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SANDSTONES IN FINLAND [1]

BY

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ABSTRACT

Sedimentary petrographic features and conditions of deposition of the sandstones in Finland are briefly described. The late pre-Cambrian, Jotnian arkosic sandstone of Satakunta shows characteristics of the postgeosynclinal piedmont facies of sedimentation. Arkosic sandstones showing petrographic features similar to those of the Jotnian sandstone also occur in the Muhos formation south of the Oulu river, where the sandstones are closely associated with red silstones and shales. On the basis of a tectonic classification of the sandstones the Muhos formation is closely related to the Jotnian formation, which is postgeosynclinal (postorogenic) in relation to the Karelidic orogeny. In addition to the arkosic sandstones, many small occurrences of pure quartz sandstone are known in Finland. These quartz sandstones are nonorogenic deposits of a stable platform, and they represent the transgression of the Cambrian sea over a peneplained surface.

CONTENTS

INTRODUCTION

Finland is part of an old pre-Cambrian Shield where only very few occurrences of sandstones and associated sedimentary rocks overlie the

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metamorphosed and plutonic pre-Cambrian rocks. The oldest unmetamorphosed sandstone in Finland is the late pre-Cambrian Jotnian formation (Sederholm, 1897). A fossiliferous Cambrian sandstone occurs in Åland (Tanner, 1911) and many small occurrences of pure quartz sandstone in Finland are believed by various authors to be deposits of the transgressive Cambrian sea. Different opinions have been presented, however, regarding the geological age of many unfossiliferous sandstone deposits in Finland. The sandstone occurrences and opinions presented concerning their geological age are listed in Table 1, and the geographic distribution of the rocks is shown in Fig. 1.

Table 1. Sandstone occurrences in Finland

Occurrence	Proposed geological age and references
Satakunta	Cambrian (Gylling, 1887); Jotnian (Sederholm, 1897; Laitakari, 1925; Kahma, 1951)
Muhos	Mesozoic (Brenner, 1941 and 1944); Jotnian (Ödman, Härme, Mikkola and Simonen, 1949; Enkovaara, Härme and Väyrynen, 1953)
Saltvik	Cambrian (Tanner, 1911; Metzger, 1922)
Lemland	Cambrian (Kaitaro, 1949)
Kökar	Cambrian (Sederholm, 1924)
Eckerö	Cambrian (Asklund and Kulling, 1926)
Brändö	Cambrian (Sederholm, 1934)
Åva	Cambrian (Kaitaro, 1953)
Parainen	Mesozoic (Hausen, 1934)
Vestanfjärd	Cambrian (Eskola, 1913); Mesozoic (Hausen, 1934)
Hiittinen	Cambrian (Edelman, 1949)
Hanko	Cambrian (Sederholm, 1913 b)
Lauhavuori	Cambrian (Sederholm, 1913 a); Jotnian (Laitakari, 1925)
Karstula	Cambrian (Sauramo, 1916)

The main purpose of this investigation is to present the sedimentary petrographic characteristics of the unmetamorphosed sandstones in Finland. The new data presented are chiefly based on the microscopical study of thin sections. New, more detailed field work for this study was carried out only in the sandstone area of Lauhavuori in southern Ostrobothnia. On the basis of the sedimentary petrographic features the depositional history of the sandstones is briefly discussed and some suggestions on the correlation and geological age are presented. The lower Cambrian quartz sandstones in Enontekio, Lapland, thoroughly described by Hausen (1942) were not taken for petrographic study presented in this paper.

The present study was planned by the senior author (A. S.), who has written the entire manuscript and is responsible for the conclusions. The junior author (O. K.) did most of the laboratory work.

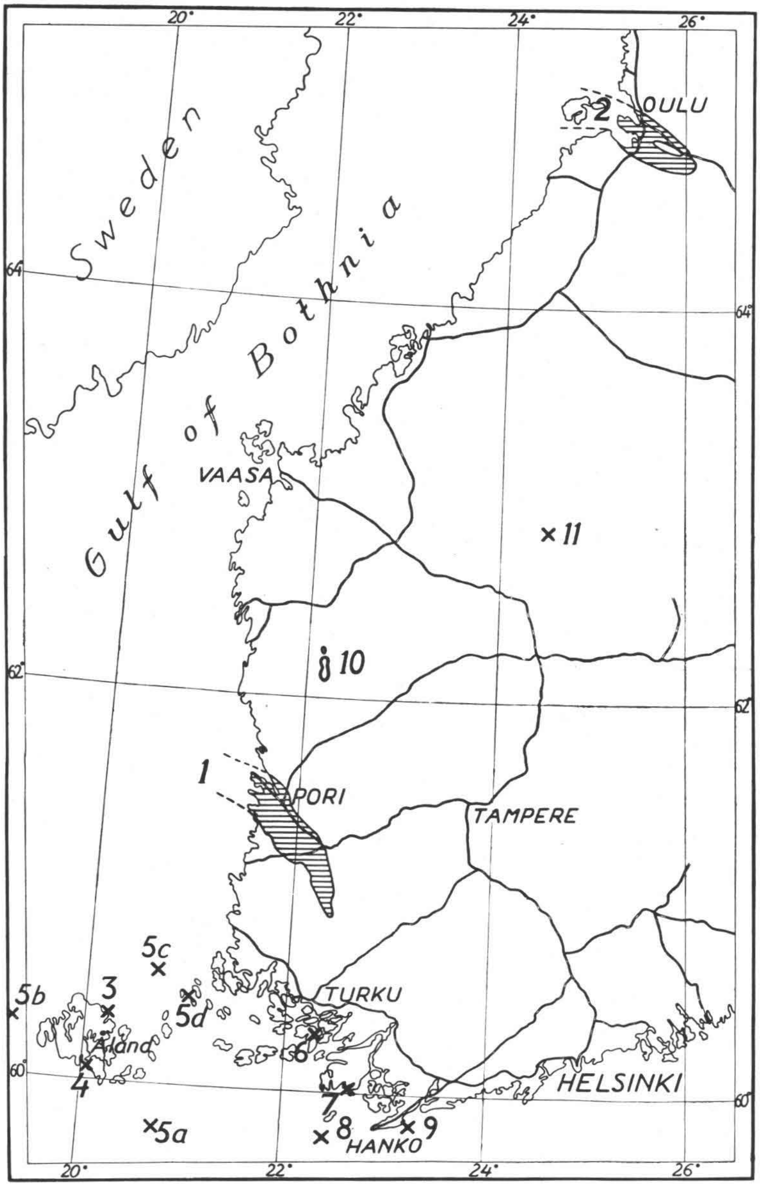

Fig. 1. Location of the unmetamorphosed sandstones in Finland. 1, Jotnian sandstone of Satakunta; 2, Muhos formation; 3—11 quartz sandstones; 3, Saltvik, Åland; 4, Lemland, Åland; 5a, Kökar, Karlbybådar; 5b, Eckerö, Yttre Borgen; 5c, Brändö, Bredan; 5d, Åva, Kummelören; 6, Parainen; 7, Vestanfjärd; 8, Hiittinen; 9, Hanko, Skarvkyrkan; 10, Lauhavuori; 11, Karstula.

JOTNIAN SANDSTONE OF SATAKUNTA

The Jotnian sediment formation of Satakunta occupies a wide area extending from the town of Pori to Lake Pyhäjärvi. The distribution and the field description of the sandstone are given by Laitakari (1925). Red-colored, stratified arkosic sandstones with thin intercalated beds of red or black shales predominate. A conglomerate with quartz pebbles has been found, and conglomeratic sandstone with Archean granite pebbles occur among the Pleistocene glacial boulders derived from the sandstone formation.

The stratification of the sandstone is generally horizontal; the thickness of the deposit is unknown. The gravimetric measurements carried out by the Geodetic Institute suggest, however, a thickness of some hundred meters (cf. Kahma, 1951 p. 10). Many sedimentary structures indicating terrestrial conditions of deposition are described by Laitakari (1925). Current bedding is common and ripple marks (Plate II, Fig. 7). occur in the fine-grained and quartz-rich varieties of the sandstone. Furthermore, mud cracks, clay galls, and rain drop impressions (Plate II, Fig. 8) have been found.

The ripple marks, made by water, in the Jotnian sandstone are symmetric or asymmetric. No definite aeolian ripple marks have been found. The measurements of the wave lengths and amplitudes of the ripple marks from 6 specimens are presented in Fig. 2, which shows that the ripple index (wave length: amplitude) ranges from 7 to 10. The ripple index found in the Jotnian sandstone is typical for the aqueous ripple marks, whereas the index of the aeolian ripple marks ranges usually from 20 to 50 (cf. Twenhofel, 1950).

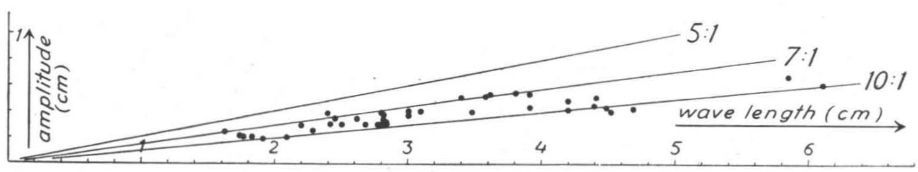

Fig. 2. Wave lengths and amplitudes of the Jotnian ripple marks.

Fourteen specimens of the Jotnian sandstone in Satakunta were selected for more detailed petrographic study. The mineralogical composition of these specimens was determined from the thin sections on the integration stage and the grain size distribution of 4 specimens was measured. The heavy mineral fraction of 2 specimens was separated by centrifuging in Clerici solution. The identification of triclinic and monoclinic modification of the potash feldspar was made by means of the powder X-ray diffraction data using a Geiger Counter Recording X-ray Spectrometer (Norelco).

The afore-mentioned methods of investigation were also used in the petrographic study of the other Finnish sandstones.

Table 2. Mineralogical composition (volume per cent) of the Jotnian sandstone in Satakunta

Locality	Particles					Cement and intergranular matrix
	Quartz	Potash feldspar	Plagioclase	Rock fragments	Accessories	
1. Nakkila, Leistilänjärvi	49.2	20.9	17.4	0.3	0.3	11.9
2. Ulvila	57.1	15.2	24.0	—	—	3.7
3. Säkylä	48.6	30.0	2.3	2.9	1.8	14.4
4. Nakkila, Leistilänjärvi	56.3	21.2	14.8	0.6	1.1	6.0
5. Kauttua	57.0	27.5	1.4	1.1	0.2	12.8
6. Säkylä	64.2	27.9	0.9	5.9	—	1.1
7. Harjavalta	53.1	12.9	9.1	4.5	3.0	17.4
8. Eura, Kiperjärvenoja	65.8	24.5	—	0.4	0.3	9.0
9. Luvia, Korvenkylä, Markkula	65.0	19.6	1.6	0.7	1.0	12.1
10. Kiukainen, Panelia	56.5	16.8	0.3	1.7	0.1	24.6
11. Kiukainen, Panelia	50.2	12.8	1.6	4.3	0.1	31.0
12. Eura, Kiperjärvi	71.3	16.8	0.7	—	0.2	11.0
13. Luvia, Lappäng	70.9	15.5	1.7	2.0	0.2	9.7
14. Yläne	78.2	0.7	4.9	—	2.3	13.9

The mineralogical composition of the Jotnian sandstone is presented in Table 2. Quartz is always the main component of the mineral particles. The content of feldspar varies greatly. The composition of the various specimens ranges from arkose (feldspar over 25 %) through feldspathic sandstone (feldspar 10—25 %) into quartz sandstone (feldspar under 10 %). The quartz to feldspar ratio is presented in Fig. 13. The feldspar is predominantly potash feldspar, but in some few specimens (Table 2, specimens 1, 2 and 4) the content of plagioclase is high. The feldspar is usually rich in hematite pigment, and is clouded and altered. Many specimens contain, however, both clouded and fresh feldspar grains. This indicates that the erosion which acted upon the feldspar-bearing rocks derived detrital material from both unweathered basement complex and its partly decomposed mantle.

