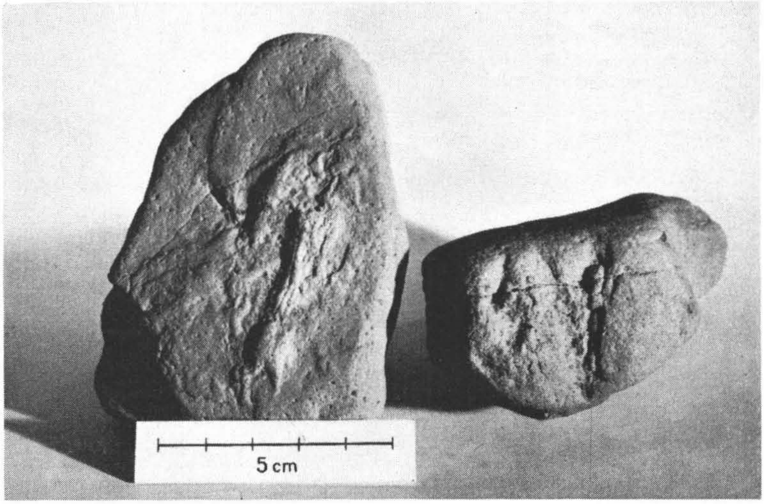

FIG. 8. Trail (cobble on left) and tube in fine-grained sandstone, Hailuoto. Photo E. Halme.

yellowish brown. Sandstone pebbles are ubiquitous comprising 2—3 % of the material selected for the count. Sandstone of cobble size appears to be rare and no boulders composed of sandstone have been found. The sandstone is generally of a medium grain size, grey, light grey, white, violet or reddish in colour. As to its mechanical strength, the coloured types are hard, often classifiable as quartzites. A great part of the hard sandstone, and especially the quartzitic types, can be classified as Karelian.

The sandy shore, about 300 metres in length, on the eastern side of Keskiniemi cape on the NW coast of Hailuoto, has proved the most rewarding place for finds of a certain sandstone type. A pebble count revealed an amount of 6 % of this sandstone on the shore. The sandstone is light grey in colour, well consolidated, even-grained and of fine to medium grain size. The rock is composed predominantly of quartz, feldspar and mica are accessory components. Oval shaped green grains resembling glauconite, as well as turmalite crystals, occur exceptionally.

Some samples of this type contain tubes, about 3 mm in diameter, sometimes at right angles, sometimes in an inclined position to the stratification. In one case the inclined tube was U-shaped the arms being some 2 cm apart. On the side of one flat sample there is a relief, 4 cm long and 0.5 cm broad, resembling the mold of a trail. Fig. 8. The above-mentioned shapes, though not comparable in their degree of perfectness, are very similar to those met with in late Precambrian and early Paleozoic sandstone, which have been interpreted in various instances as worm burrows and trails.

It should be mentioned that, except on Hailuoto proper and on the mainland shore east of Hailuoto, this type of sandstone has not been met with elsewhere in the coastal region.

No boulders, cobbles or even pebbles of any of the sedimentary rocks that have been verified by drilling as forming the bedrock of Hailuoto, have been found in the drift on the island. This may be due to the great friability of the rock in the succession. It seems possible, however, that the proper sand in Hailuoto as well as the sand which extensively covers the sea bottom especially west of the island, may well have its origin in the weakly-consolidated sandstone.

Seismic survey

Since no information regarding the bedrock at Hailuoto was available, the Geological Survey decided to carry out an investigation of the island starting with seismic measurements which were later followed by deep drillings.

The seismic measurements were carried out at 13 points in different parts of the island, Fig. 9. The method used was the so-called reverse »end-to-end» sounding where the geophone line, 110 metres in length, was stable and the explosions were performed at varying distances (from 1 to 4 000 metres) from both ends of the geophone line. The results obtained yielded the following five velocity groups which are also graphically shown in Fig. 9.

1	velocity	1 500—1 795	m/sec.
2	»	2 320—2 650	»
3	»	2 965—3 200	»
4	»	3 900—4 100	»
5	»	5 000—6 000	»

The first velocity related to the loose sand cap, the thickness of which varied between 22 and 67 metres, with an average of 44 metres. The depths obtained by drillings have been in accordance with those obtained seismically.

The second velocity appeared in all instances (except one, SB) below the first one and indicated a layer varying from some metres to 180 metres in thickness. This was interpreted as semisolid sediment.

The third velocity was assumed to be due to a somewhat more solid sediment of the same stratum as the second. The geological interpretation of the second and the third velocities has remained somewhat inconclusive, however. In one case, R 1-S 5, where the drill penetrated both the second and the third velocity layers, the two did not show any differences in rock qualities. On the other hand, in another case, R 2-S 2, where two different sediments were penetrated by drilling, they only expressed themselves seismically by one, the second, velocity. Together, the second and third velocities are assumed to indicate sediments which, according to obtained

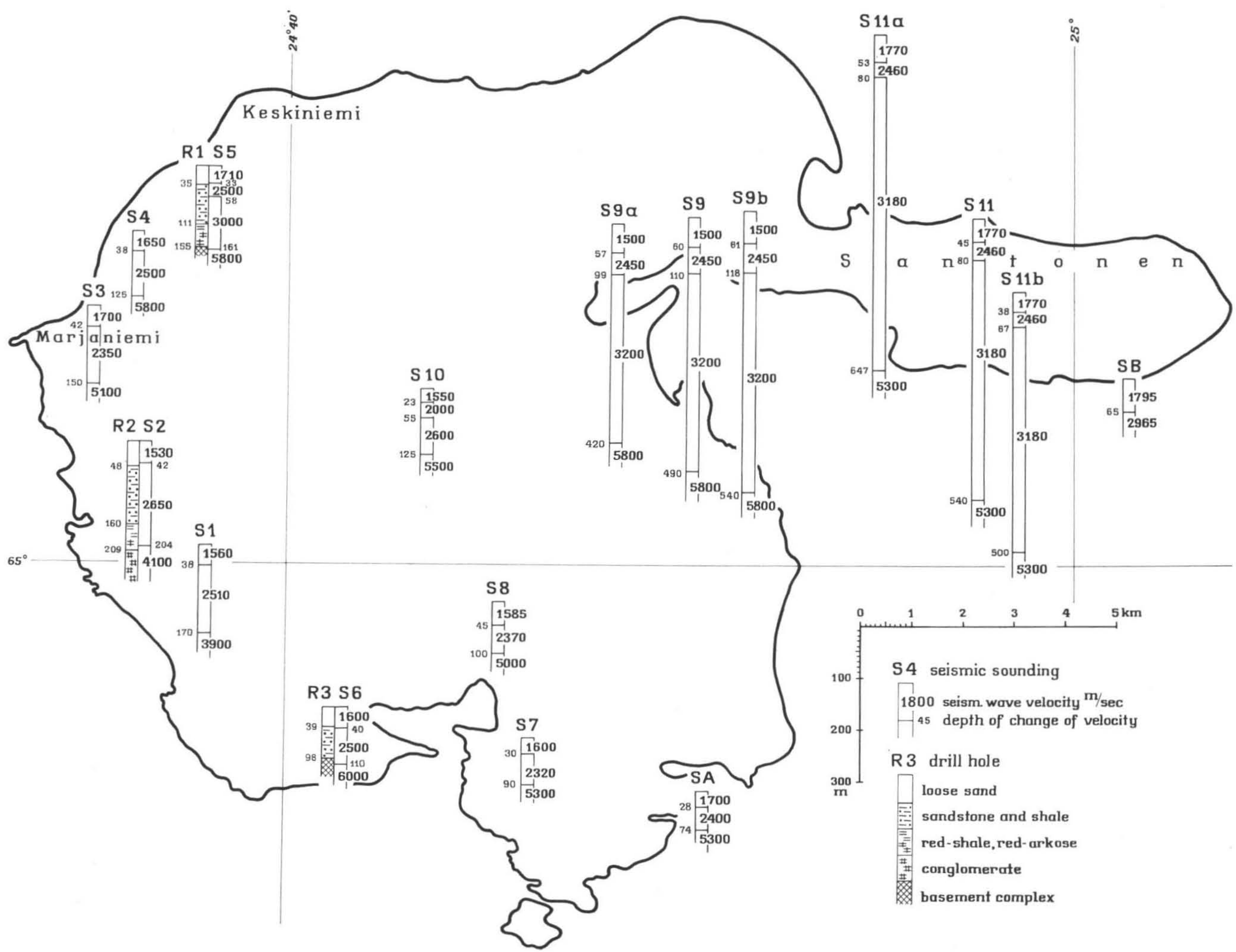

FIG. 9. Graphic presentation of the seismic measurements connected with deep drillings at Hailuoto

drilling samples, may be composed of sandstone and shale. It should be pointed out that, except in one case (seismic measurement S 5), the layer indicated by the third velocity is entirely lacking in the western and central parts of the island, whereas in the eastern part, at Santonen, it appears to form a mighty layer up to 560 metres in thickness.

The fourth velocity is met with only on two occasions (S 1, S 2) which lie next to each other in the southwestern part of the island. In the course of the seismic measuring the velocity was interpreted as indicating a basement complex, and the work was in consequence discontinued. The drilling showed the velocity to be due to a conglomerate, however.

The fifth velocity, as well as the fourth, was supposed to indicate the basement complex. The matter was confirmed in two cases by drillings, holes R 1 and R 3.

In addition to the above relatively easily defined velocity groups, a velocity figure of 2 000 m/sec. was established in one single instance, S 10. A geological interpretation of this velocity has not been attempted, however.

