SUOMALAISEN TIEDEAKATEMIAN TOIMITUKSIA. Sarja A. Nid. XXXVI, N:o 4.
ANNALES ACADEMIÆ SCIENTIARUM FENNICÆ. Series A. Vol. XXXVI, N:o 4.

CONDITIONS DURING THE EARLIEST GEOLOGICAL TIMES

AS INDICATED BY THE ARCHAEAN ROCKS

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PRINTED BY O.-Y. SANA A.-B.

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Introduction.

One of the main problems of the Archaean geology of Fennoscandia has been concentrated upon the question: Is the actualistic (or uniformitarian) method applicable to the study of the Archaean? In Finland, J. J. Sederholm has for forty years been an enthusiastic and victorious advocate of the actualistic principle, while in Sweden more exceptionalistic or antiactualistic views have partly survived.

Every geologist who has visited the Tampere region where Sederholm performed the great work of his youth (Sederholm 1899), will understand that he was impressed by the actualistic views of nature itself. Many of the outcrops of the so-called Bothnian conglomerate so perfectly resemble recent accumulations of gravels alternating with sand beds that, at the first glance, they might be taken for such, if it were not for the tilting up of the strata. And in the varved phyllite on the low rocky shores of Lake Näsijärvi one may study the bedding of the varves in the finest details just as well as in any late-Glacial varved clays. Geologists who visit these wonderful exposures for the first time usually feel doubt, not about the rock's nature of a normal aquatic sediment, but far more about its belonging to an old pre-Cambrian series.

As the observations in Finland and Sweden continued, increasingly larger parts of the Archaean rocks, in spite of their more or less thorough metamorphic habit, could be definitely interpreted either as normal sediments or as normal volcanics. All the rocks not belonging to the one or the other of these supracrustal rock classes could be referred to as deep-seated rocks, excepting those in which metamorphism has obliterated every trace of primary texture and any determination of their mode of origin is therefore not possible. To this extent the actualistic principle was adopted almost unanimously more than twenty years ago [1]).

HOLMQUIST (1907, 1908) and SEDERHOLM (1908) opened in „Geologiska Föreningens i Stockholm förhandlingar" a lively discussion of the problems of the Archaean and the application of the actualistic principle, which they have since continued in many writings. HOLMQUIST's two chief theses against SEDERHOLM were 1) that strictly actualistic principles are applicable to the later Archaean and Algonkian complexes, but not to the earlier Archaean which, according to HOLMQUIST, differs from the former especially in the

[1]) In Sweden A. E. TÖRNEBOHM had earlier stood for rather antiactualistic ideas regarding the genesis of the granite gneisses, such as the „iron gneisses" of Western Sweden, which he believed to form the substratum of the leptite formation and to have originated by a mixing of granitic magma with water vapor under the high athmospheric pressure of the primaeval ages of the earth. In his last article (1908) he wrote (in translation): „Our oldest formations, i. e. the lower part of the iron gneiss formation, have chemically and also petrographically so strong a granitic character (Swed. „tycke") that their origin must be assumed to stand in close connection with granitic masses, whose material may have undergone some, though not thorough, re-making". TÖRNEBOHM, at that time aged 70 years, concludes the paper with the following noble words of a great naturalist who regards his life-work as finished: „I have written down the above brief synopsis in order that my final view concerning the geology of our Archaean — the future may prove it to be right or wrong — cannot be misunderstood. And hereby may my contributions to the problems of the Archaean be concluded".

Since 1906 H. E. JOHANSSON († 1931), and in the last few years N. SUNDIUS and B. ASKLUND, who have done admirable work on the Archaean geology of Sweden, have advanced theories rather opposite to the somewhat neptunistic views of TÖRNEBOHM. They have applied the hypothesis of liquid immiscibility and to a certain extent rejected the theory of metamorphism. In the present paper I shall discuss some of their theories which are by their adherents rather inadequately expressed as the magmatic view (magmatiskt åskådningssätt). Great credit was due to JOHANSSON for having emphasized the chemical relations of the rocks and the ores, whatever the interpretation of these relations may be.

absence or rarity of products of normal weathering and conglomerates containing pebbles of true deep-seated granites and 2) that mountain building in the Archaean period was not confined to certain mountain chains as in later times but that the Archaean rocks show everywhere a strong deformation.

The problem of the Archaean mountain making has not yet been solved and has only recently been taken up in serious research. It will no doubt be a main problem for a coming generation of geologists. This problem will not be discussed in the present paper. Concerning the first-mentioned thesis, also, the Fennoscandian geologists have not yet become unanimous, in spite of the enormous progress in geological information.

Some of the old questions still wait to be answered and new questions have been raised: How far can the actualistic mode of origin be traced back in the Archaean series? Of what kind are the very oldest rocks? Are the hälleflintas and leptites representatives of these, and are they in all respects of the same character as acid volcanics of later ages? The physical conditions having not been uniform through the ages, but showing cyclic changes following the alternation of orogenic and anorogenic periods, it may be asked for closer details of the characteristics of „the climate witnesses", or the indicators of physiographic conditions during the Archaean periods. The earth is changeable; we must realize that it once had its origin and will once have its end. If the extension of geological knowledge, downwards in series of strata and backwards in time, will successfully continue, the actualistic method may be expected some day to prove unsatisfactory in accounting for the oldest formations. Are there any signs in the earliest formations pointing in this direction, and does it seem probable that historic geology can ever reach the time limit where the actualistic method fails definitely?

As correctly pointed out by E. Kaiser (1931), actualism is a method, not a theory, still less a law. Or, as Holmquist expressed it (1908), actualism is nothing more than a good working hypothesis.

Information concerning the conditions of origin indicated by Archaean rocks may be found in many regional investigations. Concerning the leptite regions in Sweden the works of SUNDIUS (1923), and MAGNUSSON (1925) may be mentioned among many others. On the other hand, only a few general discussions have occurred in the Fennoscandian geological literature of the last few years, perhaps the best known of these being the very suggestive paper by A. HADDING on the first rains and their geological significance, holding the idea that the leptitic rocks were deposited soon after the first condensation of water on the earth's surface. It was thought worth while, therefore, te reopen the old discussion, especially as augmented knowledge at present offers somewhat better facilities for discussing these questions than a score of years ago. We know now a little more about the regional geology of the Archaean territories of Fennoscandia. Soil science has tought us what weathering can accomplish in different climates. Experimental and theoretical petrology has furnished the means of estimating how far metamorphism may have changed the composition of the Archaean rocks.

In order to scrutinize the hypothesis of the exceptionalistic origin of the oldest Archaean rocks it seemed desirable to secure a more detailed investigation of the process of the first condensation of water upon the globe. I therefore asked Mr. RISTO NIINI, a student of mathematical physics, to perform a theoretical study of this subject starting from certain simplifying assumptions. The study of NIINI has now been published (1932). It is proposed in what follows to examine, to what degree the characters of the oldest Archaean rocks are conformable to the idea that they could have originated either before the condensation of water was completed or immediately after so that the materials of the leptites or other oldest rocks should bear witness to an origin under conditions essentially different from those which have prevailed throughout all the geological ages proper.

After this paper had been planned and the investigation work partly completed SEDERHOLM published a new paper (1931a) devoted to the problems of a sub-Bothnian unconformity and on Archaean rocks formed by secular weathering. Agreeing with SEDERHOLM as to the general bearing of the climate witnesses in these and other Bothnian rocks I shall briefly discuss certain aspects of the phenomena described in the paper just referred to.

In the summer 1931, during geological field work done for the Geological Commission of Finland, I chanced to encounter some schistose rocks showing well-preserved varve structures and calcareous concretions. These rocks show features throwing light on their mode of origin from the actualistic view-point, as they can be compared in great detail with similar formations of later times. Therefore my field observations and laboratory investigations concerning them will be described briefly below. With this description is connected a brief abstract of some other features of Archaean argillaceous sediments, especially the occurrence of carbon in them.

Varved Schist in the Archaean of Finland.

One of the newly discovered occurrences of metamorphic varved sediments in eastern Finland is situated in the Hyrsylä area, only one km from the eastern frontier of Finland at 62° N. latitude where the frontier sends out a curious projection into the Russian territory. The Hyrsylä area, being underlain by sedimentogeneous and volcanogeneous schists with basic intrusions, serpentines etc., is at present supposed to belong to a division of the Archean older than the main part of the rocks within the zone of the Karelides, although presumably younger than the ancient granites of the vast granite gneiss area of eastern Fennoscandia.

In the village of Ignoila, within the Hyrsylä area, an argillaceous schist strikes in a north-southerly direction parallel to the boundary against the supposedly older granite which lies to the east. The argillaceous schist, like the other schistose rocks of the Hyrsylä area, is much sheared up and shows a distinct linear structure in an almost vertical position. With the aid of the microscope this rock is found to be composed of quartz, biotite, and chlorite, to which is often added amphibole and epidote. Veinlets of quartz traverse the rock in the direction of the schistosity. No primary sedimentary features can be traced except in one spot which is on the south shore of the great Suojoki river where the rapids Keihäskoski are. The exposure is a low shore rock measuring only a few square metres. Pl. I fig. 1 shows its structure.

The varves are only a few millimetres thick and exceedingly distinct (Pl. I fig. 2). The direction of the varves is N 70° W, and the position vertical. The lower side of the varves faces to the northeast. A transversal shearing in the general trend of the schistosity of the surrounding rocks, here measured at N 5° W with a dip 85° W, renders the rock a well pronounced schistosity in that direction. Microscopically the minute flakes of mica and light green chlorite are found to be orientated parallel to this secondary schistosity, but there is also a parallel arrangement of components in the direction of the lamination.

Starting from the bottom of a varve, where it is lightest coloured and contains the least amounts of chlorite and biotite, it grows gradually darker from the increase of these dark minerals. The chlorite, being pale green in colour and optically positive, occurs mainly as elongated lenticular spots arranged parallel to the varves. The uppermost boundary portion of the varve is marked by an almost continuous row of chlorite spots. These spots are pseudomorphs after some aluminous silicate mineral, perhaps cordierite.

As visible from the picture, many of the shearing planes in the direction of the secondary schistosity are developed as small faults, the western side of each fault plane having moved relatively towards the south.

The transversal shearing up of the rock offers much of interest for the problem of the origin of slaty cleavage, whereas the schistose rock in its relict primary lamination is one of the best examples of varve structure which necessarily must be supposed to be due to a seasonal variation of the conditions during its deposition from water. The rock has a typical clayey composition.