The composition of the plagioclase grains varies greatly. Variations from An_5 to An_{30} are observed in the same specimen. To obtain the relative abundance of the different plagioclases the composition of 50 plagioclase grains was determined by means of refractive indices or on the universal stage. The results of measurements are presented in Fig. 3. The plagioclase particles showing the composition An_{7-10}, An_{14-16}, and An_{29-31} are most common. The source of these plagioclase grains is, however, impossible to determine, because the composition of the plagioclase varies irregularly between wide limits in the surrounding country rocks. The absence of basic plagioclase is probably due to the better resistance of alkali feldspars during weathering and transportation.

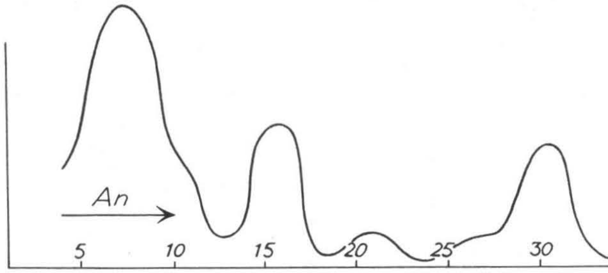

Fig. 3. The relative abundance of different plagioclases in the Jotnian sandstone. Abscissa, composition of plagioclase; ordinate, relative abundance (number of particles).

Altogether 35 potash feldspar particles from four different localities (Harjavalta, Luvia, Sassilanjuopa, and Säkylä) were studied by means of the X-ray powder method to determine the monoclinic or triclinic symmetry. All the potash feldspar grains showed the diffraction lines typical of triclinic modification; no grains with monoclinic symmetry were detected. In this case the presence of the triclinic potash feldspar suggests the source rock of the deposited material, because the potash feldspar of the Archean basement complex surrounding the sandstone area is microcline and that of the normal rapakivi granite, occurring south of the sandstone area, is predominantly orthoclase [1]. The study of the potash feldspar particles in the Jotnian sandstone indicates that the detrital material of the sandstone is derived from the Archean basement. This conclusion is in harmony with the fact that the Glacial boulders of the conglomeratic sandstone contain pebbles of Archean granites.

Biotite, muscovite, and chlorite are the most common accessory minerals of the Jotnian sandstone in Satakunta, but small quantities of many other minerals are also present. Laitakari (1932) studied the heavy minerals of 2 sandstone specimens from Yläne and found the following: garnet, ilmenite, magnetite, zircon, topaz, and monazite. According to Laitakari (1932), the presence of topaz suggests that the rapakivi granite south of the sandstone deposit was the source rock of the detrital material, because topaz occurs in some rapakivi varieties. As, however, topaz also occurs in certain Archean pegmatites, the conclusion is not quite decisive. On the other hand, the garnet is surely derived from the metamorphic Archean rocks.

The present authors have separated the heavy minerals from two sandstone specimens by means of Clerici solution (sp. gr. = 2.9). The heavy minerals observed in the specimens studied are listed below:

[1] The study of the potash feldspars of the Finnish rapakivi granites is in the research program of Dr. K. J. Neuvonen, Geological Survey of Finland. According to an oral communication of Dr. Neuvonen, the potash feldspar in the normal Laitila rapakivi, south of the sandstone occurrence, is predominantly monoclinic.

Sandstone, Harjavalta: biotite, chlorite, magnetite, garnet, rutile, sphene, apatite, sillimanite, tourmaline, and epidote;

Sandstone, Nakkila, Leistilänjärvi: biotite, hornblende, magnetite, rutile, zircon, tourmaline, sphene, and apatite.

All these minerals are present in the Archean rocks surrounding the sandstone occurrence and the presence of the garnet and sillimanite is especially diagnostic of the high-rank metamorphic source rocks. No heavy minerals definitely indicating detrital material derived from the rapakivi granites have been found in the specimens studied by the present authors. In view of the study of heavy minerals and feldspars it seems reasonable that at least the main part of the detrital material of the sandstone is derived from the Archean basement complex.

Small rock fragments of black shale and fine-grained quartzite also form particles of the sandstone. The fragments of black shale are angular and those of the quartzite are rounded. The black shale particles are petrographically similar to the interbeds of black shale in the sandstone and they are considered as products of channeling of the deposited sandstone with interbeds of clayey material. The quartzite particles were derived from the metamorphic terrain.

The intergranular matrix is rich in quartz. Minute flakes of sericite and chlorite are also sometimes abundant. They probably were formed from original argillaceous material. The content of mica minerals in the matrix is especially abundant in the sandstones whose intergranular matrix occupies over 20 volume per cent of the whole rock. In some few cases introduced siliceous cement has caused the secondary outgrowth of the quartz particles.

Table 3. Chemical composition of the arkosic sandstones

	1	2	3	4	5
SiO_2	79.30	81.10	82.14	73.32	75.5
TiO_2	0.22	0.09	—	—	—
Al_2O_3	9.94	9.64	9.75	11.31	11.4
Fe_2O_3	1.00	0.28	} 1.23	3.54	} 2.4
FeO	0.72	0.65		0.72	
MnO	0.02	0.03	—	tr.	0.2
MgO	0.56	0.76	0.19	0.24	0.1
CaO	0.38	0.80	0.15	1.53	1.6
Na_2O	2.21	1.78	0.50	2.34	2.0
K_2O	4.32	3.79	5.27	6.16	5.6
P_2O_5	0.05	0.08	0.12	—	tr.
H_2O+	0.55	0.77	} 0.64	{ 0.30	{ 0.6
H_2O-	0.41	0.17			
CO_2	—	—	0.19	0.92	0.4
	99.68	99.94	100.18	100.38	99.8

1. Jotnian sandstone. Köyliö, Muurunmäki, Anal. H. B. Wiik (Lokka, 1950).
2. Jotnian sandstone. Köyliö, Tuiskula. Anal. H. B. Wiik (Kahma, 1951).
3. Torridonian sandstone. Kinlochewe. Mackie (1901).
4. Old Red Sandstone. Foyers, Loch Ness. Mackie (1901).
5. Average arkose. Pettijohn (1949).

Chemical analyses of the Jotnian sandstone in Satakunta are presented in Table 3 (Anal. 1—2). These analyses are very similar and are also similar to the chemical composition of arkoses in thick accumulations of other geological formations. The chemical analyses of the well-known classical Torridonian and Devonian Old Red Sandstone arkose deposits and the average chemical composition of arkose given by Pettijohn (1949) are presented for comparison (Table 3, Anal. 3—5). Chemically the Jotnian sandstone is characterized by the high content of alkalies. The low value of the ratio $Al_2O_3 : Na_2O$ shows that the effectiveness of the weathering has not been strong.

The Jotnian sandstone in Satakunta is usually coarse-grained. Most of the particles are subangular or subrounded (Plate I, Figs. 1—2). These textural features suggest that the abrasion history was rather brief.

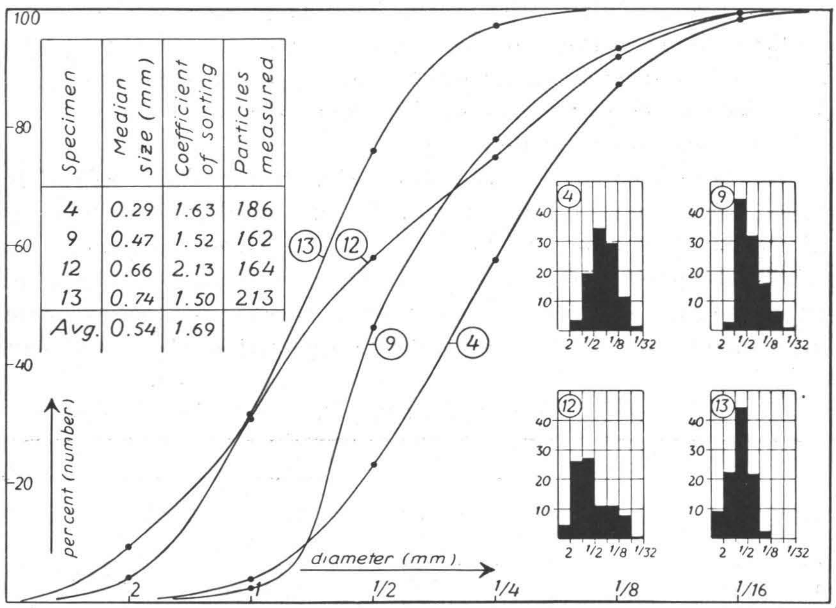

Fig. 4. Grain size distribution of the Jotnian sandstone in Satakunta. The numbers of the specimens refer to Table 2.

The grain size distribution of 4 specimens is presented in Fig. 4, which shows cumulative grain size curves, histograms, median grain size, and coefficients of sorting. The number of sand particles in different size groups was determined from the thin sections. The grain size varies between wide limits and the size distribution indicates that the Jotnian sandstone is not well sorted.

Mineralogical and chemical composition of the Jotnian sandstone in Satakunta is typical for sandstones of the arkose suite. Some mineralogical characteristics (triclinic symmetry of the potash feldspar particles and presence of garnet and sillimanite as heavy minerals) show that the source of the detrital material was mainly the metamorphic Archean basement complex. The quartz to feldspar ratio and the textural features, poor roundness and sorting, show that the Jotnian sandstone belongs to the class of immature sands which are products of rapid erosion and deposition controlled by the conditions of steep relief. The sedimentary structures (ripple marks, cross bedding, and mud cracks) and the red color indicate a terrestrial oxidizing environment in the source area and at the place of deposition. All these features of the Jotnian sandstone in Satakunta are similar to the arkoses that are characteristic of thick terrestrial piedmont facies in postgeosynclinal basins (cf. Pettijohn, 1949).

MUHOS FORMATION

Unmetamorphosed conglomerates, sandstones, siltstones, and shales occupy a wide area in northern Ostrobothnia south and southeast from the town of Oulu. These so-called Muhos sediments are protected from erosion, because they are downfaulted along the northern boundary. The Muhos formation is covered by thick accumulation of the Pleistocene deposits and only one exposure is found in the valley of the Oulu river at Kieksi in the parish of Muhos. The distribution of the Muhos rocks has been studied

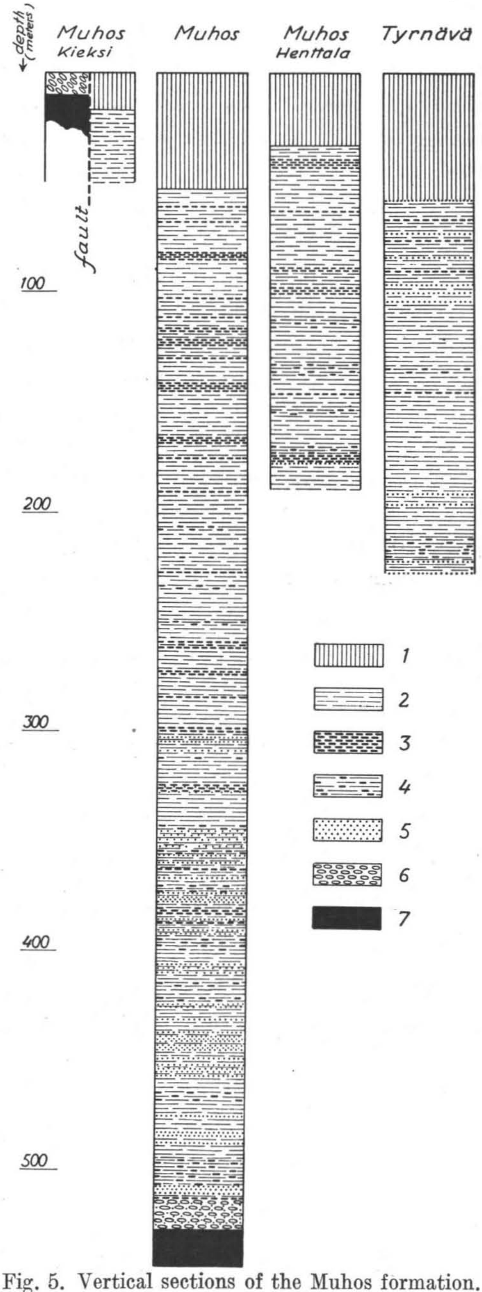

Fig. 5. Vertical sections of the Muhos formation. 1, Pleistocene deposits; 2, red siltstones and shales; 3, grey and green shales; 4, intimate alternation of red and grey shales; 5, sandstone; 6, conglomerate; 7, Archean rocks. This figure is based on the published data of Th. Brenner (1941 and 1944) and on the unpublished reports of the drill holes made by the Geological Survey and Pargas Kalkberg A. B.

by means of drill holes, geomorphological, and glaciogeological data. The material of these investigations has been studied by Veikko Okko, M. A., who will present his observations on the distribution and manner of occurrence of the Muhos formation in the near future. Preliminary reports of the Muhos sediments have been published by Brenner (1941 and 1944).