Deep drilling

The location of the drill holes was based on results obtained from the seismic survey. The principal idea was to penetrate as many different seismically determined layers as possible and to reach the basement complex below. On the other hand, due to the working capacity of the equipment, the maximum drilling depth had to be fixed at 250—300 metres. Accordingly, all three holes were placed on the western side of the island, viz. hole R 1 on the site of the seismic measurement S 5 on the NW coast of the island, hole R 2 on the S 2 in the western part, and hole R 3 on the S 6 close to the southern shore of the island, Fig. 9. All holes were drilled vertically.

The stratigraphy of the drill holes is shown in Fig. 10. The most notable feature of the drill series is the great variation of the profiles in all the holes, considering the rather short distance of less than 10 km. This applies specially to the lowermost parts of the strata. Thus in hole R 3 there is sandstone on top of the crystalline basement, whereas in hole R 2 the bottommost rock is conglomerate which does not exist elsewhere. There appears to be no connection in the stratigraphic succession in other details either, although the rock types in the different sections are as such well comparable.

Considering the penetrated sedimentary stratum as a whole, a division into two parts, the upper and the lower, has been considered advisable.[1] The most striking visual feature is the great difference in colour. The rock components of the upper part are in general paler and »non-coloured» whereas those of the lower

[1] The petrographic description has here been restricted to a scale suitable to the present regional study. A comprehensive study of the so-called Muhos formation including its isolated manifestations, still remains to be done.

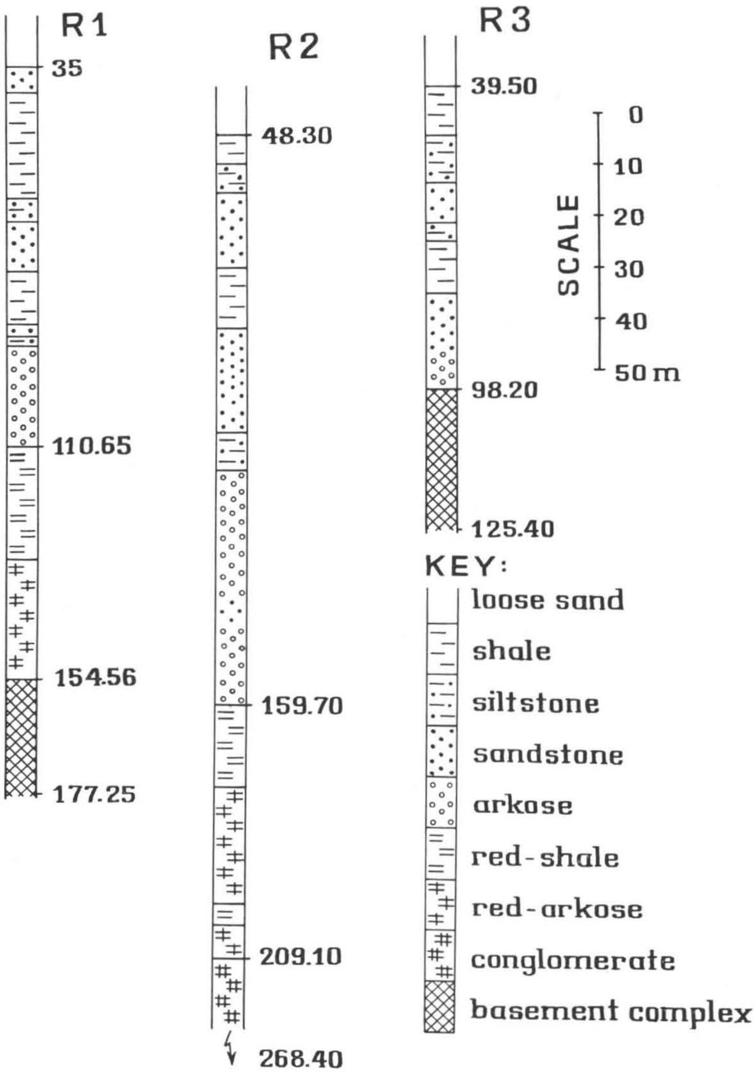

FIG. 10. Profiles showing the stratigraphy of the cores of deep drillings at Hailuoto. For location see Fig. 9.

part display, irrespective of their petrographic composition, a strong red to buff colouring throughout. The two parts differ from each other also in composition. The upper part includes well-assorted and homogeneous sedimentary rock types while the rocks of the lower part show throughout a poorer sorting and a greater heterogeneousness. Judging by X-ray determinations made of the comparative rock types of the different parts, those of the lower part reveal a slightly greater content

FIG. 11. Typical rock samples from the sedimentary succession in Hailuoto. From the left: shale, siltstone (mixed with shaly matter), sandstone, arkose, red-shale (showing green shale spots), red-arkose (showing red-shale interlayer), conglomerate, rock pebbles detached from the conglomerate. Photo E. Halme.

of iron. In order to distinguish the different varieties the prefix »red» has been used to define the rock types of the lower part. The conglomerate which occurs bottommost in one drill hole (R 2) belongs to the rocks of the lower part. Fig. 11.

Pale pink and light green are typical colours of the sandstone in the upper part. The pinkish colour is caused by a light reddish tinge in the quartz grains. Stratification, which is not an outstanding feature of this sandstone, is, when it occurs, merely caused by indistincly marked beds of a more coarse-grained sandstone variety, and by occasional narrow shale and siltstone interlayers. Microscopic examination of a representative sample shows that the sandstone is even-grained, the medium grain size being 0.2—0.4 mm in diameter. The grains are sub-rounded. The majority of the grains are composed of quartz, the amount of feldspar grains, which form the other essential component, is less than ten percent. Grains composed of very fine-grained quartzite, as well as mica flakes, occur as accessories. Due to the ready disintegration of the sandstone, the composition of the cement has only seldom been observable in microscopic sections. It seems to be composed of very fine-grained mass consisting of light, sharp-edged particles.

Towards the bottom the sandstone gradually alters into a more coarse-grained and more feldspar-bearing type. The final stage of this rock is a coarse arkose. The colour of the arkose varies from pink to brownish. The pinkish colour is due to the yellowish red feldspar grains. The brown colour appears as spots in the less-coloured base and it is clearly a post-depositional feature caused by iron. The stratification is caused by the small variation in the grain size and by occasional interlayers composed of shale. The medium grain size of an average type of arkose is 1—3 mm in diameter. The grains are semi-rounded. They are composed essentially of quartz and feldspar, plagioclase as well as potassium feldspar are present. The average ratio between the amounts of feldspar and quartz is in the order of 1:2. A minor part of the grains consists of rock derivatives composed of fine-grained sediments. The cement consists of fine-grained, angular material and is apparently quartz for the most part.

In some cases the grain size of the bulk of the arkose may be as much as 5—10 mm in diameter. This conglomeratic variety appears, however, within the ordinary arkose and its thickness remains in the order of a few decimetres. In a couple of instances loose quartz pebbles occur among the disintegrated drilling material. The pebbles are from some millimetres to three centimetres in diameter, well-rounded, milky-white and polished on the surface. The form of some pebbles suggests wind action.

Siltstone does not form independent layers of any greater magnitude, but occurs intimately associated with thin layers composed of shaly matter. The associations may form beds of considerable thickness, which may sometimes exceed ten metres. The position of these beds seems to be in between the sandstone and the shale. With one exception the siltstone-bearing beds are always above the sandstone and below the shale stratum, but in the exceptional case, the succession is reversed.

In addition to well-marked stratification, cross-bedding is a frequent feature. Fig. 11. The microscope reveals the siltstone as being composed of angular grains embedded in a dense mass.

It has been a difficult task to draw a distinction between the siltstone and the shale. In many cases when the rock has been classified as shale a closer examination has revealed a varying content of fine sand. Shale composed entirely of cryptocrystalline matter occurs in abundance, however. Compared to the sandstone the shale is more solid, disintegration during drilling has been noted only occasionally. Grey, green and purple-red are the dominating colours. The margin between the different colours can be sharp and may not accord with the stratification. The stratification is well visible, the thickness of the individual layers varies from less than one millimetre to a couple of centimetres. The stratification is in the main horizontal, in some cases an inclination up to 30 degrees may occur, however. The shale splits readily into plates; the hard varieties often have conchoidal fracture. Diminutive pyrite crystals may occur sparsely. An X-ray diffraction diagram of a representative shale shows strong kaolin and relatively weak quartz and feldspar patterns. Megascopic research has revealed no features that could be suspected of being biogenic in origin.

According to the dominating grain size, the rock of the lower part divides into three varieties, viz. red-shale, red-arkose and conglomerate. In terms of the entire series, the three types appear separated, the conglomerate lowermost and the red-shale uppermost in the succession. In a more minute examination, the different varieties may, however, turn out to be intermixed — with the exception that the conglomerate is not met with in the finer varieties.

Red-shale forms the basement of the arkosic sandstone of the upper part in the drill core profiles of the holes R 1 and R 2. The contact between the sandstone and the red-shale is not readily distinguishable owing to the disintegration of the drill core. No intermixing of the two rocks has been observed in the contact zone, however. The red-shale is reddish brown in colour. Structural features pointing to stratification are caused by layers showing an increasing denseness of coarser grains and by narrow interlayers composed of »purer» shale material. Small mica flakes, feldspar and quartz particles can be distinguished megascopically. Microscopic study reveals that angular and sharp-edged quartz, feldspar and mica grains are embedded in a fine-grained and sub-crystalline groundmass. An X-ray examination shows that the groundmass is composed of minerals which, in a decreasing quantitative order, rank as follows: quartz, potash-feldspar, kaoline, mica, hematite, plagioclase.