The wide-spread distribution of varved schists within the vast area of mica-schists north of Lake Laatokka (Ladoga), in the parishes of Impilahti, Suistamo, Soanlahti, Ruskeala, and Harlu is known from the results of geological mapping (HACKMAN 1931). The area of their occurrence is chiefly that which was earlier separated as Ladogian, the mica-schists being regarded as an older division of the schists of Karelia. At present they are mostly grouped together with other formations of the orogenic zone of the „Karelides" (WEGMANN 1928) and the word Ladogian is used to designate a definite metamorphic and primary facies type, although it is understood that the Karelide zone probably encloses several age groups whose stratigraphy is not yet clear. In the following I shall use the term Ladogian in the sense just mentioned, i. e. Karelian schists of the Ladogian type.

HACKMAN calls the varved schists phyllites and describes them apart from the mica-schists. There are, however, all degrees of gradual transition between more coarsely and more finely crystalline varieties of schists. HACKMAN mentions varved phyllites from the north shore of Suistamojärvi in Suistamo, Soanniemi in Soanlahti, the tracts of Hämekoski on the Jäniskoski river and the village of Kerisyrjä in Impilahti, from the last-mentioned locality after the observations of SEDERHOLM.

The schists largely bear much staurolite or andalusite, and the writer has found examples of varved schists in which the crystals of staurolite are chiefly concentrated in the dark, „clayey" upper portions of the varves (fig. 1). The crystallization of staurolite in such cases is evidently due to the primary argillaceous composition of those parts of the varves. Mostly the typical varved schists do not contain megascopical porphyroblasts of aluminous minerals except mica and chlorite, but some almandite and pseudomorphs after andalusite have been commonly met with in the darker portions of the varves. I have collected specimens of varved schists from Soanniemi in Soanlahti containing staurolite and almandite. Fine exposures may be found especially on the shores of lake Jänisjärvi.

Recently a new railroad has been built from Läskelä to Pitkäranta, running through the area of the Ladogian mica-schist. East

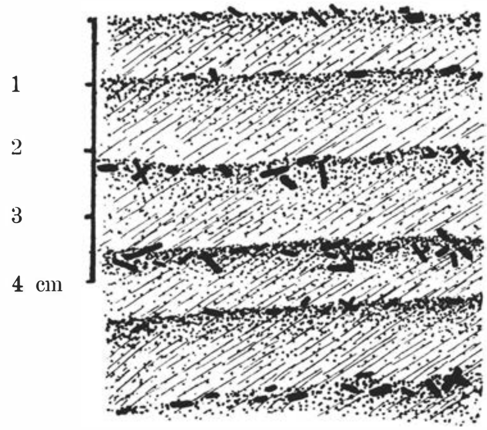

Fig. 1. Varved mica-schist showing transverse shearing and porphyroblasts of staurolite in the darker layers. Leppäsyrjä, Suistamo, Karelia.

of Läskelä the schist now exposed in many cuts is largely staurolite-bearing, and often showing lamination and calcareous concretions. The best development of the varve structure as well as the concretions were observed in the neighbourhood of the well-known old iron mine of Välimäki and the railroad station of the same name. The locality belongs to the village of Kerisyrjä where SEDERHOLM has studied varved schists.

Two single varves were loosened from a specimen collected from the railroad cut near Välimäki (where the road leading from the highroad to the mine crosses the railroad). The darkest portion of the one, and the adjacent lightest portion of the other were subjected to a quantitative examination. Each varve measured 2.5 cm passing from its quartzitic light bottom portion quite gradually over into the darkest variety at its top. The sample representing the „light portion" was 1 cm thick, taken from the bottom, and that representing the „dark portion" was of the same thickness taken from the top. A part of the intermediate middle portion was thus left. These samples were analyzed chemically by Dr. L. Lokka with the result given below (1 and 2). For the sake of further discussion I quote two analyses of the lighter and darker portion of a varve from the Bothnian phyllite on the east shore of Lake Näsijärvi in the Tampere region (3 and 4).

As there seemed to exist no modern analyses of the lighter and darker portions from a single varve of the late-Glacial sediments to be directly compared with the Archaean varved schists I asked Dr. Lokka to analyze a late-Glacial varve clay. Professor M. Sauramo kindly selected a sample for this purpose. It represents the year — 24 in Sauramo's chronology (Sauramo 1923), i. e. the varve which has been formed during the period of still-stand of the land-ice margin at the Second Salpausselkä, 24 years before the start of a new recession from this position. This varve has markedly different and sharply bounded lighter (summer) and darker (winter) portions, both about 0.5 cm thick (analyses 5 and 6).

As Sederholm remarks (1931 a), the lighter portions of the varves in the varved schists in the region north of Lake Laatokka are rather quartzitic in composition, while they have in the Tampere region the composition of an intermediate igneous rock. This difference is clearly shown by the above analyses.

Microscopically the lighter portion (fig. 2) is found to be composed of lenticular grains of quartz about 0.5 mm in their average longest diametre. The grains are mostly individual crystals and show but slightly undulating extinction. They are surrounded by flakes of biotite and chlorite, and a little muscovite. Next to the quartz grains the flakes are conformable to the outlines of these, but straight, not bent. The chlorite is pale green penninite, optically positive; its birefringence is so weak as to be hardly discernible even with the aid of a sensitive gypsum plate. Minute, almost

	1	1a	2	2a	3	3a	4	4a	5	5a	6	6a	7	7a	
SiO_2	88.36	1.4653	60.09	0.9965	63.93	1.0602	56.63	0.9391	59.20	0.9818	50.33	0.8347	57.52	0.9539	SiO_2
TiO_2	0.38	47	1.56	195	0.82	102	1.04	130	1.20	150	1.13	141	1.47	183	TiO_2
Al_2O_3	4.13	404	17.24	1687	16.92	1656	22.41	2193	16.14	1579	19.17	1876	19.26	1884	Al_2O_3
Fe_2O_3	0.65	41	1.47	92	0.79	49	0.58	36	4.36	273	6.50	407	2.94	184	Fe_2O_3
FeO	2.13	296	6.75	939	5.04	701	5.05	703	3.24	451	2.52	351	6.90	960	FeO
MnO	0.03	4	0.09	13	0.04	4	0.06	7	0.09	13	0.13	18	0.07	10	MnO
MgO	1.43	355	3.88	962	2.15	533	2.35	583	3.14	779	3.77	935	4.86	1205	MgO
CaO	0.45	80	0.95	169	1.36	242	1.28	228	2.52	449	1.43	255	0.67	119	CaO
BaO	—	—	—	—	tr.	—	0.05	—	—	—	—	—	—	—	BaO
Na_2O	1.05	169	2.08	335	1.98	319	2.31	373	3.82	616	1.78	287	1.22	197	Na_2O
K_2O	0.72	76	3.13	332	4.94	524	6.15	653	1.97	209	4.03	428	3.18	338	K_2O
P_2O_5	tr.	—	0.02	1	0.16	11	0.12	8	0.17	12	0.14	10	0.03	2	P_2O_5
S	—	—	—	—	0.02	—	0.08	—	—	—	—	—	—	—	S
$H_2O +$	0.73	—	2.33	—	1.43	—	2.19	—	1.16	—	4.87	—	1.65	—	$H_2O +$
$H_2O -$	0.09	—	0.23	—	0.23	—	0.18	—	1.15	—	3.74	—	0.12	—	$H_2O -$
C	—	—	—	—	—	—	0.31	—	1.94[1]	—	0.41[1]	—	—	—	C
	100.15		99.82		99.81		100.79		100.10		99.95		99.89		

1. Varved mica-schist, lighter portion. Railroad cut, Välimäki, Impilahti, E. Finland.
2. The same, darker portion.
3. Varved „phyllite“, lighter portion. Ajonokka, Messukylä. J. J. SEDERHOLM (1911).
4. The same, darker portion.
5. Varved sediment, late-Glacial, SS II, varve no. —24, lighter portion. Leppäkoski.
6. The same, darker portion.
7. Staurolite mica-schist. Railroad cut 1 km W. of Välimäki, Impilahti. 1a — 7a the molecular numbers.

1—2 and 5—7 analyzed by L. LOKKA, 3—4 by P. ESKOLA.

[1]) Organic substances (humus).

pigment-like opaque grains or plates may consist of iron ore, perhaps ilmenite. — From the analysis the rock may be calculated to contain 81 percent quartz, the larger part of the remainder being biotite.

The dark portion is similar in its qualitative mineral composition and also in texture, but the quartz grains are smaller and much less numerous, in proportion about 34 %. Besides the evenly distributed flakes of micas and chlorite this portion contains many nodules, some of which show nearly rhombic sections. The biggest

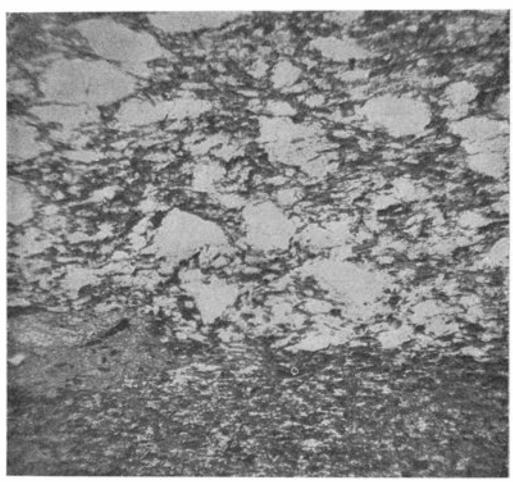

Fig. 2. Varved schist from Välimäki. On top of the lower varve there is (to the left) a spot composed of fine-crystalline muscovite, believed to be a pseudomorph after andalusite. Magn. 25 ×.

nodules are most numerous along the top line of the dark layer and are composed of a fine aggregate of muscovite; they are probably pseudomorphs after andalusite. Other smaller nodules consist of almost isotropic chlorite and may possibly be pseudomorphs after cordierite. A single nodule was found which was composed of biotite, muscovite and chlorite and contained in its centre a crystal of garnet.

The texture of the light portion with its rounded quartz grains apparently represents a primary clastic texture of quartz sand.