The vertical variations in the stratigraphic column are presented in Fig. 5. The Muhos formation begins with basal conglomerates and coarse-grained arkoses lying unconformably upon the Archean basement complex. According to Brenner (1944), the polymictic basal conglomerate at Kieksi is separated by a vertical fault from the corresponding basal beds which are situated in the drill hole at Muhos at a level about 500 meters deeper. The basal conglomerate contains rounded and angular pebbles of granite and schist and its matrix is brown-colored arkose rich in silty material. The conglomerate-arkose association forms an accumulation about 20 meters thick at the base of the Muhos formation and it is overlain by thick deposits of red, brown or greyish green siltstones and shales with thin interbeds of arkosic sandstone.

Table 4. Proportions of common types of sedimentary rocks in drill holes of the Muhos formation

%	Muhos	Muhos Henttala	Tyrnävä
Red and brown siltstones and shales	81.5	86.8	91.0
Grey and green shales	11.1	13.2	5.3
Sandstones and conglomerates	7.4	—	3.7

The proportions of common types of sediment in the Muhos formation are presented in Table 4. The red and brown siltstones and shales are predominant, forming 80—90 per cent of the total thickness. Grey and green beds do not form thick, continuous accumulations, but they occur as thin intercalations through the whole section. Sandy material is present in many siltstones and it is associated predominantly with the red beds. The arkosic sandstone occurs as thin interbeds especially in the lower part of the stratigraphic column (cf. Fig. 5).

Altogether 19 complete chemical analyses of the sedimentary rocks in the drill hole Muhos were published by Lokka (1950). These analyses, giving a good idea of the chemical characteristics of the Muhos rocks are presented graphically in Fig. 6. Most of the analyses (Anal. 3—16) represent red or green siltstones and shales. Three analyses (anal. 17—19) represent arkosic sandstones and two (Anal. 1—2) are gypsiferous shales.

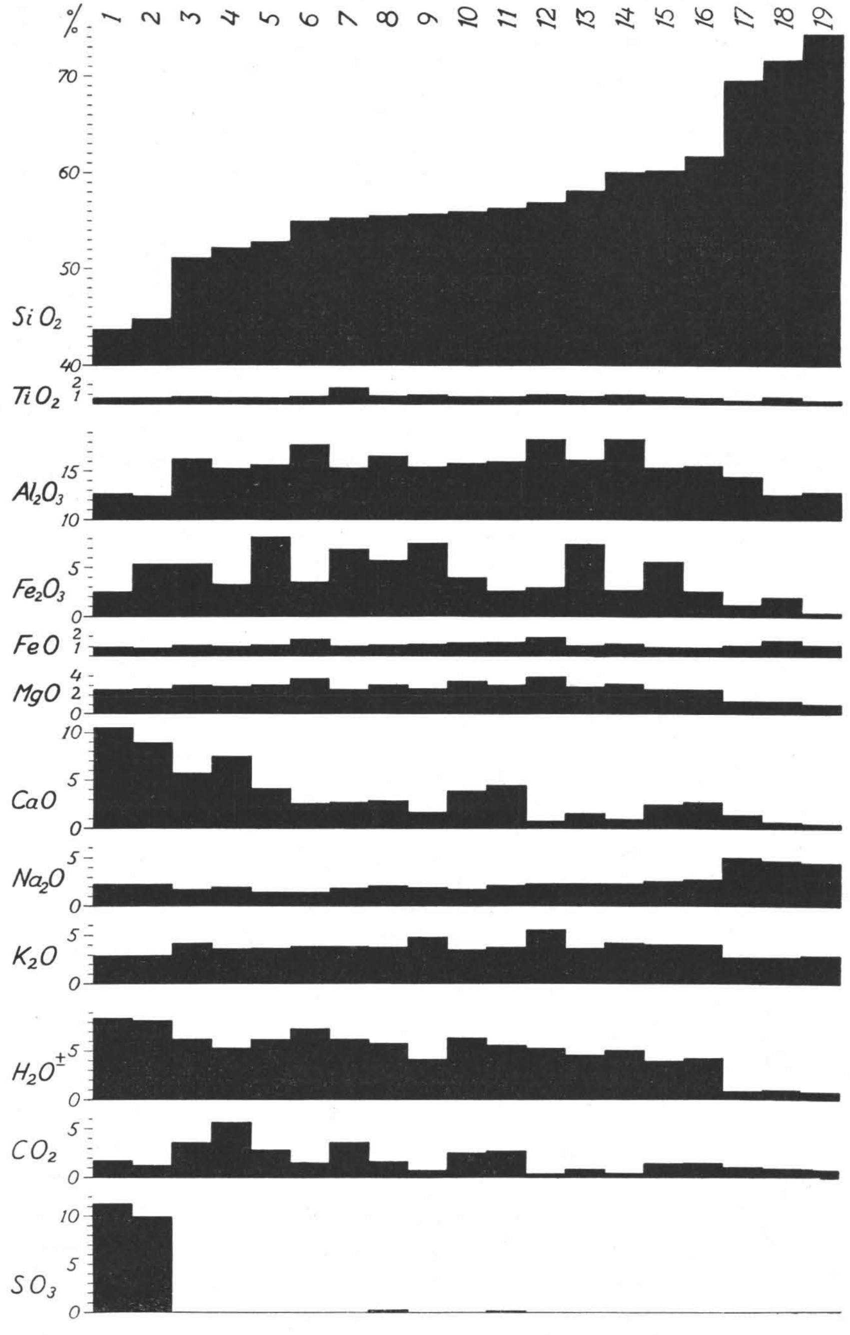

Fig. 6. Chemical composition of the Muhos rocks. Based on the chemical analyses published by Lokka (1950). 1—2 gypsiferous shales; 3—16, shales and siltstones; 17—19, sandstones. 3, 5, 7, 9 and 13, red beds; 4, 6, 10, 12 and 14, greenish grey beds; 8, 11, 15 and 16, red beds with grey spots.

The most remarkable variations in the chemical composition of the shales and siltstones are caused by the different contents of Fe_2O_3, CaO and CO_2. The red and brown beds are regularly characterized by a higher content of Fe_2O_3 than those of grey and green shales. A small amount of CO_2 is always present and the variations in the content of CO_2 appear clearly also in the content of CaO. The percentage of K_2O in the shales is higher than that of Na_2O, but this ratio is reverse in the sandstones. The relatively high content of Na_2O in the shales and siltstones is due to the presence of unweathered feldspar, which shows that the sediment had not undergone complete chemical weathering.

Table 5. Average compositions of the Muhos rocks

	1	2	3	4	5
SiO_2	56.28	54.68	56.09	58.10	71.86
TiO_2	0.88	0.98	0.85	0.65	0.50
Al_2O_3	16.32	15.83	17.14	15.40	13.28
Fe_2O_3	4.91	7.14	3.30	4.02	1.17
FeO	1.21	1.10	1.43	2.45	1.29
MnO	0.08	0.07	0.10	—	0.07
MgO	3.03	2.81	3.42	2.44	1.20
CaO	3.11	3.14	3.07	3.11	0.83
Na_2O	2.05	1.87	1.93	1.30	4.75
K_2O	4.06	4.06	4.14	3.24	2.75
P_2O_5	0.38	0.41	0.33	0.17	0.48
H_2O	5.40	5.33	5.89	5.00	0.89
CO_2	2.00	2.11	2.05	2.63	0.55
SO_3	0.02	—	—	0.64	—
BaO	—	—	—	0.05	—
C	—	—	—	0.80	—
Cl	0.01	—	0.01	—	—
	99.74	99.53	99.75	100.00	99.62

1. Average shale, Muhos formation. Anal. 3—16 in Fig. 6.
2. Average red shale, Muhos formation. Anal. 3, 5, 7, 9 and 13 in Fig. 6.
3. Average greyish green shales, Muhos formation. Anal. 4, 6, 10, 12, and 14 in Fig. 6.
4. Average shale. Clarke (1924).
5. Average sandstone, Muhos formation. Anal. 17—19 in Fig. 6.

Average composition of the shales in the Muhos formation (Table 5) is very similar to the average shale presented by Clarke (1924). The most striking difference between the average composition of red and green beds appears in the content of Fe_2O_3.

On the basis of the chemical analyses published by Lokka (1950) the ratio of iron in Fe_2O_3 and FeO in the red and green shales of the Muhos

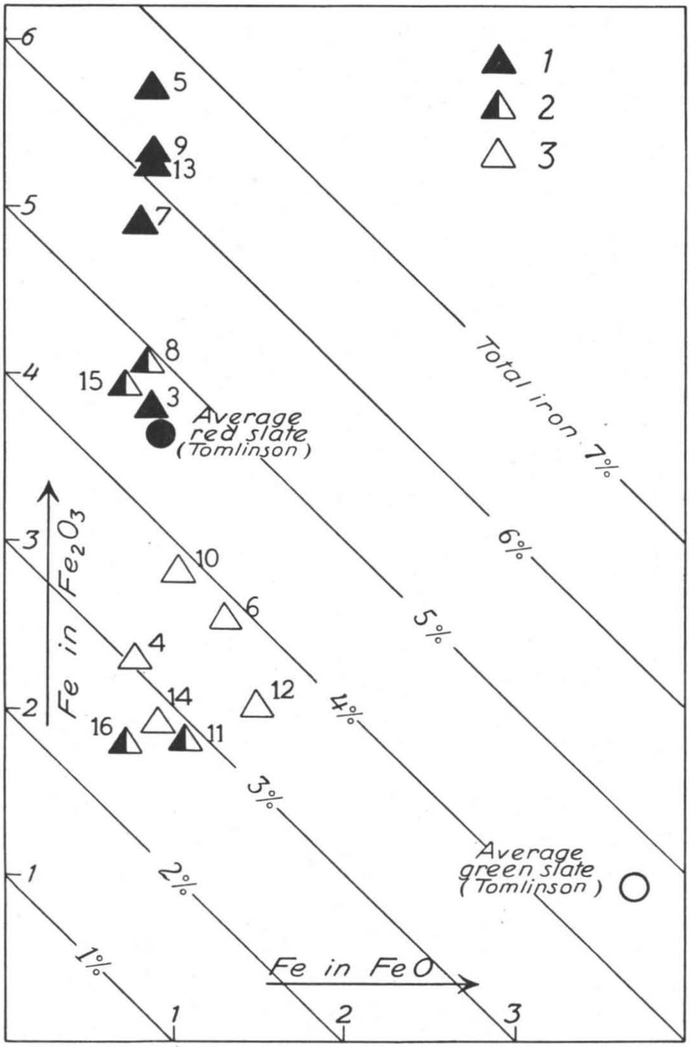

Fig. 7. Relation of iron in Fe_2O_3 and FeO in the red and greyish green shales of the Muhos formation. 1, red beds; 2, red beds with grey spots; 3, greyish green beds. The numbers 1—16 refer to the analyses in Fig. 6.

formation is plotted in Fig. 7. The total content of iron in the red beds is much higher than that of the greyish green beds. These data contradict the observations of Tomlinson (1916) who has shown that the red shales do not contain more total iron than the green and black shales, but the different color is only due to the different degree of oxidation.