Red-arkose occurs below the red-shale. The boundary is, however, not well marked and intermixing of the two rock varieties occurs frequently. Stratification is mostly caused by layers of different grain density. Interlayers completely devoid of grains are also common. The average grain size of the red-arkose is from 2 to 6 mm in diameter. The form of the grains is sub-angular to sub-rounded. The grains are composed mainly of quartz and feldspar, although rock fragments, mostly of

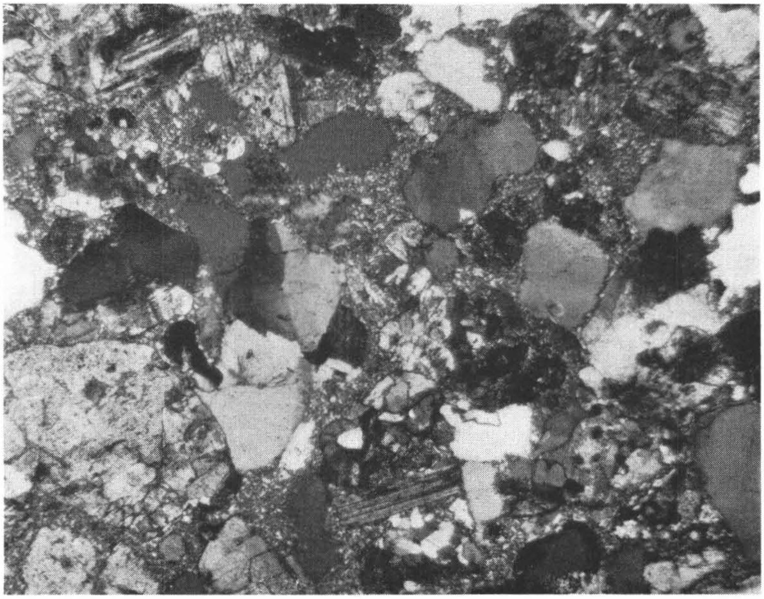

FIG. 12. Microscopic photograph of red-arkose. 32 x. Photo E. Halme.

fine-grained sedimentary rock, are frequently met with, Fig. 12. The larger grains, which may measure up to 10 mm in diameter, are generally rock fragments. The groundmass looks like red-shale. An X-ray determination reveals, however, that it is composed essentially of quartz, plagioclase and potash-feldspar. Hematite enters into the picture, too, but no kaoline seems to be present. Occasionally, the intergranular space is composed of carbonate and the filling material in the cracks of the grains may also turn out to be carbonate.

Conglomerate occurs only in a section of the drill hole R 2, where it appears below the red-arkose. The rock is characterized by balls greatly varying in size. The biggest ones (penetrated right through) have been up to 15 cm in diameter. They are semirounded to rounded in form. Fig. 11. The surface of the balls is generally smooth, although in some cases it may be either ragged or well-polished. Scratches which could be interpreted as glacial striations have not been observed; the present definition may not, however, be conclusive owing to the relative scantiness of the observation material. The majority of the balls consists of darkish, fine-grained quartzite bearing a resemblance to the corresponding Karelian rock type. The second group is formed by medium-grained slightly foliated granite. As additional rocks porphyritic granite and gneiss in a state of decomposition may be listed. None of these are represented in the basement complex of the area (see next paragraph). The intermass is a mixture of red-arkose and material similar to red-shale. The

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mechanical strength of the conglomerate is weak, and in fact the ready dislocation of the balls in the course of the drilling finally brought the operation to a halt. Consequently, some features, e.g. possible stratification, could not be investigated.

The basement complex was reached in two drill holes, R 1 and R 3. The drill core of the hole R 1, 23 metres in length, consisted of the following rock varieties: granitoid medium-grained feldspar-mica rock, pegmatitic granite, fine-grained granite. The drill core (length 27 metres) of the hole R 3 consisted of metamorphic rock suggesting an earlier composition of amphibolite. Closer to the bottom the structure of the rock gradually alters into that of augen-gneiss, the »augen» probably representing original feldspar phenocrysts. The metabasite is cut by narrow granitic dykes. The dip of the bedrock is steep.

The upper part of the basement complex shows slight alteration due to weathering.

The shore at Piehinki

The pebble counts executed by Okko (1949) reveal, as already stated (p. 6), a sandstone maximum on the coastal strip between Raahe and Kalajoki with its centre in the shore area at Pyhäjoki. Within this area the present author has found a limited shore strip which, in type variation and amount of sandstone, has served exceptionally well the purpose of this work. The strip stretches about 300 metres along the northern coast of a small (Lohikari) peninsula to the north of Piehinki. In addition to the large quantities of varying types of proper sandstone, most of the mineralized sandstone described below has been found in this locality. The explanation for the preservation of the rather friable sandstone is presumably to be found in the flatness of the place, which may have levelled down the destructive force of the waves. This assumption is supported by the results of the pebble counts, starting from the most shallow and sheltered part of the beach and advancing up to the tip of the cape facing the open sea. The counts, four in number, placed at intervals of about 300 metres, have given the following figures, which include, besides sandstone, also mineralized sandstone: first count, 6.0 %; second count, 3.6 %; third count, 1.9 %; fourth count 0.8 %. The amount of mineralized sandstone is about one-tenth of the total.

The destructive force of the waves may also furnish an explanation to the fact that no sandstone has been found in Maakalla and Ulkokalla which are small open-water gravel banks about 10 nautical miles west from Kalajoki.

Sandstone cobbles

The sandstone varies greatly in its quality. Light red and grey seem to be the prevailing colours, although rusty and pinkish shades of red, greenish, yellowish and violet types are also frequent. Snow-white and all-yellow colours are rare. The

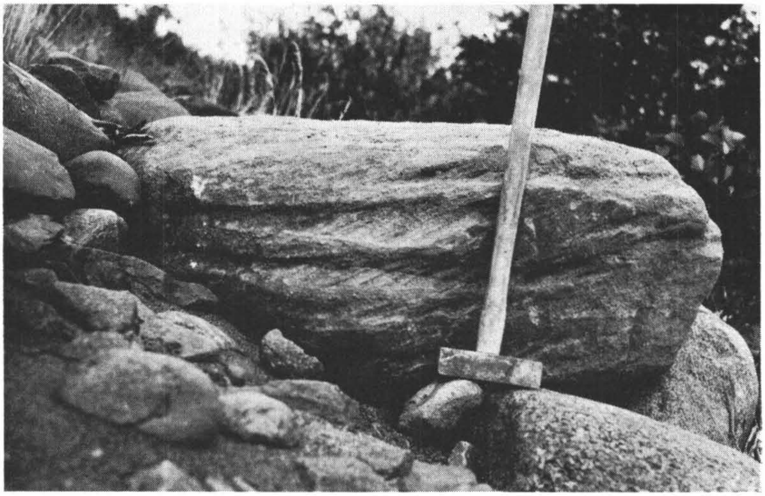

Fig. 13. Sandstone boulder on the shore of Piehinki. Length of hammer 70 cm.

average size is that of an apple, although boulders more than one metre in diameter have been found, Fig. 13. The mechanical strength varies from that of quartzite to something easily crushed between fingers. Even-grained sandstone of medium grain size is the most common type. The difference in grain size may, however, range from that of a pelite to that of rock including fragments up to 6 cm in diameter.

Stratification is a regularly occurring feature in the sandstone samples. It is mostly caused by an alternation of layers of different grain size; in the finer grained varieties it may be due to some variation in the qualitative composition of the layers. Stratification that indicates negative sedimentation has been observed in a couple of samples. It is presumably due to the wind removing the fine sand material whereby a coherent stratum composed of cobble-size stones has remained, »armoured desert» (»gepanzerte Gewüste», Walther, 1900). Ideal »drei- and vierkanter» are plentiful in the loose beach gravel or fixed on to the boulders, Fig. 14. Cross-bedding and ripple marks have been observed in a few instances — a distinction between aqueous and eolian agents has not been possible. In this respect the sandstone boulders of the Bothnian Bay coast seem to differ considerably from those of the coast of the Bothnian Sea where slabs showing well preserved ripple marks are quite frequent.

Sandstone with carbonate matrix is common among the finds. General features of this rock are its grey colour with a possible tinge of green or red, and an even-grained and rather fine grain size. The grains are predominantly of quartz embedded in carbonate composed of crystals bigger than the grains. There is, however, a type

FIG. 14. Ventifacts, separate and paving a sandstone boulder. Photo E. Halme.

of sandstone that differs from the average in its dark violet-brown colour. In grain composition it does not differ from the average type except that each grain is covered with a thickish limonite crust. The siderite cement is relatively finely crystallized the inter-crystalline limits being distinctly marked by limonite. Judging by the texture the rock would seem to have been formed in circumstances similar to those producing caliche in arid or semiarid conditions by evaporation.

Off-white slabs having an average size of a cigarette packet and composed of dense matrix with round quartz grains ranged in layers suggesting stratification occurred frequently. The microscope revealed the rock as almost monomict, composed of quartz which, however, showed two differing appearances, i.e. well rounded quartz spheroclasts and sharp-edged diminutive quartz grains as matrix to the former. A couple of small, almond-shaped, pleochroic, greenish grains suggesting glauconite were noted.

As an exceptional type may be considered the coarse-grained variety which is composed of round polished quartz grains the size of a pea, embedded in a more fine-grained matrix.