At a comparison of the three pairs of analyses of varved rocks given above we may first ask to what degree the differences in their composition are to be accounted for by the composition of the original material. The varved phyllite from Ajonokka in the Tampere region apparently has been derived from volcanic rocks somewhat altered by weathering. As seen in thin sections under the microscope, the lighter as well as coarser portions of the varves are markedly clastic in texture and chiefly composed of rather angular grains of potash feldspar. The cement, containing abundant biotite etc. accounts for the rather high percentage of iron oxides shown by the analysis. The closest approximation to this composition among the igneous rocks would be found among syenitic granites. Thus the high percentage of potash is apparently due to the original material.

The late-Glacial varved sediment from Leppäkoski, on the other hand, has a bulk composition which resembles the calculated average of the earth's crust in Finland (SEDERHOLM, Fennia 45, No. 18), the most notable difference being a larger percentage of silica (67.45) and smaller one of magnesia (1.69) and iron oxides (4.40) in the latter.

The composition of most other Fennoscandian late-Glacial sediments analyzed is in this respect similar to the Leppäkoski sediment. The most natural explanation of these features would seem to be found in the sorting of the materials during the glacial wear and glacifluvial outwash whereby quartz has been concentrated in the coarser sand while the softer minerals, especially biotite, have been ground finer and concentrated in the clay.

The mineralogical composition of the varved schist from Keihäskoski which has not been analyzed shows, judging from its mineral composition, a chemical character much resembling that of the late-Glacial varve sediment, also considering the difference between its lighter and darker portions.

The composition of the varved schist from Välimäki, again, also indicates a derivation from a country where granitic rocks predominated. But this sediment clearly tells of a much more profound weathering than the other above examples. Before the transportation and sedimentation the rock ground must have been disintegrated, its feldspars entirely decomposed, and large parts of its lime and alkalies leached away while the material was comparatively enriched in alumina and iron oxides; quartz was mainly left intact. This is the picture of weathering in the humid temperate climate zones of the present time. The weathered material was then attacked by the eroding work of water, transported by intermittent currents and deposited in water basins. Hereby it became well assorted, the coarser quartz being concentrated in the lighter portions while the insoluble residual products of weathering formed the essential part of the finer layers. The composition of the darker layer actually shows a high excess in alumina and a close resemblance to many recent weathering soils. The resemblance would be still closer, if iron were present as ferric oxide, while actually ferrous oxide is overwhelmingly predominant, but this feature, in all probability, is due to a change in the stage of oxidation of iron during metamorphism, being common to most highly metamorphic, i. e. once deeply buried sedimentogeneous rocks.

Thus the chemical character of the Ladogian varved schist is qualitatively similar to recent varved sediments, but more differentiated. To be sure, if in some parts of the areas of the Pleistocene glaciation varved sediments would have been formed from highly weathered materials, these could well be chemically similar to the varved Ladogian sediments. Actually some coarse late-Glacial sediments analyzed show percentages of silica up to 80 % which are considerably higher than those of the average granites.

West of Välimäki the varved mica-schist grades over into a variety containing frequent crystals of staurolite, up to 2 cm long, in a schistose mass of quartz, mica, and chlorite (analysis 7). The close similarity of this analysis with that of the fine dark portion from the varved schist is apparent. It is the same chemical composition which with very small variations characterizes shales and phyllites as well as clays of the temperate climate regions, as may be found by comparison with any set of analyses of such sediments. I regard it unneccssary to reproduce analyses for comparison. Suffice to refer, for instance, to the analyses quoted by SUNDIUS (1923, p. 44) of Cambro-Silurian and other shales from the Scandinavian mountains and other regions.

At many places near Välimäki varve structure has been considerably disturbed by a transversal shearing; quartz veins, often contorted, traverse such varieties of the schist (Pl. I, fig. 3). But at other places the sedimentary bedding is very little deformed, as shown in an exposure in a railroad cut just east of the road crossing (close to that place from which the specimen used for the analyses was collected) where the primary bedding in its finest details is visible. The strike of the bedding as well as of the schistosity is here N 20° E. The light portions, or the bottom sides of the varves, are here directed towards the west. The lighter portions of the individual varves show a cross-bedding like that often seen in sandy varves of late-Glacial sediment. Since my photograph of this phenomenon, though very distinct, did not turn out well enough, I refer to a photograph of a perfectly similar varved phyllite from the Tampere region reproduced by SEDERHOLM (1911, p. 22).

Another fine outcrop (Pl. II, fig. 4) was studied in a railroad cut about 1 km east of the Välimäki road crossing. The main strike is N 50° E, but small darker spots (pseudomorphs after cordierite?) are elongated in N 10° W, which is also the direction of many small faults (visible in the picture). The bottom lies here towards the east, unlike the outcrop described previously. The varves are really composed of numerous almost homogeneous thinner layers, and it is only as the total impression that the varves show a gradual transition from the light to the dark portions. Similar composite lamination is well known in many late-Glacial varve sediments and its meaning has been recently discussed by the northern Quaternary geologists (SAURAMO 1931). The phenomenon is believed to depend upon variations of shorter periods within those longer, yearly, periods which depict themselves in the varves. Each varve has its own very pronounced individual characteristics; thus the number, the mutual proportions and the texture of the varves of the smaller periods may be followed throughout the outcrop. Some varves, moreover, have upon their darkest top portions a thin layer of a quite light colour, in texture much resembling some of the calcareous concretions to be described below.

Calcareous Concretions in the Archaean Varved Schists.

In a railroad cut at the Välimäki station just west of the road-crossing the varves (Pl. II, fig. 5) are of a very variable breadth, from 2 to 30 cm. Strike N 5° E, dip 85° W. The varve bottoms are directed towards the west, as at the locality east of the road cut described above. Some exceptionally thick varves, one of which is visible in the photograph, contain calcareous nodules which are believed to be concretions and are thus referred to in the present paper. Here they are hardly at all flattened or elongated, but rounded, somewhat irregular, and varying from a few centimetres to a few decimetres in diametre. There are numbers of these thick varves with concretions in this outcrop; counting from the concretionary varve seen in the photograph the twentieth varve in one and the seventh varve in the opposite direction has again concretions. Thus there is no regular periodicity in the occurrence of the varves, and the same is also the case at other places.

These calcareous concretions are widely spread in the region in question and they have repeatedly been described and discussed. It is to be noted that the Karelian schists also contain other kinds of nodules or concretions, but here only the calcareous concretions will be considered. Even these are exceedingly variable in composition, as will appear from a brief enumeration of some examples.

Starting from those depicted in Pl. II, fig. 5, one of them was found to consist mainly of calcite and epidote, the latter forming big poikiloblastic individuals of variable birefringence. At the

	8	8a	9	9a	10	10a	11	11a	11b
SiO_2	61.76	1.0242	66.20	1.0978	73.44	1.2179	23.92	0.3967	53.48
TiO_2	0.44	55	0.47	59	0.46	57	0.62	77	1.39
Al_2O_3	17.73	1735	15.08	1475	13.57	1328	6.82	667	15.25
Fe_2O_3	0.08	5	0.04	2	0.54	34	1.12	70	2.50
FeO	3.60	501	2.94	409	2.64	367	2.57	358	5.75
MnO	0.14	20	0.18	25	0.04	6	0.93	131	2.08
MgO	1.42	352	1.12	278	0.86	213	2.26	560	5.05
CaO	13.31	2373	12.31	2195	2.98	531	31.35	5589	1.01
Na_2O	0.66	106	0.77	124	2.94	474	1.16	187	2.59
K_2O	0.18	19	0.07	7	1.45	154	1.84	197	4.11
P_2O_5	0.32	22	0.23	16	0.13	9	0.36	25	0.80
H_2O+	0.52	—	0.49	—	0.72	—	2.04	—	4.56
H_2O-	0.10	—	0.08	—	0.06	—	0.64	—	1.43
CO_2	—	—	0.53	—	—	—	24.24	5509	—
	100.26		100.51		99.83		99.87		100.00

Calculated mineral composition:

	8	9
Quartz	29.6	36.5
Orthoclase	1.1	Labrad. An_{65} 20.3
Albite	5.6	
Anorthite	39.7	
Grossularite	8.5	22.7
Actinolite	14.2	18.0
Apatite	0.8	0.5
Titanite	0.5	1.0
Calcite	—	1.0
	100.0	100.0

	10
Quartz	43.0
Andesine An_{33}	37.5
Biotite	18.0
Titanite + zircon	1.2
Apatite	0.3
	100.0

8. Concretion in mica-schist. Tulolansaari, Sortavala.
9. „ „ „ „ „
10. Granitized mica-schist, including the concretion of analysis 9.
11. „Imatra stone", calcareous concretion in late-Glacial clay. Imatra, East Finland.

8a, 9a, 10a, 11a, molecular numbers; 11b = 11 recalculated without $CaCO_3$. Analyses 9 and 10 quoted from V. HACKMAN (1931). „Calculated mineral composition" for 9 and 10 after Hackman.

margins highly anorthitic plagioclase, a bytownite, is added and thereafter quartz and long stripes of biotite which appear to be pseudomorphs after something else, probably hornblende.

Another concretion from the same varve also consists chiefly of calcite but contains garnet (probably grossularite) instead of epidote. A marginal zone consisting of bytownite and light green hornblende forms the transition into the mica-bearing quartzitic main mass.

The country-rock of the concretions, or the main mass of the exceptionally thick varve, is quartzitic with some mica, but without feldspar. The concretions thus seem to have been formed in sandy material during a time when the sediment was an unhardened soil, just as in recent varve clays calcareous concretions are formed in the sandy portions which are more easily permeable by water than the clayey portions. Prof. SAURAMO has shown me examples of small concretions in the sandy summer portions of a varve clay from Leppäkoski.

The exceptionally thick varves in which the concretions occur are in themselves remarkably analogous to the „giant varves" in the late-Glacial varved sediments, interpreted as discharge varves formed by the sudden discharge of ice-ponded lakes.

A concretion taken from a railroad cut near Läskelä about 6 km west of Välimäki shows a hornfelsic mass composed of calcite, quartz, and bytownite, with many big poikiloblastic crystals of garnet, and numerous minute rounded grains of titanite. This concretion is megascopically granular, almost „granite-like".

A number of years ago I collected specimens of calcareous concretions from the mica-schist on the island of Tulolansaari in Lake Laatokka. An analysis of this concretion, made by Dr. L. LOKKA is given below (8) together with other analyses quoted from HACKMAN's explanation of the geological map sheet (1931).