Table 6. Mineralogical composition (volume per cent) of the sandstones and sandy siltstones in the Muhos formation

Locality	Particles					Cement and intergranular matrix	Calcite	Gypsum
	Quartz	Potash feldspar	Plagioclase	Rock fragments	Accessories			
15. Muhos, Kieksi	20.4	1.5	3.2	15.6	2.8	56.5	—	—
16. Muhos, depth 53.2 m	88.8	1.4	—	—	0.1	9.7	—	—
17. Muhos, depth 254 m	30.9	—	8.9	0.2	1.2	57.1	1.7	—
18. Muhos, depth 305 m	12.5	0.2	7.3	4.8	0.4	74.8	—	—
19. Muhos, depth 310 m	21.7	23.6		3.3	0.8	49.2	1.4	—
20. Muhos, depth 347.8 m	40.4	18.4		4.8	1.7	8.4	—	26.3
21. Muhos, depth 509.3 m	26.4	6.3	9.7	34.0	0.9	22.7	—	—
22. Liminka, depth 65 m	40.4	10.3	28.5	—	0.5	15.2	5.1	—
23. Liminka, depth 109 m	8.9	1.9	2.7	2.0	0.1	84.2	0.2	—
24. Liminka, depth 237 m	25.0	3.4	9.5	15.0	0.2	46.9	—	—

Altogether 10 specimens of the Muhos rocks containing sandy particles were selected for more detailed petrographic study. The mineralogical composition presented in Table 6 shows that the sandstones range from arkoses through silty sandstones into siltstones. Only one thin bed of a quartz sandstone 7 cm in thickness (Table 6, n:o 16) has been found. Quartz, feldspar, and small rock fragments of granite and schist form the sandy darticles of the arkoses. Feldspar is mainly plagioclase which is unusual for arkoses generally. This indicates that the detrital material is derived from a rock complex where the content of plagioclase has been higher than that of potash feldspar. Furthermore, decomposition of the deposited material was very incomplete. The composition of the plagioclase varies from An_{10} to An_{34}. Grains showing the composition An_{20-30} are most common. Fresh and much altered particles of plagioclase occur together. The ratio of quartz to feldspar in the specimens studied is presented in Fig. 13 and the values obtained are very similar to those of the Jotnian sandstone in Satakunta. The high content of the intergranular silty material is characteristic of the sandstones in the Muhos formation.

The chemical composition of the Muhos sandstone (cf. Fig. 6 and Table 5) is related to that of the arkose sandstone in Satakunta. The abundance of silty matrix in the Muhos sandstone produces the higher content of Al_2O_3 and the predominance of plagioclase among the detrital feldspar causes an extremely high content of Na_2O, which indicates the immaturity of the Muhos sandstone.

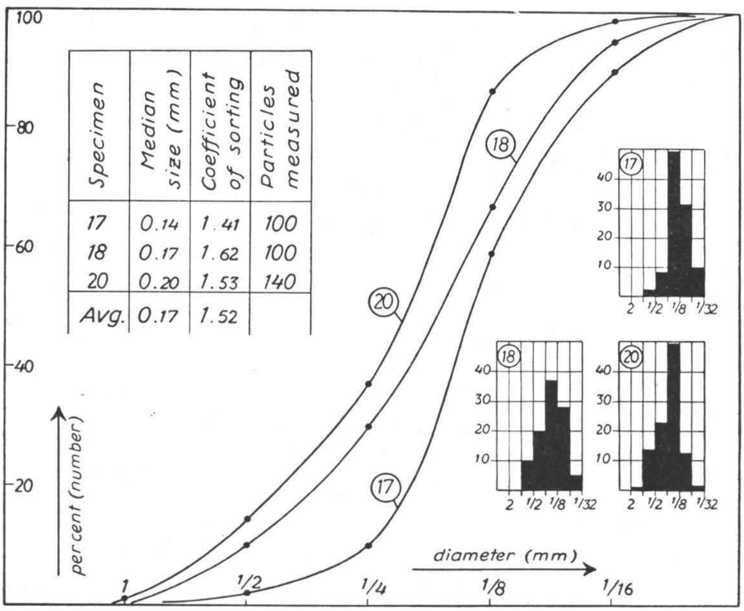

Fig. 8. Grain size distribution of the sandstones in the Muhos formation. The numbers of the specimens refer to Table 6.

Stratification and cross bedding are the only sedimentary structures observed in the Muhos sandstone. The sandy particles are mostly subangular or subrounded (Plate I, Figs. 3—4) and the grain size distribution (Fig. 8), determined from the thin sections of 3 specimens, shows that the sandstone is not well sorted. These textural features also point to the immaturity of the Muhos sandstone.

The petrographic characteristics of the sandstone in the Muhos formation are related to those of the Jotnian arkosic sandstone in Satakunta. Accordingly, the Muhos sandstone belongs to the immature sandstones which represent tectonic accumulations of slightly decomposed detrital material. The sandstones of the Muhos formation deviate, however, from those in Satakunta through a higher content of intergranular matrix and detrital plagioclase. Some silty varieties resemble graywackes, but their red color and extremely high content of Fe_2O_3 are not characteristic of sandstones of the graywacke suite. The predominance of red beds in the Muhos formation indicates an oxidizing condition of terrestrial sedimentation. The association of red shales, siltstones, and sandstones is typical of many floodplain deposits in the piedmont facies in postgeosynclinal basins.

QUARTZ SANDSTONES

COASTAL AREA OF SOUTHWESTERN FINLAND

Many small exposures of quartz sandstone are known from the coastal area of southwestern Finland. All of these sandstones are protected from erosion, because they occur as fillings of fault cracks in the pre-Cambrian rocks or are fillings of cavities in the pre-Cambrian crystalline limestone. The ancient peneplain on which these sandstones were deposited has stood slightly above the present surface. A brief petrographic description of the different sandstone occurrences is given below.

Saltvik. This yellowish grey sandstone occurs as filling of vertical fissures in the late pre-Cambrian rapakivi granite. Altogether 8 sandstone dikes, measuring from a few centimeters up to 60 cm in thickness, have been found in Långbergsöda, Saltvik. One of these dikes contains fossil Brachiopods of Cambrian age. The mode of occurrence of the sandstone has been reported by Tanner (1911) and the fossils have been described by Metzger (1922).

Table 7. Mineralogical composition (volume per cent) of the quartz sandstones in the coastal area of southwestern Finland

Locality	Particles				Cement and inter-granular matrix
	Quartz	Feldspar	Rock fragments	Accessories	
25. Saltvik	73.8	5.0	8.8	1.0	11.4
26. Saltvik	86.2	1.9	0.5	0.5	10.9
27. Saltvik	72.2	1.5	0.5	1.1	24.7
28. Saltvik	66.6	1.3	12.9	0.6	18.6
29. Saltvik	81.3	1.3	1.5	0.5	15.4
30. Lemland, Lemböte	74.8	9.5	1.7	0.8	13.2
31. Vestanfjärd, Lammala	90.9	—	—	0.3	8.8
32. Hiittinen, Sisan	86.3	0.2	1.5	—	12.0
33. Hanko, Skarvkyrkan	81.2	0.4	0.3	0.4	17.7

The mineralogical composition of 5 sandstone specimens from Saltvik is presented in Table 7. The sandstone is rich in quartz and poor in feldspar. The quartz particles are rounded or subrounded. The feldspar is red-colored potash feldspar whose X-ray diffraction data shows a monoclinic symmetry, indicating that the feldspar is derived from the surrounding rapakivi granite. Small rock fragments of rapakivi granite are also present. The angularity of most of the feldspar particles and rock fragments indicates that they are not primary components of the highly decomposed sandstone, but are probably derived from the walls of the sandstone dike. The rich occurrence of tourmaline as heavy mineral is characteristic. Also minute amounts of zircon, rutile, and apatite have been found in the heavy mineral fraction. The cement is siliceous and a secondary outgrowth of the quartz particles is common.

The grain size distribution and sorting (Fig. 9) varies greatly in different specimens. It is probable that the observed grain size distribution does not represent the original grain size distribution, because many different sizes may have been mixed together when the sand filled the open vertical fissure.

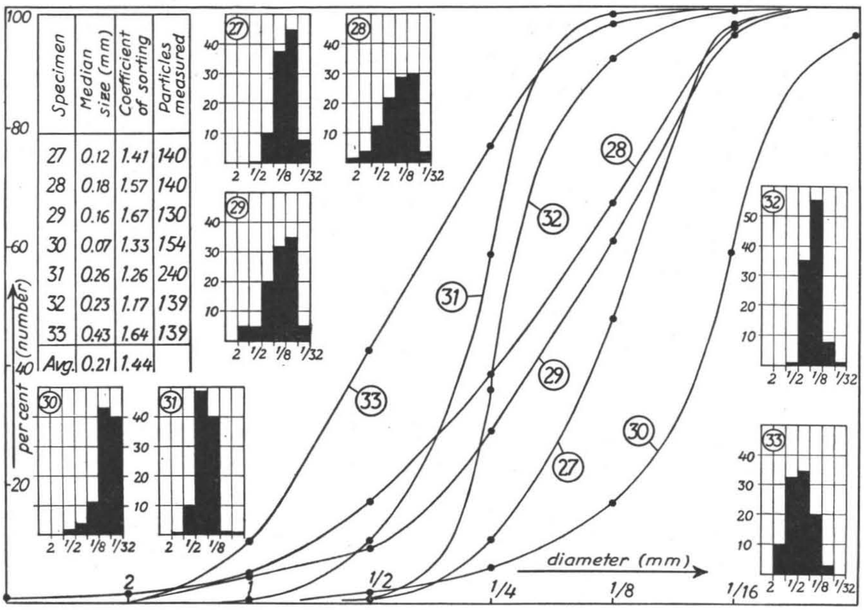

Fig. 9. Grain size distribution of the sandstones in the coastal area of southwestern Finland. The numbers of the specimens refer to Table 7.

L e m l a n d. Two sandstone dikes cutting the rapakivi granite of Åland have been found by Kaitaro (1949) in Lemland. The mineralogical composition of the sandstone at Lemböte in Lemland is given in Table 7. Quartz is the main component, but the content of potash feldspar is also remarkably high. The sandstone is rather fine-grained and most of the quartz particles are rounded. The sandstone also contains larger subangular particles of quartz, potash feldspar, and graphic rapakivi granite. It seems probable that these subangular particles were derived from the surrounding rapakivi, and that they did not take part in the long abrasion history of the small quartz particles. The introduced cement is siliceous and a secondary outgrowth of the quartz particles is common. Sorting (Fig. 9) is much better than in the sandstone of Saltvik.

O t h e r s a n d s t o n e d i k e s i n t h e Å l a n d a r e a. In addition to the occurrences mentioned, narrow sandstone dikes cutting the rapakivi granite of Åland have been found in the following places: on the skerry of Karlbybådar in Kökar (Sederholm, 1924), on the skerry of Yttre Borgen in Eckerö (Asklund and Kulling, 1926), and in the islands of Bredan and Venningbådan in the northeastern part of the Åland area (Sederholm, 1934). Furthermore, Kaitaro (1953) has found a sandstone dike in the late pre-Cambrian Åva granite on the skerry of Kummelören. The petrographic characteristics of these quartz sandstones are similar to those of the afore-described sandstones in Saltvik and Lemland.

Parainen. The petrography of the sandstone in Parainen has been described by Hausen (1934) and the following short description is based on his investigation. The sandstone bed is as much as 1 meter thick and overlies a thin kaolin bed. Both of these beds occur as fillings of a cavity in the pre-Cambrian limestone. The sandstone is a pure quartz sandstone with no feldspar. The heavy minerals are psilomelane, zircon, and magnetite. Limonite and introduced siliceous matter form the cement. The sandstone is rather coarse-grained, containing mostly particles measuring from 0.3 to 1 mm in diameter. The roundness of the particles varies greatly. Cross bedding is the only sedimentary structure observed.