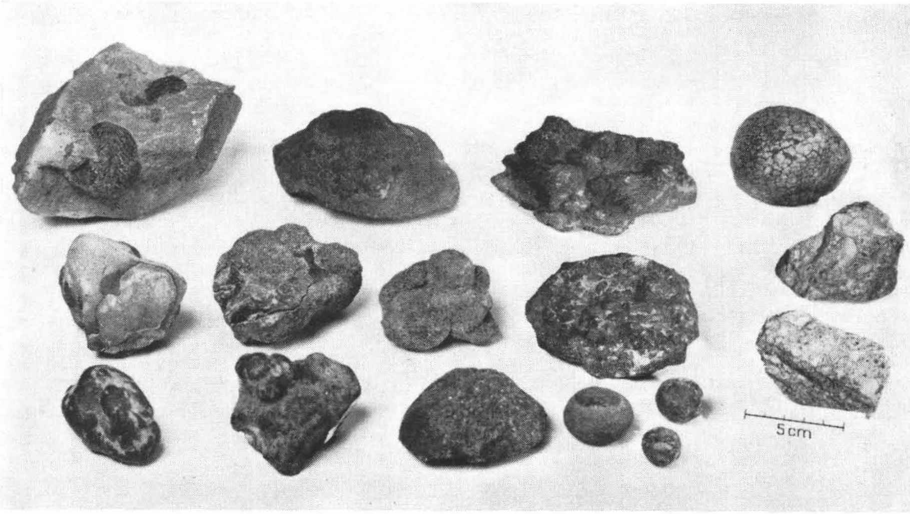

FIG. 15. Pyrite concretions from the shore of Piehinki. On the left, first samples of upper and middle row show concretions still embedded in sandstone mother-rock. Photo E. Halme.

Mineralized sandstone

Pyrite concretions

The shore strip at Piehinki has yielded a rewarding number of pyrite concretions. In order to obtain a representative collection of the different varieties, the author has assembled about a hundred samples.

The concretions can be divided into single and compound concretions, and, further, into symmetric and asymmetric ones. The sphere may be regarded as the basic shape, specimens of which (including some varieties, e.g. flattened, elongated, egg-shaped etc.) are frequent and have also been met with embedded in boulders composed of even-grained sandstone, Fig. 15. The size of the spherical concretions can vary between that of a pea and an apple. The compound shapes of the single globular concretions could be described as kidney- or cluster-shaped. These concretions can be flattened or of equal dimensions. The protruding semi-spheres are distributed all around the concretions. The asymmetric varieties are the half-globes as well as the botryoidal concretions with one flattened side. Presumably the asymmetry, and particularly the flattened side, is due to a dividing plane between two different substances. This is indicated by the flattened side often showing molds or remnants of much coarser material than the grain material the concretion itself is composed of.

The siliceous components of the pyrite concretions show the same multitude of variation as the sandstone without pyrite. The majority of the concretions occur, however, with quartzose medium- and even-grained sandstone types. This has been so in all the instances where pyrite concretions have been found embedded in sandstone boulders. There are, however, a few examples where the siliceous component seems to be totally lacking. In these cases the spherical structure is observable. The inner part often consists of coarse crystals while the centre is hollow.

The pyrite cement in the concretions seems entirely to have replaced the cement of the original sandstone. It appears often in large crystals which may include quite a number of sand grains. In cases where the grains are structurally deformed, the pyrite may have penetrated deep into the openings.

Many of the blocks of sandstone with pyrite cement do not appear in the form of concretions. Besides the possibility of their being fragments of broken, unusually large concretions, they may be derived from a deposit which has become mineralized to a large extent.

Marcasite

Marcasite has not been observed in connection with pyrite in cases where this has been the only ore mineral in the sandstone. When other ore minerals are included, marcasite may also enter into the picture as will be seen below.

Chalcopyrite

Chalcopyrite may be considered a relatively frequent companion to pyrite in the concretions and in the pyrite-bearing sandstone fragments. It is not restricted to any specific type of host rock. Chalcopyrite appears as aggregates greatly varying in shape. In the marginal parts of the aggregates the chalcopyrite has tended to push itself between the pyrite and the sand grains forming a thin film around the latter. The chalcopyrite may include small round pyrite spots which may contain marcasite as lamellae.

Sphalerite and galena

Sandstone blocks containing sphalerite and galena have never been observed in the form of concretions. Instead they appear in broken-off slabs, the ore minerals showing varying concentration according to the stratification. The host rock is unique in its quality: brownish, even-grained, medium-coarse sandstone with quartz as the main grain component. Both ore minerals appear as cement of the sandstone together with pyrite and in addition to siliceous and calcium carbonate cement. The crystallization succession of sphalerite and galena is not clear, both seem to have developed later than the calcite. When galena borders unto calcite there may appear a thin rim most probably composed of cerussite. The sphalerite possesses a strong brown innenreflex. The pyrite, which may appear as inclusions in the two ore minerals, may show intergrowth of marcasite. In all observed cases the sphalerite has surpassed

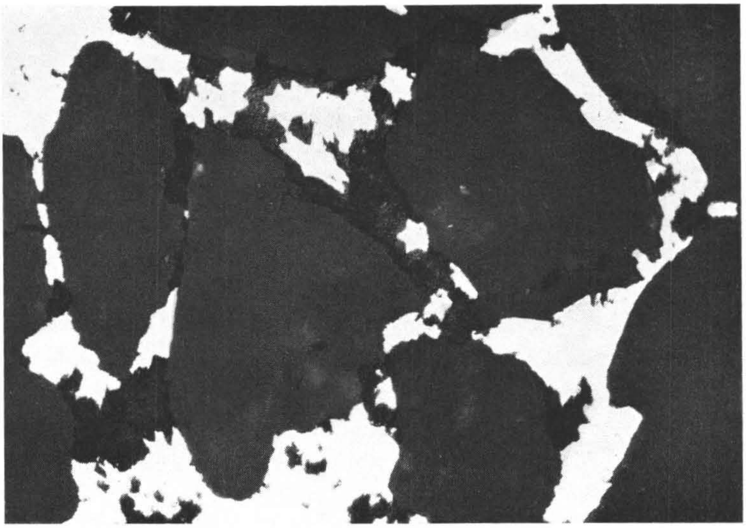

FIG. 16. Sandstone cemented by safflorite (white) and dolomite. 60 x. Photo E. Halme.

the galena in quantity. Analyses of two samples, admittedly among the richest ones, gave the following results:

	I	II
Zn	8.8 %	18.5 %
Pb	7.15 »	3.4 »
Cu	0.0 »	not determined

Safflorite ($CoAs_2$)

In a greenish grey, medium-grained, phenoclastic sandstone with carbonate as the predominant cement, there appear ragged, silver-grey aggregates some 1.5 cm in diameter. The aggregates may or may not be surrounded by a yellowish sphere about 0.5 cm in thickness and resembling pleochroic haloes. Associated with the haloes a black, loose, ochre-like stuff may occur in the diminutive crags and hollows of the aggregates.

Microscopic study reveals that the aggregates are composed of only safflorite or safflorite accompanied by other minerals.

In the first case the safflorite forms the only cement between the sand grains. Along the borders of the aggregates and outside, in the dolomite cement, the safflorite may appear as small isolated grains usually as crystal trillings often exhibiting clearly formed star-shaped figures, Fig. 16. The safflorite was separated by means of heavy

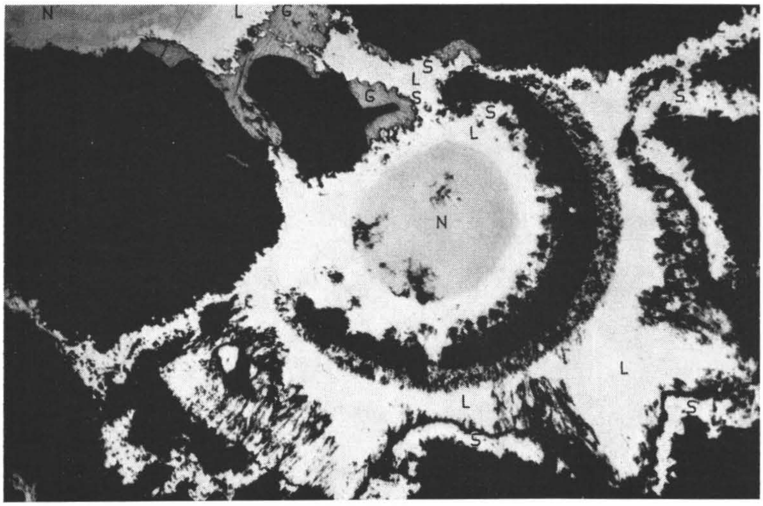

FIG. 17. Sandstone cemented by combined minerals: safflorite (S), niccolite (N), and löllingite (L). In addition galena (G). The crescent in the polished section is an open space. In the rock the space was filled with loose, black, ochre-like matter. Note the corrosion of the sand grains when in contact with safflorite. 60 x. Photo E. Halme.

liquids and analysed chemically. The trace elements were determined by semiquantitative spectrochemical analysis. The results are as follows:

Cu	2.55 %	Ni	0.01—0.1 %
Fe	14.58 »	Zn	0.05—0.5 »
Co	8.45 »	Ag	0.01—0.05 »
As	64.60 »	Bi	0.1 »
Sb	0.28 »	Pb	0.01—0.05 »
S	0.70 »		
SiO_2	5.75 »		
	96.91 %		

Although the analysis may not be reliable owing to the obvious impurity of the material, it indicates that the safflorite is a rather iron-rich variety.

In the second case the safflorite forms a sphere around the sand (quartz) grains. The surface of the grains is being corroded by the protruding safflorite crystal edges and individual crystals may also appear within the grains. The actual centre of the interstitial sandstone cement is composed of a mineral which in the microscope appears as slightly reddish, anisotropic, and shows in microanalytic examination, besides cobalt and arsenic, a strong nickel component. The characteristics of the mineral point to niccolite. Between the safflorite and the niccolite there is a circular

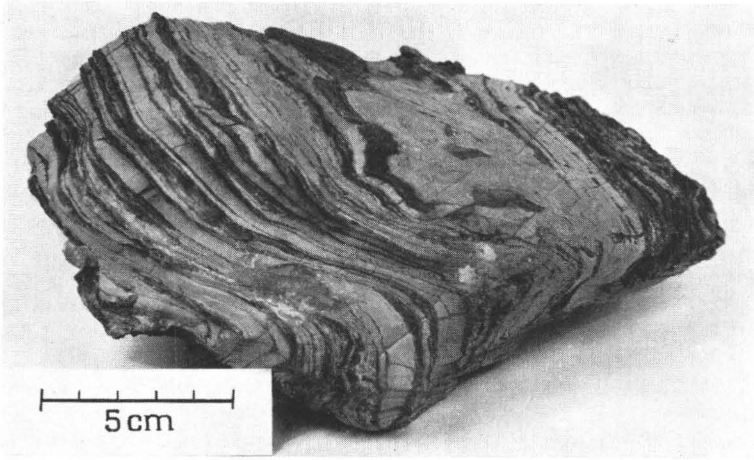

FIG. 18. Typical dolomite boulder from the Bothnian Bay shore.
Photo E. Halme.

sphere of löllingite, and löllingite may also form the larger outer area, Fig. 17. Pictures taken by the microanalysator also show somewhat ragged areas with a uranium-titanium-iron content. In addition there appear spots of galena and rutile.