The concretion used for analysis 8 is megascopically whitish and granular, „granite-like", with visible prisms of hornblende and orange grains of garnet. Its microscopic appearance is that of a hornfels with a well-developed honey-comb texture. The hornblende is light green; the simplifying assumption that it would be actinolitic in composition, as calculated above, is apparently not far from the truth. The polygonal grains of plagioclase are finely twinned and attract attention by their high refringence and large extinction angles, the maximum angle reaching nearly 45° in the zone ⊥ M. According to the analysis it is bytownite An_{87}. This description agrees well with that of HACKMAN concerning the sample used for analysis 9, except that the plagioclase of the latter is labradorite. Another specimen from Tulolansaari was found to contain pale green diopside besides light green hornblende.

This rock contains abundant quartz with an almost anorthitic plagioclase, an assemblage that does not occur in igneous rocks (BOWEN 1928, p. 20). Their lime- and alumina-rich silicates, such as anorthite, grossularite, and epidote, are believed to be reaction products between primary clayey materials and calcium carbonate of which, in many cases, large amounts have been preserved. The nodules may, then, naturally be understood to be primary calcareous concretions in the sediment.

In one of the earliest descriptions of the concretionary nodules in the „Kalevian" schists of Finland BERGHELL (1919) explained them as being formed by the contact action of later granites. SEDERHOLM (1928) also explained the nodules on Tulolansaari as „related to the nodules of granites" thinking that „there is little doubt that they are due to the secondary action of the granitic magma". Later, however, SEDERHOLM and HACKMAN (1931) both accepted the above conclusion which was communicated to them by the writer privately after his study in 1928.

These concretions would thus be analogous to the calcareous concretions in late-Glacial clays. Dr. LOKKA analyzed (n:o 11), at my request, such a concretion from the rapids of Imatra where they occur on the river bed having been washed out from late-Glacial varve clays. They are called Imatra stones, because the people believe them to be modeled by the whirls of water in the rapids. The specimen analyzed was very rich in calcite which, aside from clayey substance and grains of quartz, was its chief constituent, forming a millimetre-grained granular mass.

It would not be difficult to find, among the concretions in the Karelian schists, any which are similar in composition to the Imatra stones (cf. above p. 20). Other ancient concretions like that represented by analysis 8 are now devoid of calcite, having presumably lost their carbon dioxide at the metamorphic recrystallization. There is a multitude of mineral assemblages bearing witness to metamorphism under different temperatures and thus providing much of interest from the view-point of the mineral facies principle. The following assemblages, referred to above, should represent a series of rising temperature:

Calcite — quartz — epidote
Calcite — quartz — epidote — grossularite
Calcite — quartz — epidote — grossularite — actinolite
Quartz — grossularite — plagioclase — actinolite — calcite (calcite in small amounts, analysis 9)
Quartz — plagioclase — actinolite — grossularite (analysis 8)
Quartz — plagioclase — hornblende — grossularite
Quartz — plagioclase — hornblende — diopside

This series affords a new example of the sensitiveness of calcareous materials as indicators of gradations in the metamorphic conditions, a matter discussed before in various publications (cf. e. g. ESKOLA 1927).

In the region now under discussion crystallization of diopside has only rarely occurred in the calcareous conretions. In the metamorphic schists of the Archaean in western Finland chemically similar concretionary nodules occur frequently being mostly diopside-bearing, a circumstance which is believed to indicate generally higher temperatures of metamorphism.

Concretionary nodules of the kind under discussion are known to occur in various formations in almost all parts of the pre-Cambrian of Finland. To the examples described by BERGHELL

(1919), SEDERHOLM (1928), FROSTERUS and WILKMAN (1916, p. 105), and WILKMAN (1916, p. 8) during the time when their nature of calcareous concretions had not been recognized, may be added two others according to private information. Mr. TH. G. SAHLSTEIN collected specimens of elongated and flattened concretions from Kontiolahti in Karelia. They were studied microscopically and found to consist chiefly of basic plagioclase, quartz, and hornblende. Dr. M. SAKSELA has observed similar nodules in the schists of South Ostrobothnia. For further details of their concentric structures, concentration of apatite etc. the reader may consult the works referred to above. In this connection attention may be directed to the high percentages of P_2O_5 as well as of MnO in the Quaternary calcareous concretions (analysis 11). Analyses 8 and 9 also show rather high percentages of these oxides, a very „actual" feature of the Archaean concretions.

Besides these calcareous concretions there may exist others of different composition and character (cf. HACKMAN 1931, p. 54). Available information concerning their chemical composition is, however, insufficient to warrant any definite conclusions. Certainly quite different are the sillimanite-bearing quartz nodules in migmatitic rocks described by SEDERHOLM (1928).

Carbon-bearing Schists.

A feature of great interest to the question concerning the mode of origin of the pre-Cambrian metamorphosed rocks of Finland is the occurrence of finely disseminated carbon, in the form of graphite, in schists of argillaceous composition. The subject has been treated rather exhaustively by LAITAKARI in his study on the occurrences of graphite in Finland (1925). Referring to this work for details I shall give only a short summary of the data which have a general bearing on the problem now under discussion.

LAITAKARI classifies the occurrences of graphite in four groups: 1) Graphite in eruptive rocks, 2) graphite in limestone, 3) graphite-bearing layers of schists, and 4) graphite layers and lenses. It is chiefly the two last-mentioned groups that interest us in this connection.

The graphite layers and lenses occurring in relatively slightly metamorphosed sediments, such as the so-called shungite in the Jatulian shales in Suojärvi (METZGER 1924) are really coal-measures of small dimensions and of poor quality, owing to their large percentages of inorganic substances. Nevertheless the carbon in the shungite has actually the characteristics of graphite, even giving rise to graphitic acid when treated with concentrated nitric acid, as shown by FRAUENFELDER (1924). The purest shungite has unfortunately been found only as boulders. The neighbouring shale is richly disseminated with fine graphite. Similar to the occurrence in Suojärvi is also the „shungitic" shale at Veljakanjoki in Soanlahti.

Layers and lenses of distinctly crystalline graphite rocks in the Archaean are in many localities closely similar to the shungite in their occurrence, excepting that they are embedded in highly crystalline paragneisses or mica-schists. Their lenticular shape, like that of the shungite bodies, is probably due to tectonical movements.

Among the graphite-bearing schists of Finland one may find all degrees of transition from the Jatulian shales to the highly crystalline and partly granitized gneisses. The former may be in all essentials so similar to carbon-bearing shales, e.g. so-called alum shales, of Paleozoic and later formations, that they may be regarded as being of a similar origin. Their similarity appears in their bulk composition, being moderately argillaceous, in their sulphide-content and, where the rock is not sheared up, in their bedding, or lamination. Some extreme types of such shales may be sharply varved, showing carbon-rich layers alternating with other layers consisting of nearly pure iron pyrites (fig. 3). Such primary bedding structures occur more especially in the Jatulian types of the Karelide zone, but also in the Archaean of Central an Western Finland. The Bothnian phyllites are generally carbon-bearing, especially the darker portions of the varves wich also contain cell-like sacks which are dark from disseminated carbon. SEDERHOLM (1911) supposes them to be organic remains and has called this form *Corycium enigmaticum*. In the leptite regions of Finland, so far as I know, no carbon-bearing sediments show any well preserved primary varve structures, but banded fine-grained

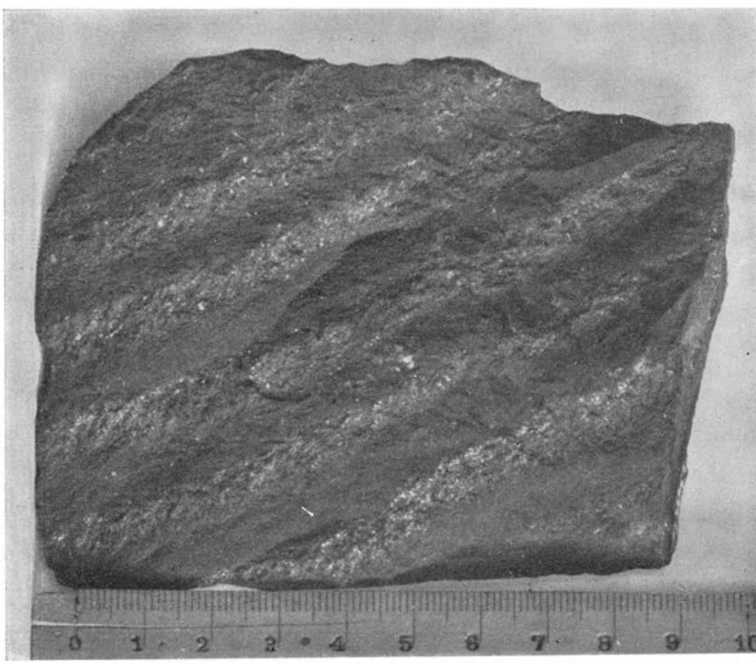

Fig. 3. Varved shale composed of carbon-rich layers alternating with layers consisting largely of pyrite. Sattasjoki, Sodankylä.

schists of the kind which is typical of the alum schists and their pre-Cambrian equivalents are exceedingly common. From them there are all stages of transition into highly crystalline graphite-bearing schists and paragneisses whose chemical composition is typically argillaceous, having excessive alumina, as often appears from the presence of sillimanite, andalusite, cordierite, almandite, or staurolite, or several of these and still other aluminous minerals; besides, pyrite and pyrrhotite may be found almost invariably in the highly metamorphic as well as slightly metamorphic schists.

A remarkable relation between the carbon content and the degree of metamorphism has been detected in the Archaean graphite-bearing schists (Eskola 1927, p. 70): They are generally much more finely grained than the related carbon-free schists. Sometimes they were therefore separated from other mica-schists on the geological maps as less thoroughly metamorphosed schists and called phyllites, and as the degree of metamorphism was generally held as an indicator of the geological age these „phyllites“ were supposed to be younger (Kalevian) than the „mica-schists“ (Ladogian). But as carbon-free layers alternating with the graphite-bearing schists or „phyllites“ are, as a rule, developed as „mica-schists“ it seems that the graphite must have in some way protected the rock from metamorphic influences.