Vestanfjärd. Two occurrences of sandstone filling cavities in the pre-Cambrian limestone at Illo and Lammala in the parish of Vestanfjärd have been thoroughly described by Eskola (1913). The sandstone is brownish yellow and quartz is the main component of the mineral particles (cf. Table 7, N:o 31). Only very few strongly weathered feldspar particles have been found. Small pebbles of quartz, 4—20 mm in diameter, and fragments of grey shale occur occasionally. The heavy minerals observed by Laitakari (1932) are as follows: zircon, rutile, magnetite, and ilmenite. Limonite and introduced siliceous matter usually form the cement, but in a few cases calcite, too, occurs as large crystals. A secondary outgrowth of quartz particles is common. The particles are extremely well rounded and the sandstone is well sorted (cf. Fig. 9).

Hiittinen. A sandstone dike cutting the Archean migmatitic basement has been found by Edelman (1949) on the skerry of Sisan in the parish of Hiittinen. This sandstone is also very pure quartz sandstone (Table 7, N:o 32) with introduced siliceous cement. Small fragments of chert also occur as sandy particles. The particles are subrounded or rounded and the sorting of the sandstone (cf. Fig. 9) is the best among the specimens from the coastal area studied.

Hanko, Skarvkyrkan. This sandstone dike cutting the pre-Cambrian migmatites was found by Sederholm (1913 b) on the skerry 20 km east of the town of Hanko. Petrographically the sandstone is very similar to the other exposures in the coastal area. Quartz is the main detrital component (Table 7, N:o 33). The cement is siliceous and secondary outgrowths on the quartz particles are common. The particles are subrounded and rounded and grades of many sizes are present (Fig. 9).

In addition to the outcrops mentioned, the Glacial boulders of sandstone are common in the coastal area of southwestern Finland. Most of the sandstone boulders consist of red-colored, arkosic sandstone of Jotnian type, but also fossiliferous Cambrian sandstone with calcareous cement is usual in the drift material. Observations on the distribution of the sandstone boulders have been given by many authors (Hausen, 1911; Eskola, 1913; Laitakari, 1925; Metzger, 1927; Hellaakoski, 1930; Edelman, 1951; Marmo and Laitakari, 1952) and it seems probable that sandstone occurs in many places at the bottom of the sea, especially north of the Åland Islands.

The sandstones in the outcrops of the coastal area are very similar to each other and their ratio of quartz to feldspar (Fig. 13) shows a maturity produced by an intense chemical weathering. The textural features, as the good rounding and sorting, are also characteristic of mature sandstones. The cement of the sandstones in the coastal area is commonly siliceous. Calcareous cement has been found only in some varieties of sandstone in Vestanfjärd and in Glacial boulders of the sandstone. These kinds of mature quartz sandstones are typical of the foreland facies of sedimentation during transgression of a stable platform with a low relief. The petrographic similarity to Cambrian sandstones in Sweden thoroughly described by Hadding (1929) and the Cambrian fossils found in the sandstone of Saltvik and in the Glacial boulders of calcitic sandstone indicate a Cambrian age for the sandstones of the coastal area. The mature sandstones of a foreland facies are commonly associated with limestones. It should be noted that Cambro-Silurian limestone is known in Lumparn, Åland, and Glacial boulders of fossiliferous Cambro-Silurian limestone are common in the coastal area of southwestern Finland. The probable association of quartz sandstone and limestone, representing the same facies of sedimentation, also provides evidence that the sandstone outcrops belong to the early Paleozoic age. The fossils of the Cambro-Silurian age found in sandstones and limestones in southwestern Finland have been described by Metzger (1922 and 1927). A Mesozoic age was suggested by Hausen (1934) for the sandstones in Parainen and Vestanfjärd, but no valid evidence has been found for a marine transgression at that time in southwestern Finland.

SANDSTONE OF LAUHAVUORI

The widest occurrence of quartz sandstone in Finland is in Lauhavuori, Southern Ostrobothnia. This sandstone is very resistant to erosion, and forms the wide Lauhavuori hill, which is the highest place (about 230 meters above sea level) in this part of the country.

A geological map of the sandstone area is presented in Fig. 10. This map is based on field work carried out by K. Kauranne, M. A., in the summer of 1951 under the supervision of the senior author (A. S.) of the present paper.

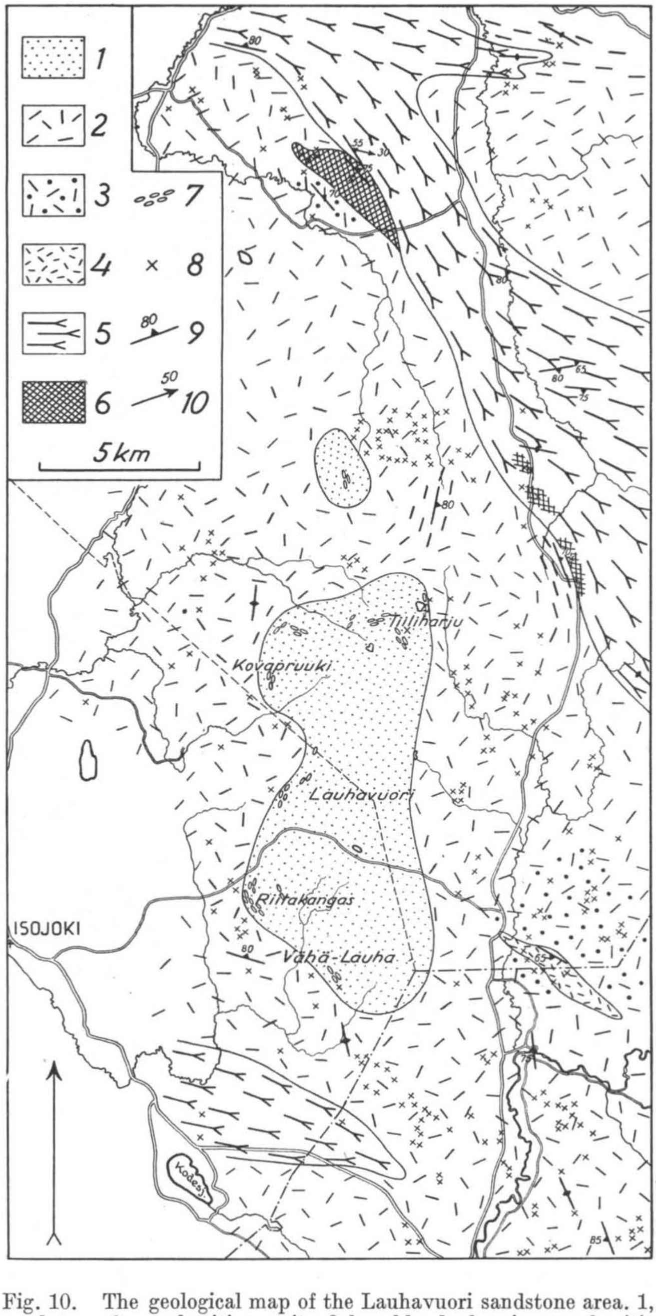

Fig. 10. The geological map of the Lauhavuori sandstone area. 1, sandstone; 2, porphyritic granite; 3, hornblende-bearing porphyritic granite; 4, even-grained granite; 5, gneissose granodiorite; 6, gabbro; 7, boulder field of the sandstone; 8, outcrop; 9, strike and dip of foliation; 10, lineation.

The sandstone occupies about 60 square kilometers. The surrounding country rock consists of pre-Cambrian igneous rocks belonging to the infracrustal rock complex of Central Finland. The sandstone is covered by Pleistocene deposits and only two outcrops of it have been found (Plate III, Fig. 9).

Boulder fields of the late-Glacial shores along the slopes of the Lauhavuori hill have been useful for geological mapping, because the angular boulders of these boulder fields consist exclusively of the local sandstone (Plate III, Fig. 10). These boulder fields, which give an idea about the distribution of the sandstone, are up to 100—250 meters long and 20—50 meters wide and the boulders measure from some dm^3 to 2 m^3 in volume. The largest boulders have been locally used as millstones.

The boulder train of the Lauhavuori sandstone owing to the movements of the Pleistocene ice-sheet also suggests a wide distribution of the sandstone (Fig. 11). The glacial boulders of the sandstone are most abundant close to the sandstone area, making up more than 1/3 of the total drift material, but farther away they become sparse. The direction of the boulder train agrees very well with the striae observed in the region around the sandstone occurrence.

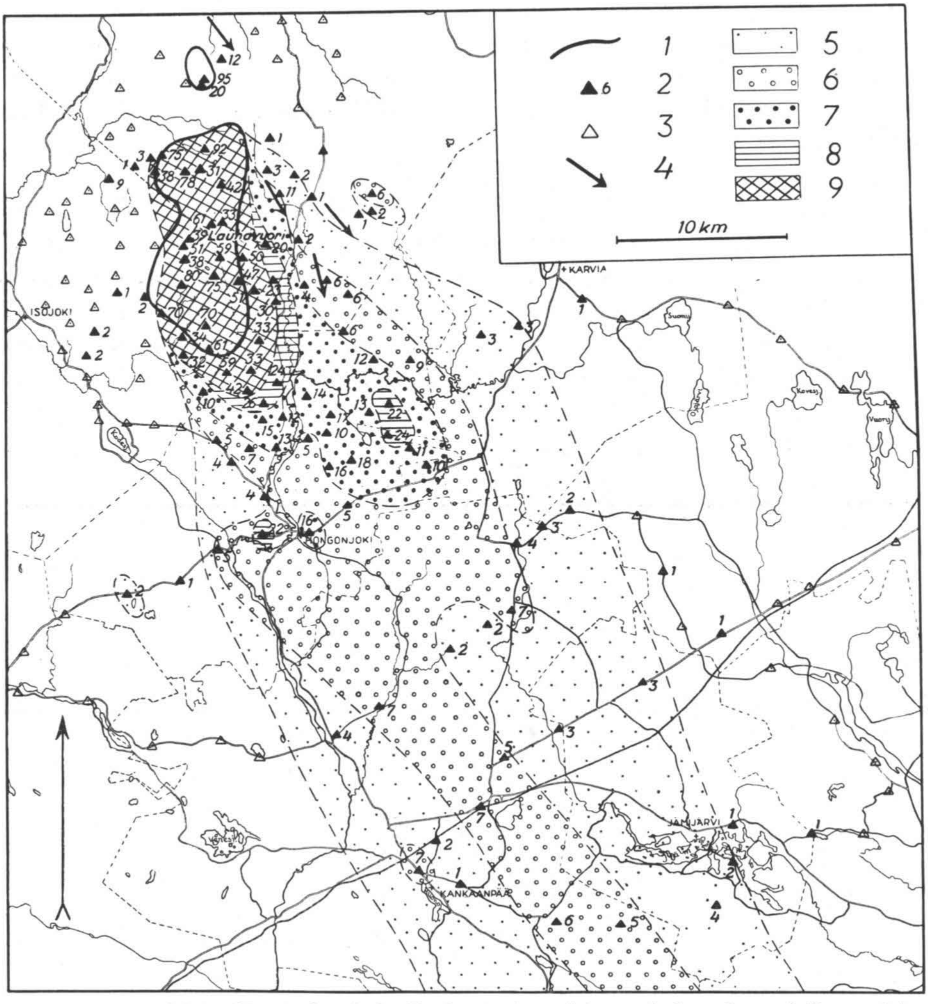

Fig. 11. The Glacial boulder train of the Lauhavuori sandstone. 1, boundary of the sandstone area; 2, percentage of Lauhavuori sandstone boulders in the drift material; 3, no boulders of Lauhavuori sandstone in the drift material; 4, striae; 5—9, contours for the frequence of distribution of Lauhavuori sandstone boulders; 5, 2—5 %; 6, 5—10 %; 7, 10—20 %; 8, 20—30 %; 9, over 30 %.

The sandstone occupies the highest places in the present topography and it occurs as a thin sheet upon the pre-Cambrian basement. The thickness of the sandstone formation is not exactly known, but on the basis of the topographic map of the Lauhavuori hill made by Olander (1934) it is only some ten meters. Outcrops of Archean porphyritic granite appear immediately below many boulder fields of sandstone blocks.