The radioactivity of the halo-bearing safflorite samples determined with a counter was 24 impulses in 30 seconds, the base of the counter being 14 imp./30 sec.

Dolomite boulders

Leiviskä (1905) noted the existence of the dolomite boulders on the shore of the northern part of the Bothnian Bay coastal area and suggested that they may be derived from the Swedish side. The present author agrees with Leiviskä in the question of their distribution on the coast. Their main occurrence seems to be along the coast between Kemi and Raahe. Their distribution is rather regular, while their proportional amount in the drift is small, 2—3 % at most. In the pebble counts executed by Okko (1949) a small amount (about 1 %) of dolomite has also been noted in the south, in the Kalajoki area. The size of the boulders seldom exceeds that of a football, their form is variable. The boulders are mostly off-white or light yellow in colour. Stratification is a common feature and is often emphasized by interlayers protruding from the surface of the boulders. Folding may be intensely marked. Fig. 18.

Microscopic study reveals that the rock is fine-grained throughout, with interlayers which may be exceedingly fine-grained. Embedded in the carbonate there are aggregates composed of small quartz grains as well as of bigger, roundish quartz granules with ragged contours. The quartz displays a strong undulatory extinction.

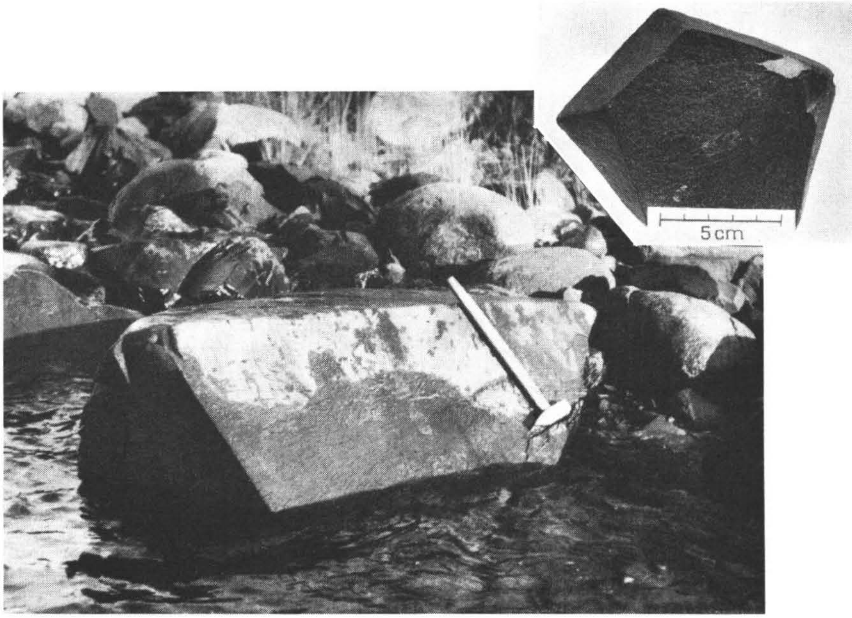

FIG. 19. Blocks indicating columnar shapes. Mutala, Saloinen.

The quartz tends to concentrate into strips parallel with the stratification. Small mica flakes and an opaque mineral, probably graphite, which forms thin streaks, occur as accessories. Chemical analysis reveals that the contents of MgO and CaO are 18.18 % and 26.04 %, respectively, the MgO—CaO ratio being consequently 0.69.

Judging by the descriptions of the dolomite occurrences both on the Finnish side and on the Swedish side (see p. 11) which are included in the Karelian supracrustal series, it seems that the dolomite boulders in question may be considered as belonging to the same Karelian series.

Blocks of extrusive rocks

Considerable amounts of loose blocks seemingly of volcanic origin have been noted along the coastal zone. For the most part they may be classified as Archean and, particularly when showing a good state of preservation of the original structural features, as Karelian. A slight increase in the number of the volcanic pebbles considered as Karelian is noted in the coastal area to the north of Pyhäjoki. The percentage remains in general quite low, less than 1 %, however.

At Mutala, some 8 km south of Raahe, about four fifths of the blocks lying on a shore strip several hundred metres long, are composed of the same rock quality, viz. black, fine-grained rock of intermediate composition. Single blocks frequently

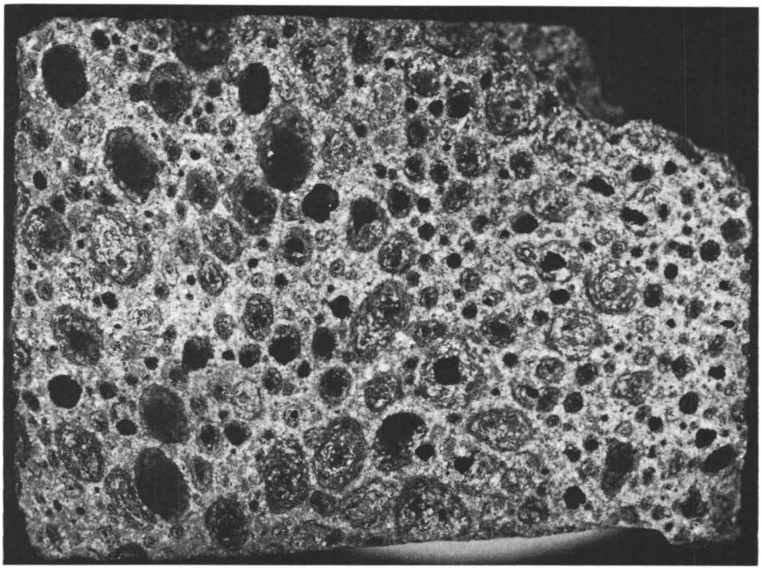

FIG. 20. Vesicular lava pebble. Nivala. Sawn surface. 4 x.
Photo E. Halme.

show columnar structures (Fig. 19) typical in many effusive rocks. The heavy concentration of the blocks into a narrow shore area undoubtedly points to a nearby provenance.

At Piehinki the author has found a number of pebbles which, owing to their exceptionally low metamorphism, may not be directly included among Archean rocks. They include tuffs, breccias and porphyries.

The archives of the Geological Survey of Finland contain a pebble of fresh-looking vesicular lava (Fig. 20) found during deep drilling in 1964 at Nivala, about 60 km SE from Kalajoki. It may be of interest that two similar lava pebbles were included among numerous samples sent, in the autumn of 1968, to the Survey by an amateur collector, who reported finding them on the shore near Kokkola. As several of the samples were typical of material used as ballast for ships arriving e.g. from the southern Baltic, the origin of the lava pebbles is still open.

Hematite-bearing blocks

The large amounts of hematite-bearing blocks which have been found within a broad zone extending from Haapajärvi up to the shore area south of Raahe, have been referred to in a previous chapter (p. 7). The experience of the present author accords with that of Oivanen (1960) particularly on the point that the quality of

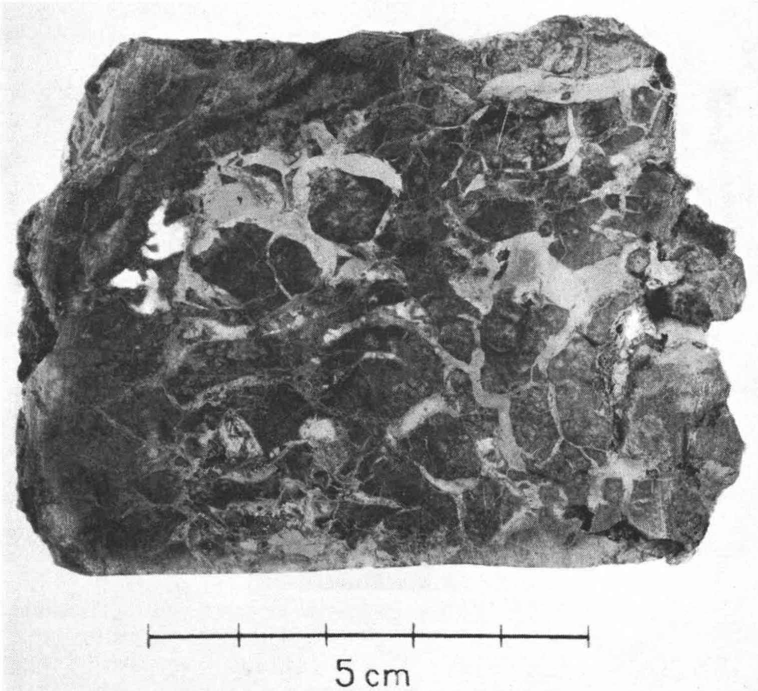

FIG. 21. Brecciated rock of chert composition invaded by secondary hematite and carbonate (white spots). Sawn surface. Photo E. Halme.

the host rock invaded by hematite varies greatly and that a majority of the boulders shows a considerable degree of degradation.

The southernmost place where the present author has found hematite-bearing pebbles is the sandy shore at Mutala in Saloinen. In general the hematite-bearing pebbles in the drift may be considered rare. Their occurrence seems to be concentrated to the area around Raahe.