Väyrynen thoroughly investigated the carbon-bearing schists of the Kainuu region (1928, p. 96—102) and was able to explain satisfactorily this curious behaviour. He found the graphite to be disseminated in such a fine-grained form that it even protects the silicate compounds from the influence of hydrofluoric acid. He therefore compares the dissemination with an actual solid solution. This is a strong evidence for the assumption that carbon is a primary constituent of the sediment, and not added to it by metasomatic processes. Only where the metamorphosing agencies have been particularly strong and the schists are more or less granitized has the graphite also been recrystallized.

The carbon-bearing schists must therefore have been subaquatic sediments originally, and organic life may have existed in those waters from which they were deposited.

The Finnish geologists are well aware that not all occurrences of graphite are of a primary sedimentary origin. Numerous occurrences, some of them connected with sulphide deposits, have been interpreted as products of metasomatism (cf. Laitakari 1925). It is the occurrence of primary sedimentary structures, observed at all different stages of metamorphism, even in the older Archaean, that has led the investigators to the conclusion that the carbon-bearing schists also comprise bituminous shales formed in the same way as recent bituminous muds in deep closed basins in which hydrogen sulphide results from the decay of organic substances in the absense of oxygen.

The Breccias of Lavia and Suodenniemi.

From the actualistic principle it may be expected that primarily autochthonous soils should occur in the pre-Cambrian. In the Karelian formations FROSTERUS and WILKMAN have described numerous occurrences of so-called bottom schists, i.e. in situ laying products of weathering under beds of conglomerate or quartzite where the latter have been deposited upon a basement of granite or other older crystalline rocks. In many cases this explanation is undoubtedly right (cf. SEDERHOLM 1931). The „bottom schists“ are generally arkosic with only moderate signs of decomposition of the feldspars.

SEDERHOLM (1899, 1911, 1931 b) has devoted much work to get evidence for the assumption that certain breccias at Naarajärvi in Lavia and at several places in Suodenniemi (most of the latter occurrences having been detected in recent years by Dr. E. MIKKOLA) are weathering or disintegration breccias. They usually occur at the contact between quartz diorites and feldspathic „schists“ of a fine-grained granoblastic texture. More or less angular blocks of diorite are cemented together by a fine-grained light-coloured mass of similar appearence and composition to the schist. This breccia should represent an original weathered surface soil from the Bothnian time.

SEDERHOLM has always found it difficult to make this explanation acceptable. During the excursion of the „Reunion Internationale pour l'etude du Precambrien et des vieilles chaines“ in the summer 1931 the localities demonstrated aroused a lively interest and some discussion.

The „cement“ of the breccia and the adjacent schist from Jaakkola in Suodenniemi, according to chemical analyses, agree satisfactorily in composition. The dioritic fragments have not been analyzed, but from other analyses of similar-looking diorite one may conclude that the chief difference is a smaller percentage of iron oxides, magnesia and lime in the cement. If this latter is formed from the diorite by weathering, then a bleaching should have occurred, or an extraction of the femic substances, but practically no other change exists, especially no increase of alumina. Such a differentiation during weathering seems rather unusual. When looking for similar cases in Blanck's Handbuch der Bodenkunde, vol. III (1930), I found only one comparable example which was in the part dealing with Arctic soils, written by Meinardus. There are, on p. 61, analyses of a diabase and the weathering soil upon it from cape Diabase on Spitzbergen, investigated by Blanck. It is said to represent a characteristic phenomenon of weathering not only here but also in other tracts of the Polar regions.

„Auf dem Gestein lagert ein dem Aussehen nach schwach humoser, ziemlich trockener, hellbraun gefärbter Sandboden auf, der in seinem Anteil über 2 mm Korngrösse eckige Bruchstücke des Diabasgesteins von verschiedenster Grösse und reichliche Wurzelrückstände enthält“. Some of the more important oxides of the rock and the soil are as follows:

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_2O
Diabase	49.93	15.09	4.09	10.11	8.30	2.52	1.34	1.59
Soil ..	60.36	11.88	5.73	2.10	2.41	1.64	2.02	1.04

This result seems in fact to be a very striking proof of Sederholm's theory, as he himself asserts that „the subaërial disintegration of the rock masses in Bothnian and pre-Bothnian time indicates a temperate or cold climate, with a mean temperature rather below than above 10° Centigrade“.

As an alternative hypothesis, however, I would suggest that possibly the schist in contact with the diorite near Jaakkola has not been immediately derived from the subjacent rock by means of weathering, but has been transported in some way from the neighbourhood and been mixed with rock fragments broken up mechanically. Nevertheless some autochtonous weathering products are most probably contained in these breccias, and this is what makes them important for our present study.

So far the sub-Bothnian breccias are not very conclusive as indicators of physical conditions, but they are certainly worthy of further investigation, especially from the chemical side. In this study the possible changes during the metamorphism should also be taken into consideration.

The Value of the Archaean Argillaceous Sediments as Indicators of the Physical Conditions.

Argillaceous sediments with recognizable varve structures preserved have so far been encountered in the Karelian zone in eastern Finland, both in its supposedly younger and older divisions, and in the Bothnian schists of western Finland. The Karelian rocks of the Ladogian, Kalevian, and Jatulian types belong to the younger divisions of the Archaean and the Karelian zone is also characterized by the extensive occurrence of primarily clastic quartzites, in places with ripple-marks, and conglomerates containing boulders of abyssal rocks, granites and migmatites, which apparently mark a great unconformity. It is therefore only to be expected that their argillaceous sediments also have been formed under actual conditions.

On the other hand, the older formations in eastern Finland, probably including the rocks of the Hyrsylä area, are supposed to represent a venerably old Archaean series, the so-called Lapponian, to which also belong (SEDERHOLM 1932) the quartz-banded iron ores of Kittilä, South Varanger etc. In their geological relations these series are in many respects analogous to the Bothnian in western Finland. SEDERHOLM (1931 a) has found evidence that the latter are separated from the oldest Archaean rocks by an unconformity marked by conglomerates with boulders of deep-seated rocks in the Suodenniemi and Lavia regions. Thus these formations should represent one or several series in the middle Archaean.

As the varved sediments belonging partly to the Upper and partly to the Middle Archaean show very much the same essential characteristics, their testimony to the prevailing conditions during their sedimentation may be discussed.

All these argillaceous sediments indicate a weathering characteristic of either cool or temperate climate zones. As appears e. g. from the calculations of VÄYRYNEN (1929) of the $M_2O : MO : M_2O_3$ ratios and also directly from the analyses, they have a moderate excess of alumina over the alkalies. At the same time they contain excessive silica. They are thus what HARRASSOWITZ calls siallitic sediments. A similar characteristic appears from the analyses of the late-Glacial varve clays and the post-Glacial clays of Finland. The Archaean varve sediments also agree essentially with those of the Huronian tillite formation of North America (COLEMAN 1926, SAYLES 1919), which are unquestionably formed under Glacial conditions. As proved by experiments carried out by numerous investigators, such a degree of weathering can be simply brought about through the hydrolytic action of water upon fine-grained silicates (cf. e. g. BEHRENDS-BERG 1927, and BLANCK 1929).

In tropical regions of these days (HARRASSOWITZ in BLANCK's Bodenlehre, 1930) the products of weathering are often strongly allitic in character, on the whole either laterites or „red silts". As emphasized by HARRASSOWITZ and many others in recent years, laterite is really much less widely distributed than red silts and other related soils. Even the latter are chemically sufficently well characterized by their high excess in alumina and iron oxide, and exceedingly low percentages of alkalies, to warrant the statement that no such sediments have ever been found in the Archaean sediments. A further characteristic of tropical weathering products is the frequent occurrence of iron oxide concretions, not met with in our schists. Lime concretions, on the other hand, are found in the soils of most climate zones including the warm savannes and steppe regions. As pointed out above, the calcareous concretions found in the Karelian schists are in their primary characteristics and mode of occurrence exceedingly like those of the late-Glacial sediments whose concretions, however, may be of a more recent date.

Here it may be worth while to remember the remark of E. KAISER (1931) concerning the importance of the vegetation. KAISER refers to a partial inadequacy of the actualistic method owing to the absence of plant cover on the continents during earlier geologic times up to the early Paleozoic. Water circulation must have been swifter and water erosion much more effective. Mechanical erosion and wind transport played a far more important rôle. Due to the lack of decaying organic substances, especially of humus, chemical weathering, on the other hand, must have been far less efficient and highly different in character from what it is nowadays. Therefore the soils were chemically less decomposed; in fact the early Paleozoic and pre-Cambrian shales, according to KAISER, show an alphititic character, i. e. they mainly consist of mechanically ground and assorted but chemically unaffected materials.

We may therefore ask: can laterite or red silts of the present tropics be formed without the action of plant remains? This question has been much discussed and as yet cannot be regarded as definitely settled. To judge from the results of HARRASSOWITZ and many others, however, it seems highly probable that the action of vegetable substances is not necessary for allitic weathering.

It may also be pointed out that the statement of KAISER quoted above concerning the chemical nature of the early Paleozoic and pre-Cambrian shales and slates would rather seem to be true of greywackes and some silts, but not to be generally consistent with analyses of such argillaceous rocks which have been originally fine clayey sediments. As remarked above (p. 18) the composition of such rocks varies within a narrow range characteristic of clays of later ages and recent times as well.

The laterites of the tropics are mainly autochtonous soils. It is significant that no Archaean breccias or conglomerates which have been supposed or proven to contain autochtonous weathering products have ever been found showing an allitic composition.

The water-laid clayey sediments, deep-sea clays etc. of the warm regions are usually mixed up with undissolved quartz and silicates, and their allitic tendency is somewhat obscured, though often apparent from the molecular figures. The same is true of the shales from tracts which were tropical at the time of their forming, such as many shales from the Carboniferous of Central Europe.

Still one may ask whether it is not possible that the composition of the Archaean sediments may have undergone considerable changes during the metamorphism. The problems of metasomatic changes due to the addition of substances as well as that of metamorphic differentiation in previously existing materials are of as great importance as they are difficult to study. Some aspects of these problems will be touched upon below. As to the highly aluminous rocks, they clearly show a tendency to absorb potash during the metamorphism. No thorough changes can be supposed, however, in view of the well preserved primary structural and textural features. We must assume that an allitic composition would result in the crystallization of corundum during the metamorphism. This is a mineral which would not have been entirely obliterated.

The conclusion therefore is that the Archaean varved sediments originated under conditions considerably cooler than those of the tropical zones of our days. This conclusion — which is by no means new — seems as safe as any conclusion can be considering the fact that it is largely based upon negative evidences, i. e. upon the absence of products characteristic of weathering in warm regions. But it is considerably strengthened by real positive evidences, viz. the structural characters.