The Lauhavuori sandstone is light-colored with shades of pale red, yellow or brown. The size of the sand particles varies greatly in different beds. Usually the grain size ranges from 0.2 to 0.5 mm, but conglomeratic varieties with well-rounded quartz pebbles also occur. The diameters of the quartz pebbles are commonly 0.5—2 cm but the largest quartz cobble observed was 15 cm in diameter. Conglomeratic sandstones are abundant in the boulder fields of Riitakangas and Vähä-Lauha in the southern part of the sandstone area. A few boulders containing angular fragments of very much altered porphyritic granite have also been found in the boulder field of Vähä-Lauha (Plate IV, Fig. 13). The red-colored porphyritic granite boulders are strongly silicified and the feldspar grains are entirely kaolinized. The matrix is quartz sandstone rich in kaolin. These conglomerate boulders probably represent the basal part of the Lauhavuori sandstone deposited on a deeply weathered surface of porphyritic granite.

Table 8. Mineralogical composition (volume per cent) of the quartz sandstones in Lauhavuori and Karstula

Locality	Particles				Cement and intergranular matrix
	Quartz	Feldspar	Rock fragments	Accessories	
Lauhavuori:					
34. Vähä Lauha	74.3	1.3	5.6	1.0	17.8
35. Riitakangas	71.9	1.4	2.9	0.5	23.3
36. Iso Lauha	73.7	1.1	0.1	—	25.1
37. Tiiliharju	78.7	0.5	0.1	0.1	20.6
38. Riitakangas	73.6	0.4	0.5	0.2	25.3
39. Kovapruuki	70.3	0.2	0.1	0.8	28.6
40. Riitakangas	75.7	0.1	5.6	0.3	18.3
41. Riitakangas	72.8	0.1	0.7	0.2	26.2
Karstula:					
42. Vahankajärvi	75.4	1.1	0.2	0.7	22.6
43. Vahankajärvi	89.3	1.0	0.8	0.3	8.6

The mineralogical composition of the Lauhavuori sandstone presented in Table 8 is typical of pure quartz sandstones. The content of strongly kaolinized feldspar is very low. Some small siliceous rock fragments are present. The content of the accessory minerals is very low. Laitakari (1932) has found the following heavy minerals: zircon, ilmenite, rutile, and magnet ite. The heavy minerals observed by the present authors in the Lauhavuori sandstone from Tiiliharju are as follows: magnetite, tourmaline, zircon, sphene, and apatite. The cement is siliceous and a secondary outgrowth of the quartz particles is common. The enlargement of the primary quartz particles by secondary outgrowth can easily be observed microscopically in the sandstone specimens, in which the original boundaries of the quartz particles are extremely clearly seen. This increase varies from 10—20 volume per cent.

Table 9. Chemical composition of the Lauhavuori sandstone from Tiiliharju (1) and composition of a clay ball (2) in the sandstone boulder from Riitakangas. Anal. Pentti Ojanperä

	1	2
SiO_2	97.36	70.21
TiO_2	0.05	0.58
Al_2O_3	0.73	10.46
Fe_2O_3	0.63	4.28
FeO	0.14	0.29
MnO	0.01	0.01
MgO	0.01	0.23
CaO	0.04	0.84
Na_2O	0.08	0.20
K_2O	0.19	0.82
P_2O_5	0.02	5.78
H_2O+	0.54	5.18
H_2O-	0.14	0.82
	99.94	99.70

The highly siliceous character of the Lauhavuori sandstone appears also in the chemical analyses presented in Table 9. The analyzed specimen from Tiiliharju contains small amounts of kaolin material.

Stratification (Plate IV, Fig. 12) and cross bedding are common structural features of the Lauhavuori sandstone. Clay balls (Plate IV, Fig. 11) in the sandstone are also found, the greatest diameter of the well-rounded or flattened balls varies from 1 to 6 cm. The material of the clay balls is very fine-grained so that microscopic determination of the minerals is impossible. The chemical composition (Table 9, Anal. 2) shows, however, that the material is a product of strong chemical weathering. The high content of P_2O_5 is remarkable, but it was not possible for the authors to identify by the microscope and X-ray powder diagram the phosphate mineral present in the analyzed clay ball. No microfossils were found in the clay ball separations made and investigated by Dr. K. Mölder.

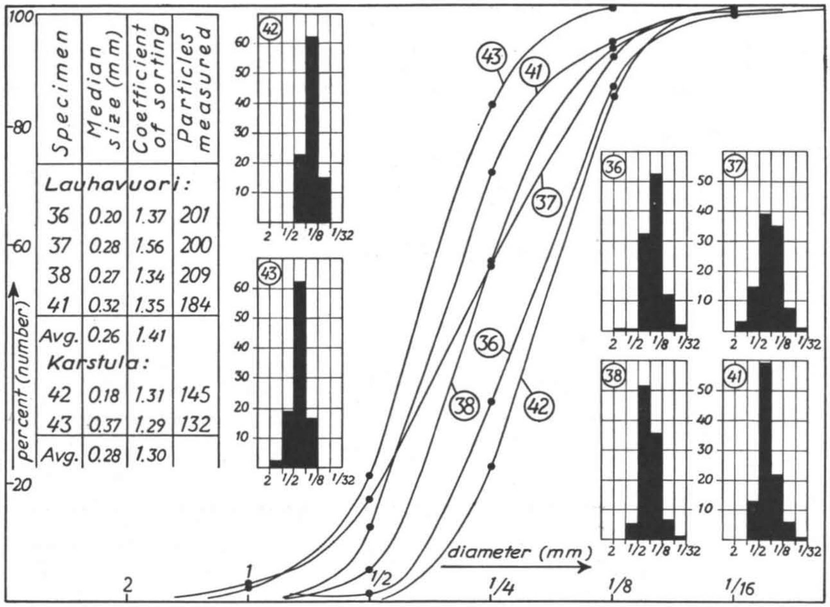

Fig. 12. Grain size distribution of the sandstones in Lauhavuori and Karstula. The numbers of the specimens refer to Table 8.

The mineral particles of the Lauhavuori sandstone are extremely well-rounded (cf. Plate I, Figs. 5—6) and the sorting (Fig. 12) is good.

Mineralogical, chemical, as well as textural features of the Lauhavuori sandstone are typical of mature sandstones which are products of prolonged chemical and mechanical processes during weathering and sedimentation. Determination of the geological age is difficult, because valid evidence is lacking. On the basis of the petrographic features the conditions of sedimentation were, however, similar to the Cambrian quartz sandstones in the coastal area of southwestern Finland. The Lauhavuori hill probably is the place where the Paleozoic (sub-Cambrian) peneplain has not been destroyed by later erosion as is the case in the coastal area where the sandstone dikes indicate that the ancient peneplain originally was a little above of the present surface.

SANDSTONE OF KARSTULA

This sandstone is known only as a rich local occurrence of Glacial boulders. Its main petrographic features were given by Sauramo (1916). The mineralogical composition (Table 8) shows that the Karstula sandstone is very pure quartz sandstone. The cement is siliceous and the secondary outgrowth of the quartz particles is common. Stratification and cross bedding are the structural features observed. The sand particles are extremely well-rounded and the sorting (Fig. 12) is very good. The petrographic characteristics of the Karstula sandstone are very closely related to those of the other quartz sandstones in Finland. The sandstone of Karstula marks, so far as known, the eastern limit of the early Paleozoic transgression in Central Finland.

SUMMARY AND CONCLUDING REMARKS

The sedimentary petrographic features described in this paper show that the unmetamorphosed sandstones in Finland are either arkoses or pure quartz sandstones. Mineralogically the most remarkable difference between these sandstone types is seen in the ratio of quartz to feldspar, which is the index of maturity giving an idea of the effectiveness of the chemical and mechanical processes. Fig. 13 shows that the ratio of quartz to feldspar

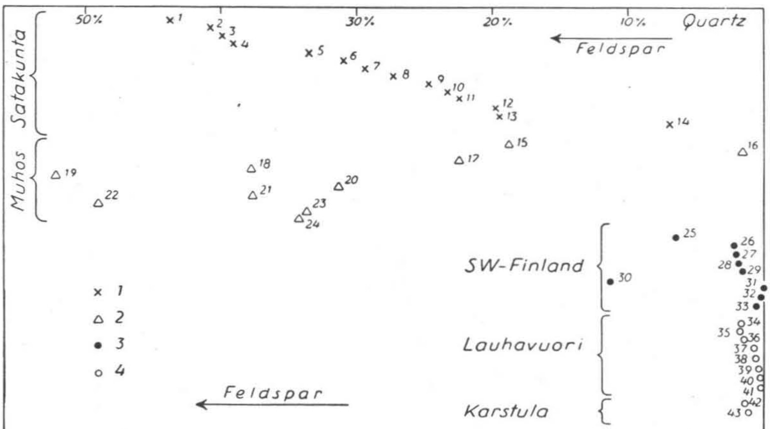

Fig. 13. The ratio of quartz to feldspar in the sand particles of the Finnish sandstones. 1, Jotnian arkose sandstones in Satakunta; 2, sandstones and sandy siltstones in Muhos; 3, quartz sandstones of the coastal area of southwestern Finland; 4, quartz sandstones in Lauhavuori and Karstula. The numbers refer to the specimens in Tables 2, 6, 7, and 8.

in the sandstones of Satakunta and Muhos varies within the same limits and the feldspar occupies commonly 20—50 per cent of the total amount of sand particles. Detrital feldspar of the Satakunta sandstone is predominantly potash feldspar, but in the Muhos sandstone feldspar is mainly plagioclase, which is unusual for arkoses generally. The quartz sandstones in Finland form a well separated group, where the content of the feldspar particles is only a few per cent. In two specimens of quartz sandstones (Fig. 13, No 25 and 30) the feldspar content is remarkable high, but a petrographic study of these specimens (see p. 72—73) revealed that the feldspar has not undergone long abrasion, as have the quartz particles.

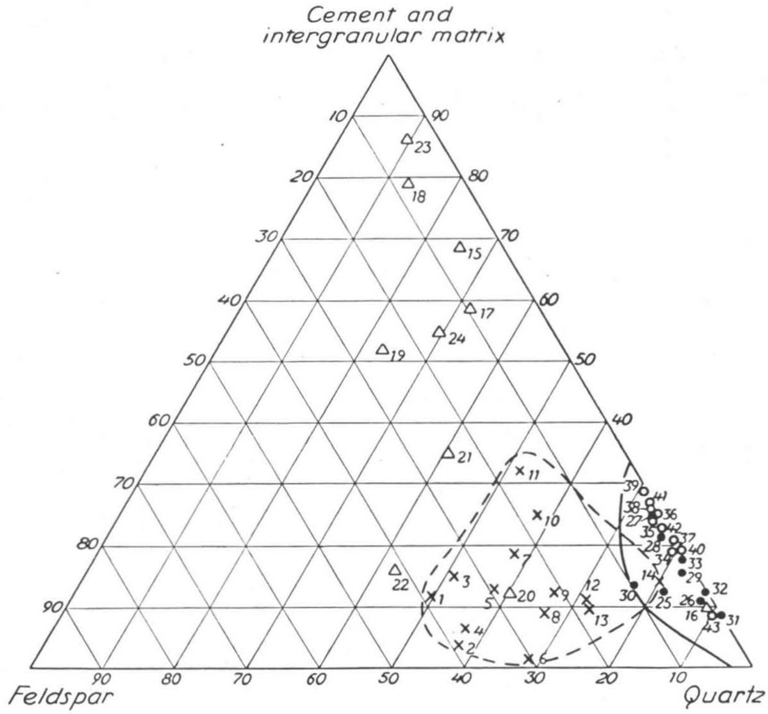

Fig. 14. The proportions of quartz and feldspar particles and matrix in the Finnish sandstones. The key is like that of Fig. 13.