In the author's collection there is a sample of an unusual type of rock which, since it has been invaded by secondary hematite, may be examined in this connection. The base of the rock is composed of green, fine-grained rock quality appearing as angular or subangular fragments surrounded by hematite, Fig. 21. In addition to the hematite, the inter-fragmental material consists, in part, of carbonate. A closer examination reveals that the fragments are composed solely of quartz appearing as diminutive angular grains. The cement is composed of silica with dense hematite pigment, and of crystalline calcitic carbonate.

If the rock is jasperated chert as the present author assumes, this may be looked upon as an indication of this rock quality being included in the Karelian rock series in the sea bottom — as is the case, in fact, on the mainland.

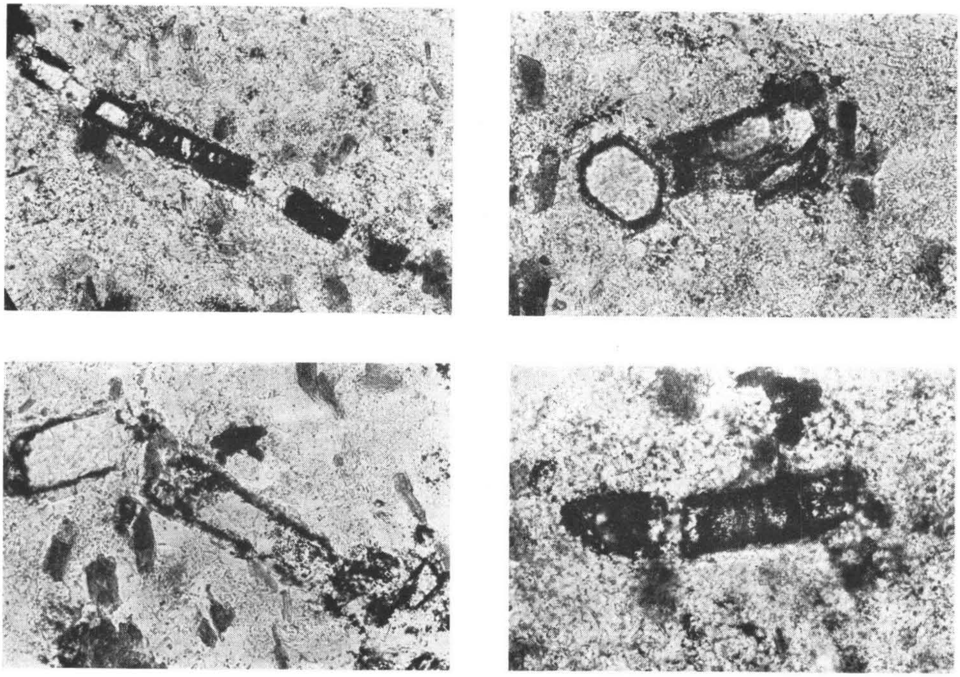

Fig. 22. Apatite crystals with graphite cover. The scale varies somewhat, the length of the object topmost on the left is about 1 mm. Photo E. Halme.

Individual pebble finds

Coal- and apatite-bearing phyllite

A single phyllite pebble found on the shore to the north of Pyhäjoki proved of interest. The phyllite is dark grey in colour, the only minerals to be seen megascopically are the diminutive muscovite flakes. On the basis of the rock type it may be classified as Karelian.

When studied microscopically the bulk of the rock appears to be composed of a very fine-grained mass consisting apparently mainly of quartz, with scattered muscovite flakes. An X-ray diffraction diagram indicates rich quartz, medium mica, and minor potash-feldspar contents. It reveals, in addition, a few lines which suggest kaolin and/or chlorite.

The rock is interesting, however, in that it contains graphite and apatite. The graphite appears as a rather thin dissemination as well as in denser accumulations. The apatite crystals are always connected with the graphite accumulations, the graphite forming a tube-like cover around the apatite. Fig. 22. The length of the biggest apatite crystals is almost one millimetre which strongly points to their being of secondary origin in the rock.

As to the origin of the graphite-apatite combinations, the author is inclined to consider them — or their components — as being of biogenic origin. Whether the tube illustrates the form of the original organism, i.e., whether the tubular hollow shape has provided the space for the apatite to crystallize in, or whether the coal as well as the other substance of the sediment have eventually been pushed aside by the crystallizing apatite, remains mere guesswork. In order to confirm the biogenic origin of the graphite-apatite aggregates, the existence of some trace elements supposed to be indicative of organic matter, was determined microanalytically. The Cu, Mo and Ge gave a negative result, whereas V yielded a distinct although weak positive result. The coal substance was separated by dissolving the other components with hydrofluoric acid. The carbon residue was identified by X-ray powder diffraction as being composed solely of graphite.

Conglomerate with carbonate cement

A single specimen of the conglomeratic rock group deserves to be mentioned. The rock is composed of sub-angular fragments up to 4 cm in diameter, cemented together by carbonate, Fig. 23. Microscopic examination shows that most of the fragments are composed of fine-grained quartzitic rock. One yellowish fragment, consisting of fine-grained dolomite, bears a marked resemblance to Karelian dolomites. Within the carbonatic cement there appears a relatively large roundish spot composed of coarse-crystalline baryte (X-ray identification).

In considering the possible relationship of the above rock with other known conglomerates, the present author is strongly inclined to draw a parallel between it and the conglomerate boulders from the Malören island which have been described by Åhman (1950), see p. 7.

Tillite

A boulder very likely of moraine origin was found on the shore of Saloinen. The rock as a whole is greenish grey in colour. No stratification can be seen. The fragments in the rock are up to 3 cm in diameter, sub-angular in shape, composed of rock and feldspar. The few bigger rock fragments consist of medium-grained granite, the smaller fragments are composed of fine-grained rocks varying in composition. Fig. 24. The groundmass consists of sharp-edged and angular quartz, feldspar and rock particles, and mica flakes embedded in a crypto-crystalline matter.

The rock does not resemble any known rock in the Finnish bedrock and naturally cannot be regarded as belonging to Pleistocene deposits. Assuming a glacial origin for the rock, the only imaginable counterpart would be the tillites produced by the Eo-Cambrian glaciation, deposits of which occur along the eastern border of the Caledonian zone in NW-Fennoscandia.

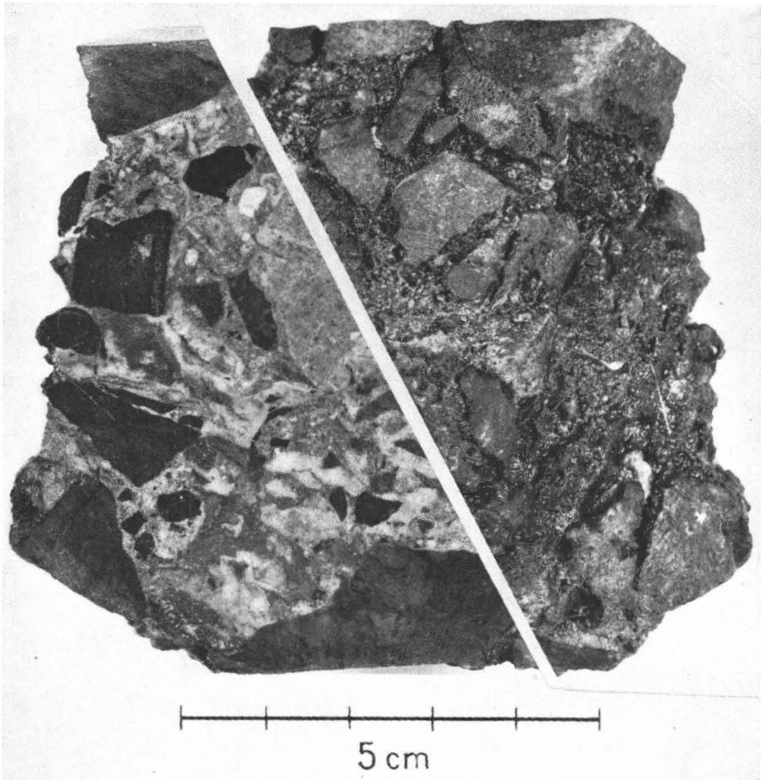

Fig. 23. Conglomerate with carbonate cement. Natural (right) and sawn surface. Photo E. Halme.

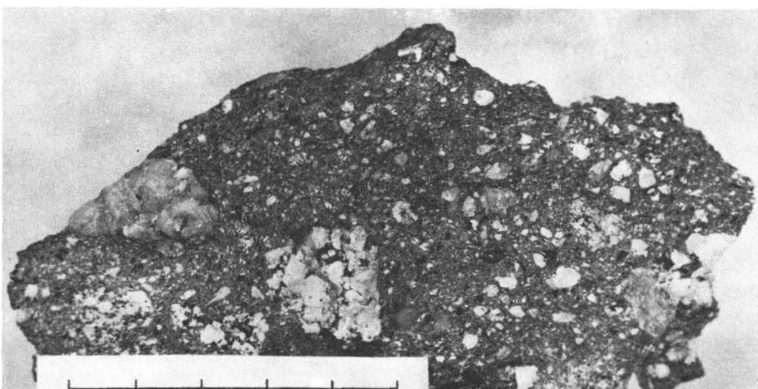

Fig. 24. Tillite boulder from the shore at Saloinen. Photo E. Halme.

CONCLUSION

The material at hand did not permit a closer study of the Archean crystalline rock crust at the bottom of the Bothnian Bay. A more general examination of the drift material, however, points to the bottom being for the most part composed of bedrock comparable to that of the surrounding costal area, i.e. a complex consisting chiefly of migmatites of varying composition. Judging by the distribution of the drift material that was considered to belong to a Karelidic sedimentary series, it seems possible that the Pohjois-Pohjanmaa supracrustal rock zone, which touches the coast north of Oulu, continues to the sea area and may even extend to the Swedish side. The supracrustal succession most probably includes ortho-quartzites, phyllites including graphite-bearing varieties, volcanic clastic rocks and effusives, dolomites — possibly to a relatively greater extent than in the corresponding area on the mainland — cherts, and jaspilites.