We may proceed asking for closer information concerning the physical conditions. E. Hitchcock as early as 1841 (Sayles 1919, p. 6) concluded that in the diluvial clay of the Connecticut valley each layer probably marks the annual deposit. De Geer accomplished the firm foundation of the theory that the varves in the varve clays register an annual periodicity of sedimentation of materials brought from melt water of the land ices. The chief conditions of the formation of varves, or diatactic mechanical sediments (SAURAMO 1923), are that the materials are discharged periodically with interruptions, as by an intermittent stream, and that the sediments spread out from its mouth in a water basin and sink down gradually, the coarsest grains first, the finest ones slowly during the period when the stream is dry, or is carrying no mud. A continuous stream with a constant mud content would give a symmict sediment with no varves. Electrolyts dissolved in water, as in sea water, make the particles coagulate. The aggregate particles thus originated sink down as swiftly as bigger simple grains, the diatactic structure thus becoming less distinct than in fresh water. Moreover, SAURAMO has pointed out that, as particles of a definite seize group sink in fresh water of a given temperature range with a definite velocity, it is possible from the grain seize of the finer portion of a diatactic sediment to draw conclusions concerning the length of the period during which it was deposited, or the period of the intermittent discharge. On the earth, the year is the only period whose length and seasonal variation of conditions, according to experiments, can account for the formations of the late-Glacial varve sediments.

Now the same is also true with regard to the Archaean varve sediments. Many investigators (SAYLES 1919, COLEMAN 1925) have therefore concluded that old laminated sediments like those of the Huronian and the Permo-Carboniferous would be seasonal yearly deposits, and moreover, that they also would have originated during glaciations. Evidences for the Glacial origin of the Huronian varve sediment are very strong because of their connection with the Huronian tillites. But no Glacial conglomerates have been found in the Archaean of Finland.

TH. BRENNER (1931) points to a further condition for the slow settling of suspended materials, viz. that the materials must be loosened and decomposed from the rock for the first time so as to become suspended as single grains, not aggregates. If earlier clay deposits are eroded anew and transported by running water, the finest particles do not fall apart, but instead from composite grains which, on re-deposition, behave like bigger simple grains and sink more swiftly.

Sauramo (1931) has directed the attention of the Finnish geologists to the experimental studies of Fraser (1929). According to this investigator the sinking velocity of the finest grain particles decreases as the temperature falls. Therefore distinctly diatactic or varved sediments should be formed only in waters bordered by ice, such as the late-Glacial water basins.

Would, therefore, the Archaean varve sediments of Finland indicate Glacial conditions? In that case they would be the only witnesses thereof, as no morainic conglomerates have been found. Sederholm (1931 a, p. 78) writes:

„Both the kind of stratification of these (laminated) sediments, which reminds one very much of varves, and their chemical characters are very similar to those of glacial clays and indicate a climate which has been so cold as to allow the freezing of the rivers in winter time."

The primary texture is exceedingly well preserved in the Bothnian varve sediments where the coarser layers are clastic, the grains being angular unweathered crystal fragments of the volcanic products of the region. The varved sediments from the Ladogian areas, on the other hand, have quartzitic lighter portions, now mainly recrystallized but nevertheless showing a clearly recognizable clastic texture, while the darker portions are clayey. As discussed above, this composition tells of a long previous history of the rock. The original material, here probably granitic, has undergone a profound decomposition and after its disintegration been well sorted. During the final sedimentation, however, the conditions would seem to have been much the same as during that of the Bothnian sediments.

The succes of the actualistic method in this case seems to be complete. In my opinion the testimony of the varved sediments is the most conclusive of all.

But the kind of conclusion here used, i. e. concluding from the results to the causes, is always open to possible error, as other, perhaps still unknown agencies may possibly bring forth similar results. There are varved sediments due to other kinds of periodicity of the conditions, such as the Karelian varved shale in Sodankylä mentioned above (fig. 3) in whichs layers rich in pyrite alternate with those of clayey material. Although possibly due to a yearly periodicity of the prevailing conditions during its sedimentation, the varve structure is in this case of a nature essentially different from that of the varve clays proper.

From the many congruent circumstances the following seems certain: The laminated Archaean mica-schists and phyllites are water-laid sediments which have originated under climatic conditions cooler than those of the tropics of our days.

In his important memoir on the Grythytte field in Central Sweden SUNDIUS (1923) describes a rock complex younger than the hälleflinta and leptite division. This younger complex is chiefly composed of greywackes and slates and shows many features similar to the Bothnian complex of the Tampere region. Varved strutuctures in the Grythytte field have been encountered in the greywackes (pp. 67—69, in the English Summary p. 341). The varves are from 2 to 50 decimetres thick or even still thicker, and their distribution is fairly irregular. SUNDIUS therefore ascribes their forming to some local events, like an intermittent supply of materials from volcanic eruptions. The structure of these varved rocks therefore is not comparable to the exceedingly regular varve structures described in the present paper. In the slates of the Grythytte field no varve structure was found, although bedding was frequently noted and the chemical composition is that of normal clayey sediments.

So far as I know, no distinctly varved sedimentogeneous schists have been found in the leptite regions of Finland or, more generally, in that part of the Archaean which is regarded as Pre-Bothnian. Several circumstances, however, should be remembered in this connection. In the first place, the stratigraphic division of the

Archaean of Finland is not by any means yet definite. This is said with due respect for the work of SEDERHOLM. The unconformity below the Bothnian series in the Suodenniemi-Lavia area has not been proved to designate the beginning of a new orogenic cycle. Accepting this unconformity as a boundary line between two divisions of the Archaean, the distribution of each of them is entirely unknown and in fact doubtless would be exceedingly difficult to decipher, even by means of the most detailed mapping. The most complete granitization and regional plutonometamorphism has taken place in the Archaean of Finland during the post-Bothnian times, and no one can tell how widely the Bothnian formations actually are distributed.

A large part of the argillaceous rocks of the leptite areas, e. g. in the Orijärvi region (ESKOLA 1914) are sheared up and recrystallized to such a degree that it is doubtful whether a varve structure could have been preserved. In many places in the Archaean of South Finland seemingly laminated or banded rocks have been formed by deformation from agglomerates or pillow lavas whose fragments have been drawn out into thin sheets (WEGMANN and KRANCK 1931). Nevertheless there are in the leptite belts sedimentogeneous as well as volcanogeneous rocks with well preserved primary structures, and the absence of varve structures *may* have some significance.

Argillaceous sediments, however, exist in great abundance in the leptite regions of Finland. They are mostly developed as cordierite leptites (ESKOLA 1914); in other tracts related rocks being more schistose have been called simply schists; they may contain cordierite and sillimanite, andalusite, staurolite or almandite. In their composition they show very much the same characteristics as the late-Glacial and post-Glacial clayey sediments of Finland. The absence of allitic sediments should have for the whole of the Archaean of Finland the same bearing with regard to the conditions of origin as it has in the cases discussed above.

I was the first to explain certain cordierite-anthophyllite rocks and cordierite quartzites („ore quartzites“) in the Orijärvi region as products of a metasomatic alteration of leptitic rocks (ESKOLA 1914). The same explanation was applied by GEIJER (1917) and other Swedish geologists to similar rocks in the Falu region and elsewhere in the ore-bearing tracts of Sweden. At present the cordierite- and anthophyllite-bearing rocks in the leptite regions of Central Sweden are generally interpreted in this way, as products of magnesia metasomatism. In southwestern Finland, however, many cordierite leptites etc., though chemically similar to some of the altered rocks, are certainly sedimentogeneous rocks of a primary clayey character. The problem of magnesia metasomatism will be discussed below.

Other Indications of the Archaean Rocks.

In the Karelide zone by far the largest part of the supracrustal rocks were originally normal sediments and are now mica-schists and phyllites, limestones, quartzites, and conglomerates. The widest areas are covered by schists derived from clayey sediments. They are geosynclinal sediments, in part flysch-like (WEGMANN 1928). Compared with the areas of the sedimentogeneous schists those of the volcanogeneous rocks are subordinate.

In the Bothnian areas of western Finland the proportion of these two classes of rocks is quite the other way. The volcanic rocks cover the larger parts of the areas, and the sediments are largely tuffogeneous. In this respect the Bothnian formations more closely resemble the „leptite formation“. Much of the fine-grained Bothnian quartz-feldspar rocks could well be called leptites, and certainly would be called so, if they occurred in the leptite regions.

At the present state of geological research the oldest basal conglomerates known containing pebbles of deap-seated rocks and having been regarded as marking a great unconformity are those in the Lavia and Suodenniemi regions (SEDERHOLM 1931 a). Below this basement of the Bothnian is the oldest Archaean of Finland, so far undivided. Its general characteristics are not unlike those of the Bothnian. In fact the oldest Archaean is even richer in sedimentary differentiation, as it includes, besides argillaceous sediments, also widely distributed limestones and occasional quartzites and iron ores etc. The most prominent feature of the oldest Archaean in regions where primary structures are recognizable is, however, the predominance of volcanogeneous rocks, as lavas, agglomerates and stratified tuffs. Acidic volcanics, i.e. the leptites, form the major part of these, but also primarily basaltic rocks, or „metabasalts", are exceedingly common.

Among these various rocks only the original mechanical sediments have any value as climate witnesses. They afford the same testimony to the conditions as the Bothnian and Karelian sedimentary series, that is, the climates have been temperate or rather cold.

Among other indications of the conditions in the earth's crust in Archaean times, that of the quartz-banded iron ores or jaspilite ores is of great interest, as these are perhaps most difficult of all to understand from the actualistic view-point. Examples of this world-wide group occur in Kittilä in Finnish Lapland (the Lapponian of SEDERHOLM 1932 and 1931 b). In Sweden they are rather widely distributed in the leptite regions. Concerning the question of their origin SEDERHOLM, faithful to his actualistic doctrine, has joined those who regard this kind of ores as normal chemical sediments whose materials have been derived from the rock ground of neighbouring areas decomposed through chemical weathering. GEIJER (1917), SUNDIUS (1923) and others ascribe them to volcanic processes, as also do most of the American geologists who have studied the analogous „iron formations" in the Keewatin of North America. I wish especially to refer to the very thorough investigations of COLLINS and QUIRKE (1926, and COLLINS 1928). The explanation of the iron formations as deposits from thermal waters seems from these and other studies well founded. I have from their memoirs a strong impression that their method of investigation is quite typically actualistic. They usually compare the various members of the iron formations with the most analogous formations of our days, as geyser deposits etc. Their conclusion, however, is typically exceptionalistic: They state that nothing of the kind of deposits consisting of alternating laminae of silica and iron oxides is known to be formed nowadays. It is certainly difficult to answer the question why they are not being formed at present. A suggestion to a working hypothesis might perhaps be contained in the following question which is also aroused in connection with many other problems of the Archaean: Has juvenile water emanated from crystallizing magmas in the earth's crust during the Archaean times in larger amounts than in the later ages? We shall encounter this question below.