The petrographic characteristics of the sandstones in Finland are also seen in the triangle diagram (Fig. 14), which shows the proportions of the quartz and feldspar particles and the matrix. The quartz sandstones form a clearly separated field in the quartz corner of the diagram. The sandstones of the Muhos formation deviate from those in Satakunta through higher content of intergranular matrix. The sandstones of Satakunta are for the most part typical arkoses, whereas the Muhos sandstones pass into impure sandstones and siltstones. Some impure varieties of the Muhos sandstone resemble graywackes, but their red color and high content of Fe_2O_3 are not characteristic of the sandstones of the graywacke suite, which are deposits of the reducing condition of sedimentation. The cement of the quartz sandstones is introduced siliceous matter and a secondary outgrowth of quartz particles is common. The intergranular matrix of the arkoses chiefly contains silty material and a secondary outgrowth of quartz particles is observed only occasionally.

The afore-mentioned mineralogical differences of the sandstones in Finland naturally cause differences in the chemical composition (cf. Tables 3, 5, and 9). The immature arkoses are characterized by a remarkable content of alkalies and Al_2O_3, whereas the quartz sandstones are highly siliceous, containing over 90 per cent of SiO_2. Furthermore, the Muhos sandstones characterized by the abundance of the silty matrix and detrital plagioclase contain more Al_2O_3 and Na_2O than the arkoses of Satakunta.

The mineralogical differences of the Finnish sandstones appear also in the quality of the heavy minerals. The Jotnian arkose sandstone contains many different species of heavy minerals, whereas the quartz sandstones contain only a few species especially resistant to weathering.

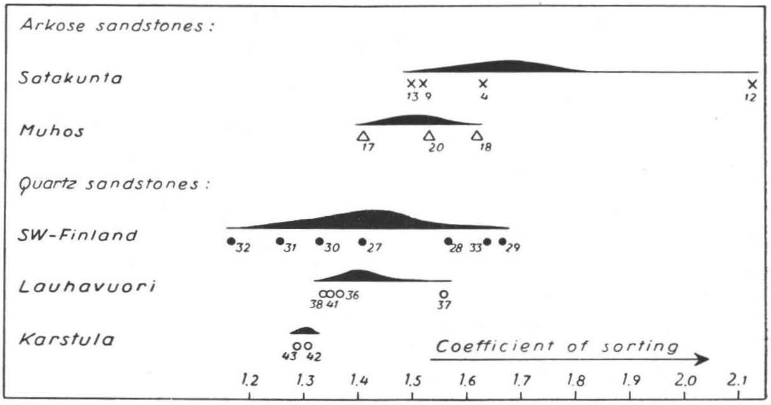

Fig. 15. The coefficient of sorting in the sandstones of Finland. Based on the determinations presented in Figs. 4, 8, 9, and 12.

Textural differences in the sandstones of Finland are found in the degree of roundness and sorting of the particles. The sand grains of the arkoses are mainly subangular or subrounded, whereas those of the quartz sandstones are usually rounded or extremely well rounded. The coefficients of sorting plotted in Fig. 15 show that the quartz sandstones are usually better sorted than the arkoses.

The petrographic characteristics of the sandstones depend on the conditions of origin and deposition controlled by tectonics. The members of the three major classes of sandstones (graywackes, arkoses, and quartz sandstones) represent certain stages in the pulse of the earth characterized by the alternation of orogenic and nonorogenic phases of evolution. The graywackes are typical orogenic sandstones deposited in geosynclinal troughs. Thick accumulations of arkose sandstone are postgeosynclinal deposits usually associated with uplift of the source area after orogenic folding. The pure quartz sandstones are typical for the nonorogenic peneplanation evolutionary phase. The three tectonic stages, controlling the deposition of the sandstones, have been emphasized especially by Krynine (1941).

In the light of the tectonic classification of sandstones we may state that the late pre-Cambrian Jotnian arkose sandstone in Satakunta is postgeosynclinal in relation to the pre-Cambrian, Karelidic orogeny. This has been generally agreed upon by Swedish and Finnish geologists. The importance of the continued vertical tectonic movements, controlling the Jotnian sedimentation, has been stressed by Eckermann (1937 a, b) in his comprehensive studies of the Fennoscandian Jotnian formations. The fault movements connected with the intrusion of the rapakivi granites (latest postkinematic granites of the Karelidic orogeny) have caused rifts and depressions where the Jotnian sediments accumulated. It should be noted that the Jotnian sandstone area in Satakunta forms a downfaulted block in the Archean basement complex.

The petrographic features of the Muhos formation support the conclusion that it belongs to the postgeosynclinal deposits. The basal conglomerates containing pebbles of the Karelidic schists indicate that the Muhos formation is postgeosynclinal in relation to either pre-Cambrian Karelidic or early Paleozoic Caledonidic orogeny. That the Muhos formation belongs to the late pre-Cambrian age is plausible, because no fossils have been found. On the basis of a tectonic classification of sandstones, the Muhos formation is related to the Jotnian formations. The correlation of the Muhos rocks with the Jotnian formation in Satakunta is suggested also by similar petrographic features and a similar manner of occurrence in downfaulted blocks of the crystalline basement. Brenner (1941 and 1944) suggested that the Muhos formation belongs to the Mesozoic age, but no valid evidence was presented. Brenner based his conclusion on the occurrence of a Belemnite fossil said to have been found in the Glacial drift material at Kankari. Later the finder of this Belemnite denied the report (cf. Viluksela, 1951).

The petrographic characteristics of quartz sandstones in Finland deviate strongly from those of the arkosic sandstones and are typical for the sandstones of the peneplanation stage. Similar sandstones of the Cambrian age occur abundantly in the Baltic countries and Sweden and it seems therefore probable that the sporadic occurrences in Finland indicate a Cambrian transgression over a stable peneplained platform. The occurrence of the fossiliferous quartz sandstone in Saltvik affords direct evidence of the Cambrian age.

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REFERENCES

ASKLUND, B. och KULLING, O. (1926), Nya data till Ålands geologi. Geol. Fören. i Stockholm Förhandl. 48, p. 498.

BRENNER, THORD (1941) Ein ungewöhnliches Kalk-Schlammsteinsediment von Muhos in Mittelfinnland. Geol. Rundschau 32, p. 535.

—»— (1944) Die Bodenbildungen des Muhos-Sediments bei Kieksi. C. R. Soc. géol. Finlande 16; Bull. Comm. géol. Finlande 132, p. 189.

CLARKE, F. W. (1924) Data of geochemistry. U. S. geol. Surv. Bull. 770, p. 34.

VON ECKERMANN, HARRY (1937 a) The Jotnian formation and the sub-Jotnian unconformity. Geol. Fören. i Stockholm Förhandl. 59, p. 19.

—»— (1937 b) The genesis of the Jotnian sediments. Geol. Fören. i Stockholm Förhandl. 59, p. 548.

EDELMAN NILS (1949) Sandsten. Geologi 2, p. 7.

—»— (1951) Glacial abrasion and ice movement in the area of Rosala-Nötö, S. W. Finland. C. R. Soc. géol. Finlande 24; Bull. Comm. géol. Finlande 154, p. 157.

ENKOVAARA, A., HÄRME, M. ja VÄYRYNEN, H. (1953) Suomen Geologinen Yleiskartta. Lehdet C5—B5. Oulu—Tornio. Kivilajikartan selitys.

ESKOLA, PENTTI (1913) On phenomena of solution of Finnish limestones and on sandstone filling cavities. Bull. Comm. géol. Finlande 36.

GYLLING, K. H. N. (1887) Zur Geologie der Cambrischen Arkosenablagerung des westlichen Finnlands. Zeitschr. d. deutsch. geol. Ges. 39, p. 770.

HADDING, ASSAR (1929) The pre-Quaternary sedimentary rocks of Sweden. III. The Paleozoic and Mesozoic sandstones of Sweden. Medd. Lunds Geol. Min. Inst. 41.

HAUSEN, H. (1911) Stenräkningar på Åland. Geol. Fören. i Stockholm Förhandl. 33, p. 495.

—»— (1934) Über ein neunentdecktes Kaolin-Sandstein-Vorkommen im kristallinen Kalkstein auf Pargas—Ålön, Gegend von Åbo—Turku, SW. Finnland. Acta Acad. Aboensis Mathem. et Phys. 8, p. 1.

—»— (1942) Der Abschnitt Finlands der kaledonischen Überschiebungszone. Soc. Scient. Fennica. Comm. Phys.—Math. 11.

HELLAAKOSKI, AARO (1930) On the transportation of materials in the esker of Laitila. Fennia 52, No. 7.

KAHMA, AARNO (1951) On contact phenomena of the Satakunta diabase. Bull. Comm. géol. Finlande 152.

KAITARO, SIMO (1949) Lisää kambrisia hiekkakivijuonia. Geologi 3—4, p. 13.

—»— (1953) Geologic structure of the late pre-Cambrian intrusives in the Åva area, Åland Islands. Bull. Comm. géol. Finlande 162.

KRYNINE, PAUL. D. (1941) Differentiation of sediments during the life history of a landmass. Bull. Geol. Soc. Am. 52, p. 1915.

LAITAKARI, AARNE (1925) Über das Jotnische Gebiet von Satakunta. Bull. Comm. géol. Finlande 73.

—»— (1932) Suomen kivien raskaista mineraaleista. Tekn. Aikakauslehti 9, p. 408.

LOKKA, LAURI (1950) Chemical analyses of Finnish rocks. Bull. Comm. géol. Finlande 151.

MACKIE, W. (1901) Seventy chemical analyses of rocks. Trans. Edin. Geol. Soc. 8, p. 33.
MARMO, VLADI ja LAITAKARI, AARNE (1952) Lounais-Suomen rikkikiisukonkretioista. Geoteknillisiä julkaisuja 53.
METZGER, A. TH. (1922) Beiträge zur Paläontologie des nordbaltischen Silurs im Ålandgebiet. Bull. Comm. géol. Finlande 56.
—»— (1927) Zur Kenntnis des nordbaltischen Kambro-Silurs auf Åland und im südwestlichen Küstengebiet Finnlands. Fennia 47, No. 12.
OLANDER, A. J. (1934) Lauhavuoren vanhoista rantamuodostuksista. Terra, p. 185.
PETTIJOHN, F. J. (1949) Sedimentary rocks. New York.
SAURAMO, MATTI (1916) Über das Vorkommen von Sandstein in Karstula, Finland. Fennia 39, No. 7.
SEDERHOLM, J. J. (1897) Über eine archäische Sedimentformation in südwestlichen Finland und ihre Bedeutung für die Erklärung der Entstehungsweise der Grundgebirges. Bull. Comm. géol. Finlande 6.
—»— (1913 a) Suomen Geologinen Yhteiskartta. Lehti B2. Tampere, Kivilajikartan selitys.
—»— (1913 b) Weitere Mitteilungen über Bruchspalten mit besonderer Beziehung zur Geomorphologie von Fennoskandia. Bull. Comm. géol. Finlande 37.
—»— (1924) Granit-gneisproblemen belysta genom iakttagelser i Åbo—Ålands skärgård. Geol. Fören. i Stockholm Förhandl. 46, p. 129.
—»— (1934) On migmatites and associated pre-Cambrian rocks of southwestern Finland. Part III. The Åland Islands. Bull. Comm. géol. Finlande 107.
TANNER, V. (1911) Über eine Gangformation von fossilführendem Sandstein auf der Halbinsel Långbergsöda—Öjen im Kichspiel Saltvik, Åland—Inseln. Bull. Comm. géol. Finlande 25.
TOMLINSON, C. W. (1916) The origin of red beds. J. Geol. 24, p. 153.
TWENHOFEL, W. H. (1950) Principles of sedimentation. New York.
VILUKSELA, ERKKI (1951) Der Belemnitenfund bei Kankari. C. R. Soc. géol. Finlande 24; Bull. Comm. géol. Finlande 154, p. 241.
ÖDMAN, OLOF H., HÄRME, M., MIKKOLA, A. och SIMONEN, AHTI (1949) Den svensk-finska geologiska exkursionen i Tornedalen sommaren 1948. Geol. Fören. i Stockholm Förhandl. 71, p. 113.