The possible existence of a rapakivi-like granite deposit in the Bothnian Bay area has been of great interest to the present author. No final conclusions can be drawn, however. No rapakivi-like rock boulders have been found on the coastal area by the author. On the other hand, the frequency of large potassium-feldspar fragments and quartz grains with a blue tinge appearing in Jotnian type sandstone blocks may speak in favour of the matter. It may be worth mentioning that the rapakivi deposits in the Bothnian Sea area were clearly reflected in the bottom samples as well as in the drift material on the shore (Veltheim, 1962).

The level coastal area is considered to be an old peneplain. In a more restricted sense the present bedrock surface must be taken as representing roughly the limit between the non-decomposed basement complex and a pre-existent weathered crust.

From the stratigraphical viewpoint, a boulder-conglomerate may be the oldest sedimentary rock deposited on top of the peneplain. The appearance of the conglomerate seems to be sporadic. It has been met with in only one bore hole in Hailuoto, and, according to seismic interpretations which seem to be quite reliable, its occurrence is restricted only to the westernmost part of the island (with a possible continuation to the sea area in the west). It is not found in any of the drill holes on the mainland. The conglomerate outcrop in Kieksi points to the likelihood of the rock occurring bottommost in the sedimentary succession in the northern part of the Muhos graben area. As for the proper sea area, the numerous conglomerate blocks found on Malören undoubtedly point to a nearby occurrence as has been suggested by Dr. Åhman. The single block find on the shore of Saloinen may indicate the possible existence of the conglomerate also elsewhere in the sea bottom.

The allothigenic nature as well as the considerable transportation distance of the material of the conglomerate has been established in the case of Hailuoto and may likewise be deduced from the description by Dr. Brenner in the case of the

Kieksi-conglomerate. The poor sorting and the heterogeneousness of the material are apparent in both cases. In consequence, the present author is inclined to apply a fanglomeratic denomination to the conglomerate. As the majority of the pebbles of the Hailuoto-conglomerate consist of Karelian-type quartzite, it seems probable that the material of the conglomerate has been transported from the north.

The red-arkose and the red-shale are connected together by frequent reciprocal interlayers. Both are, further, connected to the underlying conglomerate by the inter-boulder material which greatly resembles a combination of red-arkose and red-shale. Thus, it would probably not be out of place to consider the combination conglomerate — red-arkose — red-shale as representing one single succession illustrating a logical sedimentary development. In terms of alluvial conditions, a gradual decline of the transportation agent could be assumed.

The drill hole, 545 metres in depth, sunk down at Muhos, is the only one described in greater detail lithologically. Prof. Simonen has emphasized the immature nature of the arkosic, i.e. the lowermost rock, in the succession, as well as of the siltstone and shale varieties above. According to Prof. Simonen the sequence suggests a floodplain deposit in postgeosynclinal basins. The present author has used the original drill cores of Muhos for a comparison, and would like to underline the great similarity which exists between the rocks of Muhos and the red-arkose and red-shale of Hailuoto. In fact, an almost identical composition has been established by X-ray investigation as existing between shale samples selected on the basis of megascopic similarity.

Consequently, it seems very probable that the Muhos sedimentary succession and the lower part, i.e. the »red-sediments», of the series in Hailuoto belong to one facies of the same sedimentary sequence. Their direct conjunction will be discussed later in connection with the dislocation events between the mainland and the Hailuoto area.

The great disparity in the mechanical strength of the rocks of the two localities must be left unsolved for the time being.

An advanced degree of maturity may be noted as a general feature of the sedimentary rocks in the upper part of the sequence in Hailuoto. Thus, e.g. the sandstone is well-assorted, its grains are roundish and the grain composition places the rock into the cathegory of quartz-sandstone. The rhythmical appearance of sandstone, siltstone and shale (mostly in the order stated) links the components into a unit which could point to depositional conditions characteristic for littoral environments. In this respect the conditions of the upper part differ from those prevailing at the time of the deposition of the »red-sediments». The light-coloured arkose situated lowermost in the upper part appears both lithologically and in terms of its position as a link between the lower and the upper part of the succession.

The present author prefers to consider the lithological changes within the entire succession as being due only to general and logical evolution. A comparable evolution, viz. a change from immature to mature sediments, is common in the

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Jotnian successions in Sweden (cf. e.g. von Eckerman, 1937). The present author is not inclined to correlate the quartzitic sandstone of Hailuoto with that on the Finnish mainland, which Simonen (1955) has classified as Cambrian on the basis of the compositional similarity with some sporadic occurrences (fracture fillings) whose Paleozoic age has been proved. The great age of the Hailuoto-succession may be assumed also from the absence, even in the shaly matter, of any biogenic features.

The sea bottom samples reveal a limited area characterized by a high percentage of sandstone in the gravel. The centre of this area would seem to lie northwest of the Nahkiainen beacon, about 17 nautical miles west of Raahe. The highest sandstone percentages, in the sample W 1 — 87 % and W 2 — 98 %, lead one to assume the existence of a sedimentary deposit in situ or close to the spot.

A marked increase of sandstone in the drift has been found on the coastal area north of Pyhäjoki. As the direction from the sandstone concentration area at sea to that on the shore would be some 110°—140°, it is tempting to consider the former as the place of origin for the material found in the latter area. Assuming this to be the case, the quality of the samples collected from the shore would, in addition to those obtained from the sea bottom, reveal the composition of the bottom sediments.

A prominent feature of the sandstone samples collected from the shore and from the sea bottom is the great variety in their types. This mixture of types is worth consideration as it may indicate that this part of the sea area has been a scene for different environmental conditions during the time of deposition of the sedimentary series — an assumption which could be made already on the basis of the drill cores in Hailuoto. The majority of the sandstone pebbles represent types which have not been found in the drillings in Hailuoto, however. A large proportion of the samples is composed of sandstone which could be described as typically Jotnian, viz. feldspar-rich arkoses of medium or coarse grain size. On the other hand, rock types which are light grey or greenish in colour, evengrained and quartzitic in composition are relatively numerous.

Apart from stratification, structural features that would throw light on the environmental conditions prevailing at the time of the deposition of the sandstone are rarely observed among the boulders. This applies specially to the ripple-marks, so frequent on the boulders of the Bothnian Sea shore. The numerous ventifacts found loose and as paving on the flat blocks point, however, indisputably to an aeolian facies being included within the depositional conditions. Arid conditions may be assumed on the basis of some sandstone pebbles containing siderite cement and having a limonite crust around the grains.

The sandstone includes many ore minerals which appear as cement in the rock. Pyrite is the predominant mineral among the samples. It occurs commonly as concretions. Some fractured samples could indicate, however, that the pyrite impregnation may have taken place also in dimensions greater than ordinary concretions. Chalcopyrite appears as small irregular spots within the pyrite-impregnated sandstone samples. The combination sphalerite-galena appears as a cement in flat blocks showing fractural edges. It may be possible that a concentration of sphalerite and galena is included in the sandstone series. The dimensions of the deposit remain obscure but the zinc and lead percentage, judged on an economic basis, may prove significant. In a certain grey sandstone consisting of dolomite cement there appear smallish, ragged aggregates of safflorite, accompanied by niccolite, löllingite and some radioactive mineral. The rare occurrence, at least according to published records, of safflorite as a cement in sandstone is noteworthy.

A small amount of shale and siltstone pebbles has been noted among the bottom samples. Owing to the ready disintegration of these rock qualities it seems useless to try to estimate their relative amount in the maritime deposit.

Dyke rocks, and especially diabases, are very frequently associated with the Jotnian sandstone deposits. No direct evidence of their existence in the Hailuoto—Muhos region has been found, and as far as can be judged by the aeromagnetic map their absence seems more probable than their presence. Diabase boulders are, however, common among the drift material on the shore (Okko, 1949).

The fault troughs in the rock crust may be cited as the next great events following upon the deposition of the Jotnian sediments. The close areal relationship of the Jotnian sediments and the great grabens, has been discussed extensively. A close age relationship has been suggested by Geijer (1963) who maintains that the Jotnian time ended with, or was closely followed by, a period of faulting. Much younger ages, including Tertiary, have been suggested by various authors, however.

The entire Hailuoto area could in fact be included in a manifold dislocation complex. It seems probable that a threshold about 8 km wide running in a NW—SE direction occurs in the western part of the island. The threshold itself seems to plunge slightly, less than 1°, to the north, as is apparent from the drill holes, which reveal the basement complex at a depth of 155 metres in the northern and of 98 metres in the southern part of the island. The surface of the basement lies evidently more than 100 metres deeper on the western side of the threshold, as it was not reached with a drill hole (R 2) which was sunk to a depth of 268 metres. To the east of the threshold the difference in the depth must be considered even greater since the seismic measurements made at Santonen indicate that the surface of the crystalline basement lies at a depth of some 400—600 metres.

In a lecture in 1954, Prof. Veikko Okko outlined the supposed southwesterly boundary of the Muhos formation as running along the SW coast of the Lumijoki bay. The assumption was based on pebble counts and small-scale topographic features. The NE border, on the other hand, was sketched by Brenner (1944) as reaching the coast immediately south of Oulu. These may be taken as the fixed points on the mainland in a discussion centering on the apparent connection of the dislocated area at Hailuoto with a similar area on the mainland. The interpretation has to be based mainly on the available aeromagnetic map of the region issued by the Geological Survey of Finland, see Plate. The small-scale gravimetric map (Fig. 4) gives only the general outlines. The drill hole sunk down by the Otanmäki Oy in 1968 is the only available direct observation.