The connection of the quartz-banded iron ores with volcanic phenomena is also suggested by the fact that the metasomatic kinds of Archaean iron ores in Central Sweden have in recent times, by many geologists, been concluded to be connected with volcanogeneous leptitic rocks. Even if this theory should not prove to be right, they are at any rate connected with old Archaean granites which in turn frequently pass over into hypabyssic rocks and, also, to volcanic rocks of a leptitic character.

The Leptite Problem and the Crystallization Differentiation Theory applied to Acidic Volcanics.

In Central Sweden the hälleflinta-leptite complex seems to have simpler stratigraphic relations and at the same time further differentiated chemical characters than in Finland. Perhaps most typical is the Grythytte field, so well studied by SUNDIUS (1923). Undermost in the series is the lower hälleflinta-leptite horizon rich in limestone, skarn, and iron ores, the leptites being for the most part extremely rich in albite (up to 8 % Na_2O and from 0.1 to 0.5 % K_2O). Above this is the upper hälleflinta-leptite horizon characterized by leptites extremely rich in microcline (up to 8 or

10 % K_2O and various, sometimes quite small percentages of Na_2O), and by dolomites and limestones. Upwards in the series follows a greywacke horizon, above this the horizon of argillaceous slates, partly graphite-bearing, and on top of the series conglomerates with fragments of hälleflintas and slates.

The leptite horizons in the Grythytte field do not include appreciable amounts of argillaceous sediments, and the leptites and hälleflintas show little traces of weathering. The same seems to be true of the Persberg field according to Magnusson (1925). In some other Central Swedish leptite regions products of weathering are much more common. The porphyritic as well as stratified leptites show many indications of a volcanic origin.

The leptite problem is therefore chiefly a problem of magmatic differentiation. Both extreme varieties, the microcline-extreme and the albite-extreme leptites, occur as primary lavas, either porphyritic with phenocrysts of microcline or albite, or nearly free from phenocrysts, and it seems to be out of the question that the one or the other extreme variety would have been derived from something else by any means of metasomatic alteration or other secondary changes. Both kinds thus seem to have existed as entirely liquid masses, the potash-extreme lavas having been spread as beds upon the soda-extreme lava beds.

In his paper on the differentiation of the alkalies in aplites and aplitic granites Sundius (1926) gives a brief synopsis of the essential features of the leptites and hälleflintas concluding as follows (p. 43):

„On returning to the rocks of the Grythytte field, the writer was earlier led to the conclusion that no differentiation of the alkalies had occurred since the extrusion of the lavas — — —". „The differentiation of the alkalies, therefore, must have been accomplished in *the supplying magma and thus in the fluid state.* Now, bearing in mind the vertical distribution of the different rocks, this must imply some corresponding vertical inhomogeneity in the upper layers of the supplying magma body. In the work referred to, the writer believed this to have happened through a continuous change in the upper part of the magma. The relations found in the aplites of the urgranites, however, do not speak for a difference as to the time of the two magma parts. On account of this, we may conclude rather that both kinds of magma were contemporaneous and that of albitic composition superincumbent on the Or-rich part, thus forming the uppermost and at the same time the outermost part of the whole magma body. This is in accordance with all experience from deep-seated and intrusive rocks exhibiting this differentiation".

The reason why SUNDIUS applies to the leptites the results obtained by him from a study of the aplites is clear from his statement (p. 40):

„The whole leptite complex may thus be regarded as a formation predominantly built up of effusive forms of aplitic magmas including a high percentage of solutions containing metallic oxides, especially oxides of iron. No doubt water played an important part in these solutions". (The presence of iron oxides in the magmatic solutions is assumed to account for the iron ores connected with the leptites). After an exposition of the alkali ratios in the soda-extreme and potash-extreme leptites and of the extremely salic character of both of them SUNDIUS continues: „Evidently the differentiation of the alkalies in the leptites is of the same kind as that found in the aplites of the urgranites and no doubt both are the result of similar processes". We have therefore reason for seeing how SUNDIUS interprets the differentiation of the aplites of the Loftahammar area into plagioclase-rich and intermediate types richer in microcline. His final conclusion is (p. 35): „Summing up the facts quoted, the geological as well as the petrological, the most acceptable explanation of the differentiation in the aplites is that it occurred in the fluid state of the magma. In considering this process, the aplite magma can be regarded as a ternary system composed of plagioclase, microcline and quartz, the miscibility of the feldspars at sinking temperature becoming restricted. As a consequence of this, the quartz will also be dissolved in the two feldspar fractions in proportion to their dissolving power, thus producing a complete splitting up of the magma into two separate phases".

I have quoted the argument of SUNDIUS at some lenght because, so far as I am aware, it is the most elaborate trial to furnish actual evidences for the theory of liquid immiscibility. For the advocates of the „magmatic view" this theory, applied to the leptite-hälleflinta complex, is a cardinal point and therefore a subject which must be discussed in connection with the nature of the oldest Archaean rocks.

Leaving the question of the aplites aside we may, in order furthermore to illustrate the present state of the study of leptites in Sweden, quote (in translation) the following paragraph from Asklund (1931, p. 172):

„The chemical characters of the hälleflinta-leptite complex are exceedingly extraordinary. Among these is especially to be emphasized the absence of lime feldspar and the small amounts of femic constituents, characteristic of large areas. On the one hand there are extreme soda rocks whose feldspar consists almost exlusively of albite and, on the other hand, extremely potash-rich rocks. Intermediate rocks have an insignificant distribution. The explanation of these peculiarities has met with great difficulties. It has been assumed that the chemical extremities would be secondary, caused by the mass action of solutions rich in one or the other of the alkalies, which has metasomatically altered a formerly less extreme rock. The unaltered characteristics of their textures" (strongly resembling those of different younger volcanic rocks) „and the alternation of horizons of the potash and soda rocks do not permit such a view more than for some smaller very limited rock zones. Therefore the opinion has been more and more commonly accepted that the extreme splitting is caused by a peculiar magmatic differentiation process which preceded the eruption of the hälleflinta-leptite rocks into the positions they now occupy".

The $K_2O : Na_2O$ ratios in the leptites from Western Bergslagen where alkali-extreme leptites predominate may be seen in fig. 4 (p. 46).

Disregarding for a while the differentiation of a part of the leptites into microcline-extreme and albite-extreme types, their composition in other respects — most of all resembling that of aplitic granites — places them among the late members of differentiation series to which the theory of crystallization differentiation has on the whole proved to be successfully applicable. Arranged in differentiation diagrams they show all those regular relations which are referred to by Bowen (1928) as conclusive evidences of crystallization differentiation in general.

Those leptites showing intermediate alkali ratios, to which the greater part of the Fennoscandian leptites belong, are in their composition as well as in their primary textural features perfectly similar to the liparites and rhyolites of the later periods. But also the leptites extreme in potash or soda have their analogues among the younger rocks. In Washington's tables there are numbers of analyses of soda-extreme volcanic rocks called soda rhyolites, rhyolites, quartz porphyries, quartz porphyrites, and quartz keratophyres. Among plutonic rocks the soda-rich trondhjemites seem to represent late crystallizations of residual magmas. Potash-extreme rocks are still more common.

If we do not at once accept the theory of liquid immiscibility but try to understand the origin of the leptites as a phase of crystallization differentiation, we are led to consider the compositions of the residual liquids or, as BOWEN terms it, the liquid line of descent in fractional crystallization of magmas.

BOWEN (1928) concluded that the last residual granitic magma is likely to be enriched in potash, as especially appears from the differentiation diagram of the pitchstones. He is well aware of the fact that the explanation of potash-rich rocks from the crystallization differentiation theory encounters difficulties, writing (p. 227):

„It is very easy to derive these potash-rich liquids by means of liquid immiscibility, gaseous transfer, or the like, because these processes always do just what one may wish them to do. In the case of crystallization differentiation some difficulty is presented“.

BOWEN offers a modified explanation of the crystallization relations of the alkali feldspars to account for the origin of potash-rich granites, liparites, quartz porphyries, and related glasses. The soda-rich acidic rocks, on the other hand, cannot, according to BOWEN, be explained as resulting directly from the crystallization of residual magmas. He writes (p. 132):

„The absence of any glassy rocks corresponding with granite very rich in albite is important in connection with the tendency of recent investigators to refer albite-rich rocks to a replacement process“. — — — „The absence of glassy rocks rich in the albite molecule is thus to be taken as confirmatory of the concept that albite-rich rocks are formed by a process of replacement, probably in all cases“.

As appears from the above quotations this conclusion does not agree with the results of the Swedish investigators concerning the leptites and hälleflintas. Most of the albite leptites of the Grythytte field are porphyritic with phenocrysts of quartz and albite, but there are equally extreme and almost potash-free leptites containing almost no phenocrysts. Their groundmass probably has been glassy originally. According to MAGNUSSON the albite-extreme leptites in Filipstads Bergslag, including the Persberg field, have even better preserved primary textures than the microcline-extreme leptites. In his latest paper (1932) MAGNUSSON explicitly states that some of the soda leptites are primary.

Numerous investigators have described, from different regions, albite-extreme fine-grained or aphanitic marginal varieties of the urgranites (see SUNDIUS 1923, MAGNUSSON 1925, 1932). I have myself analyzed a soda-rich leptite-like rock forming narrow apophyses from the Orijärvi granite in amphibolite (ESKOLA 1914, p. 57), and also a quartz keratophyre from Transbaikalia (Bull. geol. Finl. 92, p. 122). It is surely difficult to conceive of a rock like this, whose aphanitic ground-mass is as soda-extreme as the phenocrysts, as a product of a secondary replacement.