EXPLANATION OF PLATES

PLATE I

Fig. 1. Jotnian arkosic sandstone of Satakunta. Eura, Kiperjärvenoja. 10 x.
Fig. 2. Jotnian arkosic sandstone of Satakunta. Luvia, Lappäng. 10 x.
Fig. 3. Muhos sandstone. Diamond drill hole Liminka, depth 217.5 m. 10 x.
Fig. 4. Muhos sandstone. Diamond drill hole Muhos, depth 347.8 m. 10 x.
Fig. 5. Quartz sandstone of Lauhavuori. Riitakangas. 10 x.
Fig. 6. Quartz sandstone of Lauhavuori. Tiiliharju. 10 x. Photo: Halme.

PLATE II

Fig. 7. Ripple marks in the Jotnian sandstone. Orientation of the ripples in the successive beds is vertical to each other. Glacial boulder collected by Dr. Edelman. Nauvo. Photo: Halme.
Fig. 8. Rain impressions in the ripple-marked Jotnian sandstone. Glacial boulder collected by Dr. Edelman. Nauvo. Photo: Halme.

PLATE III

Fif. 9. Exposure of the Lauhavuori sandstone. Tiiliharju. Photo: Härme.
Fig. 10. Boulder field consisting exclusively of the Lauhavuori sandstone boulders. Kovapruuki. Photo: Härme.

PLATE IV

Fig. 11. Clay balls in the Lauhavuori sandstone. Riitakangas. ½ nat. size. Photo: Halme.
Fig. 12. Stratification in the Lauhavuori sandstone. ½ nat. size. Photo: Halme.
Fig. 13. Angular fragments of strongly altered granite in the Lauhavuori sandstone. Vähä-Lauha. ⅓ nat. size. Photo: Halme.

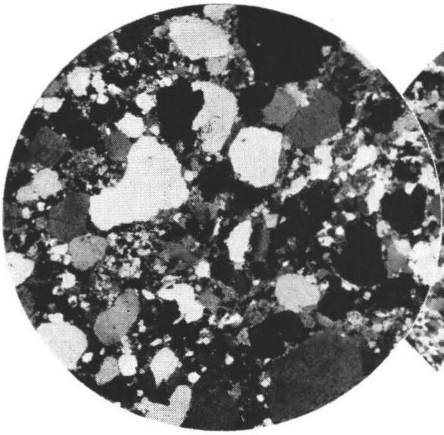
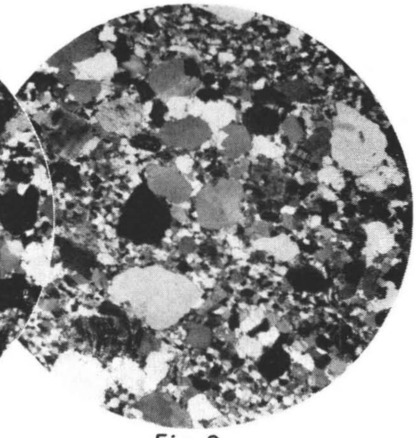


Fig. 1



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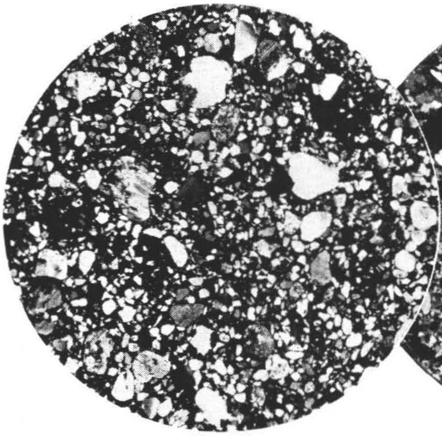

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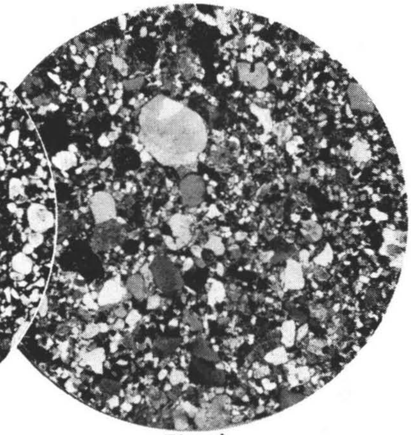

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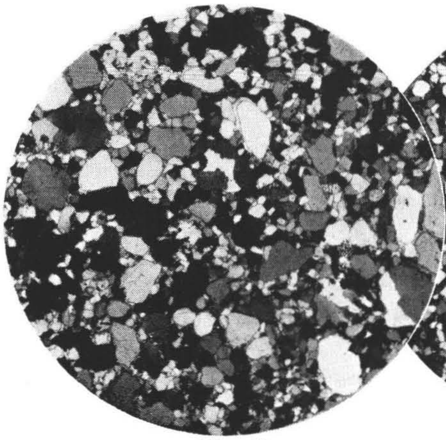

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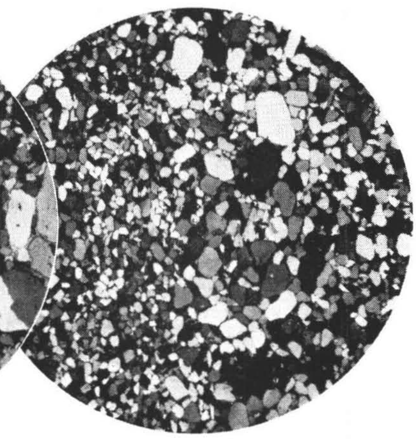

Fig. 6

Ahti Simonen and *Olavi Kouvo:* Sandstones in Finland.

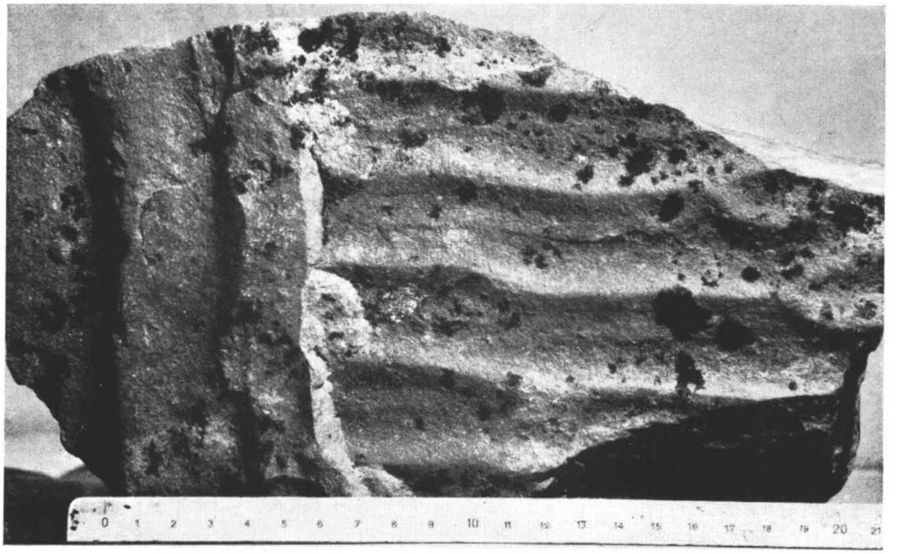

Fig. 7

Fig. 8

Ahti Simonen and *Olavi Kouvo:* Sandstones in Finland.

Fig. 9

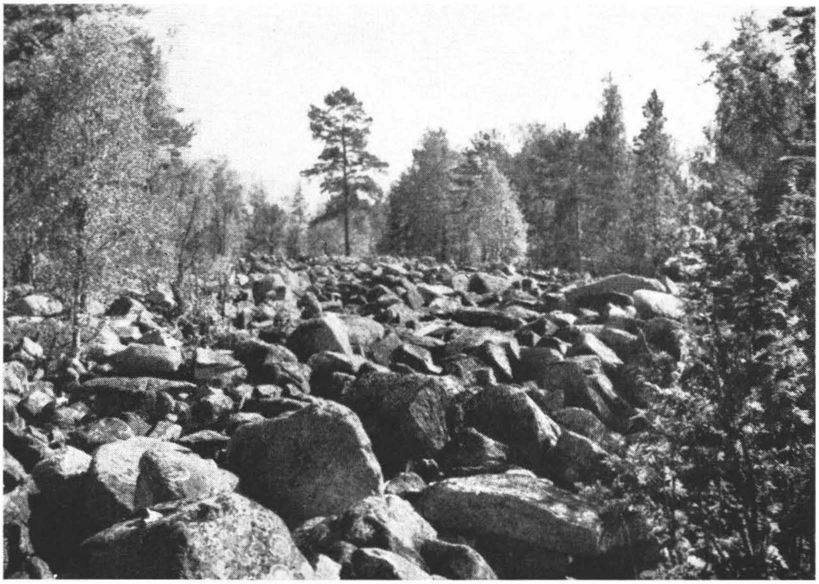

Fig. 10

Ahti Simonen and *Olavi Kouvo:* Sandstones in Finland.

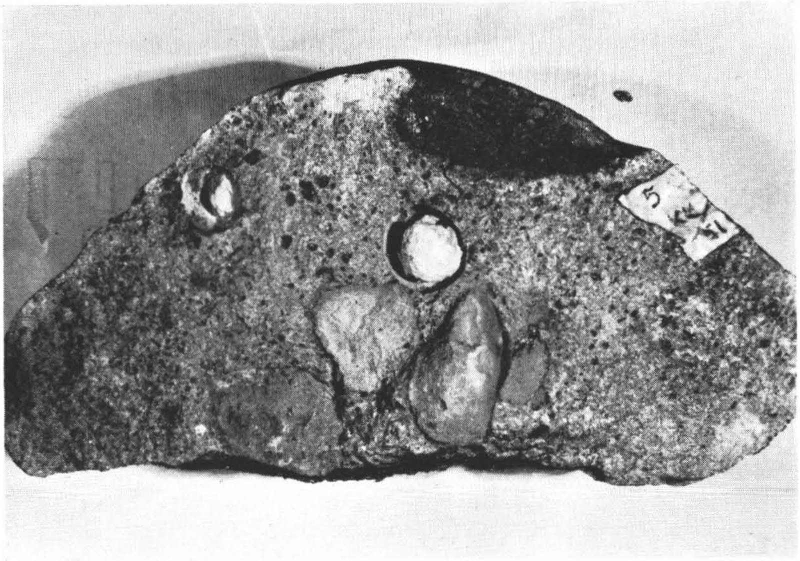

Fig. 11

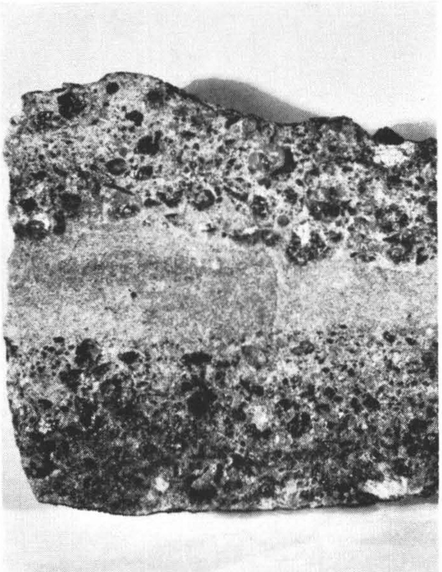

Fig.12

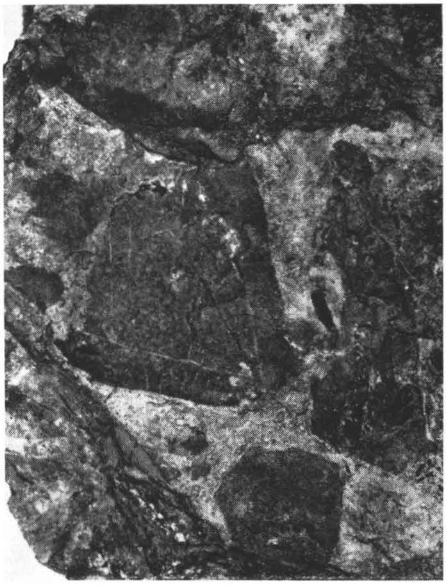

Fig. 13

Ahti Simonen and *Olavi Kouvo:* Sandstones in Finland.