The sea area between Hailuoto and the mainland is aeromagnetically rather flat and thus comparable both to the Muhos graben and the Hailuoto areas. The differences in the aeromagnetic character around the flat area, as well as some few deviations inside the area, may provide a clue to the extent of the dislocated area and to various small-scale features within it. The interpretation is based on the nature, i.e. on the steepness of the gradient of the magnetic anomaly figures. In this connection the present author wishes to refer to the investigation of Puranen (1963) who computed the thickness of the Jotnian sandstone mattress in Satakunta, southwestern Finland.

The only place on the mainland coast where the basement complex is outcropping is at the mouth of the Siikajoki river. At the same place the aeromagnetic map shows an anomaly with a steeply inclined gradient. In the NNW direction of the mouth of the river one could draw a line separating sharp gradient anomalies on the SW side and anomalies showing a slightly inclined gradient (on the NE side). Since the general strike of the crystalline basement (gneisses) is likely to run in this area in a general direction of SW—NE (interpretation from the geological map of Enkovaara, Härme and Väyrynen, 1952) the rather abrupt change in the nature of the anomalies would seem unlikely if the level of the surface of the basement complex would be relatively even. Consequently, the present author is inclined to assume that the said line indicates a fault in the basement which again would indicate the southwesternmost border of the dislocated area. Another border line could be drafted as running in the NE direction from the mouth of the Siikajoki river, i.e. along a line composed of oblong anomalies with a sharp gradient. Because of the gap in the aeromagnetic survey in the marine area east of Hailuoto, this part may be regarded as belonging to the dislocated area chiefly because it forms a direct continuation of the graben on the mainland and also on the basis of the gravimetric map.

To the SW of the southernmost point (Syökari) of Hailuoto there occurs an anomaly exhibiting steeply inclined gradients. This falls within the off-shore continuation of the above-mentioned threshold in Hailuoto and could in fact indicate the highest point of the slightly ascending tract. About 10 km to the E of Syökari there is a relatively large roundish anomaly showing a gently inclined gradient. The sedimentary bedrock of this spot has been confirmed by deep drillings by the Otanmäki Oy Company. According to oral contribution by Dr T. Siikarla towards the interpretation of the aeromagnetic anomaly, the basement complex could here be assumed to lie at a depth of 1 200 $\pm$ 100 metres. This would agree with a comparative estimation since a depth of nearly 1 000 metres has been confirmed at Tupos on the mainland and a depth of more than 500 metres has been estimated seismically at Santonen.

The supposed fault lines of the Hailuoto region and of the sea area between the island and mainland are sketched on the attached aeromagnetic map (Plate).

For want of further evidence, the question of whether the assumed sedimentary deposit at Nahkiainen appears in a graben or on top of nondislocated basement remains open. The area of the deposit falls within the negative gravimetric anomaly zone which runs NW from Pyhäjoki, it does not, however, stand out as a marked detail within the zone. This may of course be due to an insufficient density of the measuring points (dotted lines on the map). The possibility cannot be completely ruled out either that the deposit has been entirely obliterated by the Pleistocene glaciation and all that is left is the material now present in the local drift.

Conclusive evidence concerning the geological evolution during the long period of time succeeding the great faulting is scanty in the Bothnian Bay region. The kimberlite dykes occurring in the Kalix and Luleå archipelago are in fact the only occurrences in situ. Their age seems to be still in doubt and varies according to different authors (referred to by Ödman, 1957) from »yngre än algonk» (younger than Algonkian) to Permian.

Some loose blocks found in the coastal area may, however, provide a clue to the possibility that the sea area may have been a scene for some additional geological events during the time from Jotnian to Pleistocene.

The single tillite block found on the shore north of Piehinki may possibly be considered Eo-Cambrian. On the basis of such scanty evidence it is not possible to decide, however, whether the block is a »far-runner» with its origin in the northwestern part of Sweden, or whether an isolated occurrence, comparable to that at Holmajärvi at Kiruna in Sweden (cf. Ödman, 1957, p. 107), could be situated somewhere in the sea bottom.

One of the aims of the drilling activities on the Hailuoto island was to find out whether a late Proterozoic or Paleozoic stratum might possibly exist under the soil cover as seemed likely judging by the nereites (?) found on the sandstone blocks on the NW shore of the island. This was not the case, however. The fact that this unique, readily distinguished, light grey, fine-grained quartz-sandstone appears concentrated in the drift in Hailuoto justifies the assumption that its provenance may lie within a moderate distance in a westerly direction from the island. Judging by the bottom samples, in particular P 30 (2 % sandstone), the site of the deposit is likely to be within a distance of 15 km from Hailuoto.

The drift on the shore at Piehinki has displayed a number of volcanic pebbles showing a low degree of metamorphism. In addition, a pebble of pumice was encountered during drilling in Nivala. Rock of this kind does not occur in the bedrock of Finland, with the possible exception of the still disputable (Svensson, 1968) volcanic neck at Lake Lappajärvi, 100 km east of Vaasa. The relative scantines of the volcanic pebbles in the drift together with the fact than none have been noted in the bottom samples may point to a great distance as regards their source. In this connection the present author would like to call attention to the strong roundish negative gravimetric anomaly area about 30 nautical miles ESE from Piteå. The study of the cause of this interesting anomaly must be left to the Swedish explorers, however.

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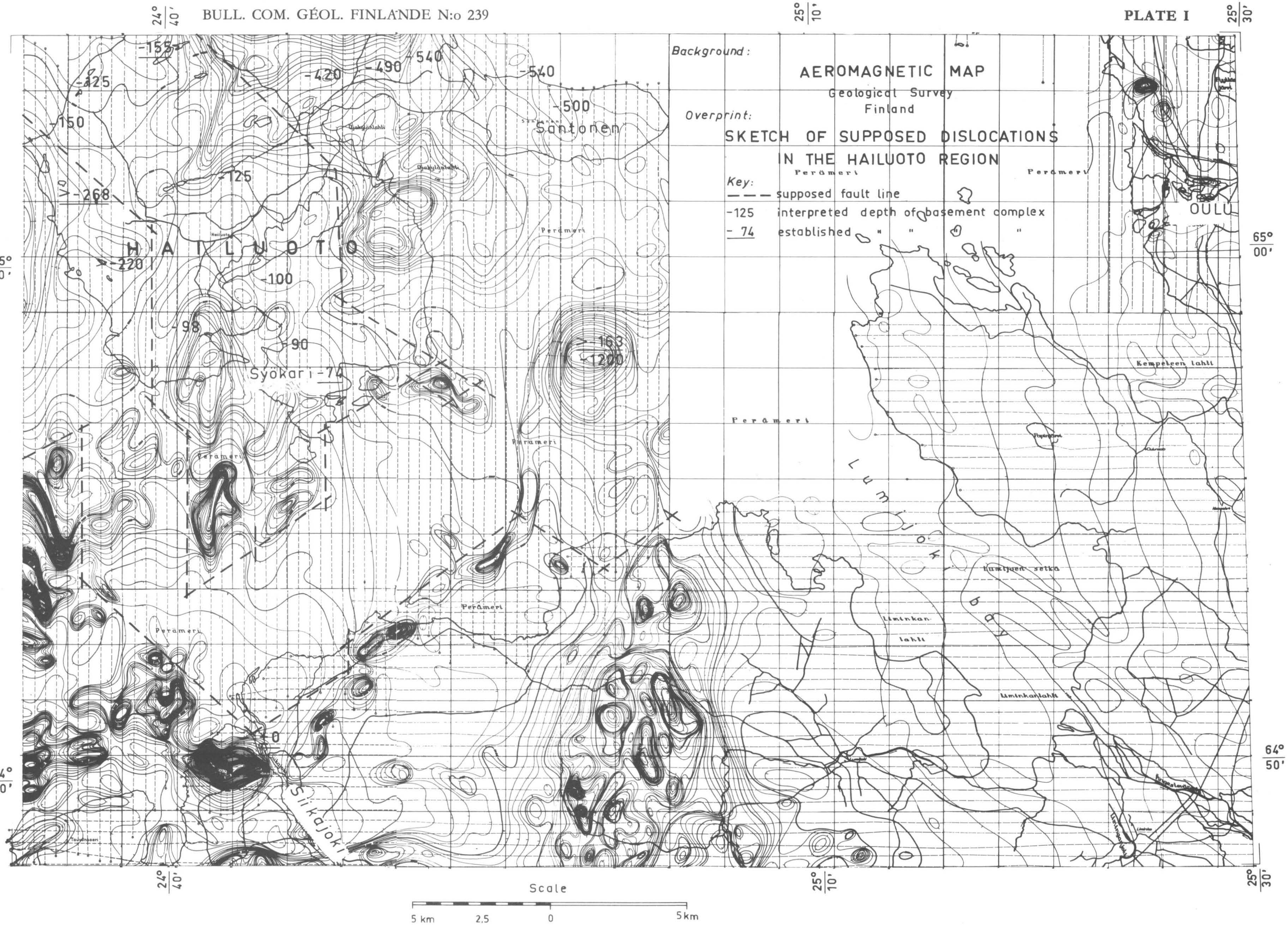
Background:
AEROMAGNETIC MAP
Geological Survey
Finland
Overprint:
SKETCH OF SUPPOSED DISLOCATIONS
IN THE HAILUOTO REGION
Key:
supposed fault line
-125 interpreted depth of basement complex
- 74 established " " "
HAILUOTO
Santonen
Syökari -74
OULU
Perämeri
Lumijoki bay
Liminkanlahti
Kempeleen lahti
Siikajoki
-155
-125
-150
-268
-220
-420
-490
-540
-540
-500
-125
-100
-98
-90
-163
-1200
0
24° 40'
25° 10'
25° 30'
65° 00'
64° 50'
Scale
5 km
2,5
0
5 km