In my opinion only an autometasomatic replacement can be considered in the case of the soda leptites. Another possible explanation of their excessive soda is by crystallization of potash at earlier stages. These two possible hypotheses will be discussed below.

In discussing differentiation problems it is customary to construct diagrams. If analyses of all kinds of leptites, including the more basic (andesitic) varieties, are plotted on the usual differentiation diagrams where silica is projected against the other oxides, the curves resulting show on the whole the features characteristic of calcialkaline rock series. For the lime-poor and alkali-rich leptites these diagrams are of little value, as their silica percentages vary only within narrow limits (mostly 70—80 % SiO_2) and, moreover, some metamorphic change due to the migration of silica must be reckoned with. Plotting, instead, the percentage ratios $FeO : MgO$ against the ratios $K_2O : Na_2O$ would be expected to give a more truthful picture of the relations. Such a diagram (fig. 4) representing the leptites from those fields in Sweden where alkali-extreme leptites occur shows a distinct though slight rise of the FeO : MgO ratio in the potash-extreme leptites. This would mean that the potash leptites have differentiated somewhat farther than the soda leptites.

The crystallization differentiation theory applied to the leptites presupposes the existence of earlier deep-seated igneous rocks. At the first look this would seem to be contradicted by the geological experience, as no plutonic rocks older than the leptites are known to exist. On the contrary, granites and diorites are always intruded

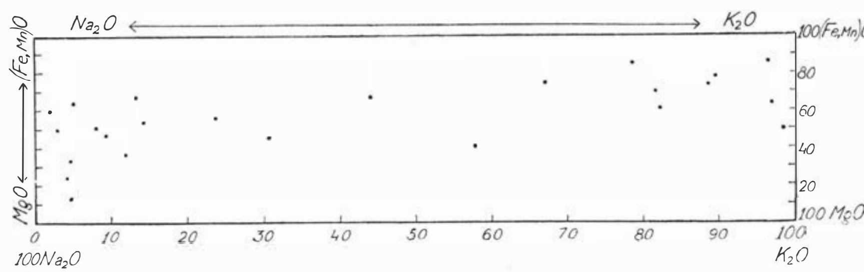

Fig. 4. The percentage weight ratios FeO : MgO plotted against the alkali ratios $K_2O : Na_2O$ in the alkali leptites and hälleflintas of the Persberg, Nordmark, Långban, Riddarhytte, Nyberg, Grythytte, Yxsjö and Åmmeberg fields in Sweden. From analyses published by SJÖGREN etc., GEIJER, SUNDIUS, I. HÖGBOM, and LINDROTH.

in the leptites, excepting those porphyritic leptite-like rocks which are seen to grade over immediately into the urgranites. On the other hand the supracrustal leptitic rocks have been described by SUNDIUS and others as volcanic rocks, including lavas, ashes, scoriae, pumice etc. poured out and spread as beds one upon the other. Volcanic eruptions in those days as at present must be conceived as a consequence of crystallization. During crystallization the residual magmas became more and more concentrated in water and other volatile substances until they were saturated and an ebullience occurred. The materials must have been erupted through a solid earth's crust.

According to Sundius, Magnusson and others, the areas where the hälleflinta-leptite complex of the Western Bergslagen in Sweden was formed, was at first for the most part dry land. A subsidence took place at a later time and was followed by the deposition of greywackes and shales. The absence or rarity of conglomerates in the leptite horizons would indicate that no particular mountain building was going on at the time of their forming. Conglomerates (with fragments of shales and leptites) are richly represented in the layers following upon the shale horizon in the Grythytte field. The forming of these layers therefore may have been contemporaneous with a mountain making. The intrusions of the urgranites, on the other hand, also apparently have taken place in connection with mountain folding, as they are typically synkinematic intrusions.

A very important conclusion resulting from the above reasoning is that deep-seated intrusives older than the leptite formations have existed and most probably still exist. They may or may not be exposed somewhere. The fact that no basement contacts, showing erosion phenomena or conglomerates, of such old granites with the supracrustal rocks of the leptite formation have ever been found, may be a consequence thereof that the volcanics formed enormously thick beds.

The hypothetical older masses of granitic magmas must have been widely spread and in their nature agreeing with the conception of subjacent masses of Daly. Actually the wide areas of granite gneisses show the closest approximation to what such masses might be expected to be. Törnebohm long ago believed that the iron gneisses of Western Sweden form the basement of the leptite formation. It might be advisable to investigate the possibilities of this old hypothesis anew.

Let us now return to the replacement hypothesis in connection with the albite leptites! Supposing that the replacement had occurred later would only mean a suspension of the point of the problem. For the solutions which should have caused this replacement must also have been derived from somewhere, and of course even their ultimate source must be sought in magma residues.

GOLDSCHMIDT has thought that sodium metasilicate solutions may have emanated from crystallizing trondhjemites causing an addition of soda in invaded shales of the Stavanger field. Applied to the soda leptites the hypothesis of a metasomatic transfer of soda would imply that it were derived from the urgranites. In view of the primary textures of the soda leptites compared, for instance, with the complete recrystallization of the metasomatically soda-enriched gneisses of the Stavanger region, this is, to say the least, highly improbable.

If, again, the replacement had been caused by solutions separated from the same magma, the process may well be supposed to result in well preserved primary structures. As concluded by myself (1925) and others, the spilitic rocks have probably originated by such an autometasomatism caused by solutions of sodium carbonate. A similar explanation has also been applied to the quartz keratophyres which are closely related to the spilites and connected with them in the field. Dikes and beds of spilitic greenstones also occur in the greywacke and shale horizons of the leptite region of Sweden. SUNDIUS (1923) and I. HÖGBOM (1920) have pointed out the close relation of the soda leptites to the quartz keratophyres. The carbon dioxide of the spilites is supposed to have entered into the calcite which is richly present in them. The soda leptites also often bear calcite. LINDROTH (1922) has published an analysis of a calcite-bearing albite leptite from the Yxsjö field.

I would therefore infer the following tentative working hypothesis to account for the albite-extreme leptites: Some parts of the deep-seated magmas crystallizing in the subjacent reservoirs were more than usually enriched in carbon dioxide which combined itself with soda to sodium carbonate. Thus bound the soda escaped crystallization at the earlier stages and concentrated in the late residual magma, until, by the law of mass action, it could replace potash and lime of the feldspars and form albite. The carbonate of lime in part crystallized as calcite and in part was leached away together with the carbonates of potash and excessive soda. The Archaean limestones may have been formed by precipitation from such thermal solutions, as in fact suggested by ASKLUND (cf. below. p. 53). The occurrence of these carbonates in many thermal waters of the present is a confirmatory evidence of such processes.

A weak point in this hypothesis is that it has not been verified by experiments. The experience from the silicate analysis shows a rather opposite effect of soda upon the silicates, but it is of course to be expected that the direction of the reaction may not be the same in magmatic solutions under high pressures as it is in the try melt in a crucible. At any rate there are many parallel circumstances in the rocks making the frequent occurrence of this replacement probable.

The rôle of carbon dioxide in the process supposed above would have been that it carried soda throughout the earlier crystal fractionation process and prevented its crystallization. I propose to call it in this character a soda carrier, or generally an element carrier. It is true that the soda replacement discussed above is rather too hypothetical to warrant a special term, but I believe that the conception of such element carriers is of a very great importance and wide applicability in the theory of magmatic differentiation, of the genesis of contact deposits, and metasomatism in general. Let us take a case which, as a whole, seems to be quite clear: The existence of contact-metasomatic iron ores and other iron ores apparently derived from magmas makes it evident that iron has escaped crystallization during all those stages where it usually crystallizes. There has apparently existed an „iron carrier", i. e. a substance forming with the iron an easily soluble compound which could follow water at the passage from the magmatic to the hydrothermal stage. As well known it is believed that in the case of iron some of the halogens, chlorine or fluorine, has played the rôle of a carrier. This question will be touched upon further below.

The enrichment of residual magma in soda may, however, be accounted for also without any replacement at all. According to the theory of fractional crystallization the composition of any residual magmatic liquid is controlled by the previous history of the crystallization process in that particular magma. If the magma is highly deprived of some compound, this is due to the fact that this compound has crystallized out already during the earlier stages. Thus magnesia usually crystallizes in the form of olivine, pyroxenes, and amphiboles in the peridotites, gabbros, and diorites, and the last granitic magma is very poor in magnesia. Concerning the alkalies we may conceive, accepting the conclusions of BOWEN quoted above, that the last magma tends to be enriched in potash. This happens, if the alkalies crystallize chiefly as alkali feldspars. But if the potash would enter into some other mineral which crystallizes earlier than the albitic plagioclase and has not the same crystallization relation to albite as potash feldspar has, then the magma could possibly become nearly deprived of its potash and develop a composition characteristic of a trondhjemite, soda rhyolite, or an albite-extreme leptite. The only possible mineral would be biotite.

This reasoning leads to the tentative hypothesis that the soda-extreme leptite lavas may have come into existence by means of an early crystallization of large amounts of biotite from the parent magma.

I was led to this conclusion independently, after considering possible ways of an early removal of the potash, but I soon found that this idea has already been applied by GOLDSCHMIDT to the trondhjemites. In his monograph on the igneous rocks of the Caledonian chain GOLDSCHMIDT merely touches upon this possibility (1916, p. 112):

„Vielleicht zweigt die Reihe der Trondhjemite schon bei den Hypersthen-Glimmerdioriten ab, deren Kali ganz überwiegend im Biotit gebunden ist und daher durch Absinken dieses Minerals entfernt werden konnte".

In his later paper on the „tribe types" (Stammes-typen") of the igneous rocks GOLDSCHMIDT (1922 a, p. 6) explicitly refers to the early crystallization of biotite as the real cause of the chemical nature of the mica diorite tribe type to which the trondhjemites belong, as appears from the following statement:

„Der wichtigste Unterschied dieser Art von Stämmen gegenüber dem im Normaldiagramm dargestellten Fall besteht in dem schon frühzeitigen und sehr reichlichen Auftreten von Biotit, womit das Fehlen oder wenigstens Zurücktreten von Kalifeldspat offenbar ursächlich verknüpft ist. Die frühzeitige Biotitbildung entzieht dem Magma offenbar so viel Kali, dass Kalifeldspat in den sauren Endgliedern entweder gar nicht zur Krystallisation gelangt, oder doch an Menge sehr zurücktritt“.

The earlier differentiates of this tribe are quartz-biotite norite and hypersthene-mica diorite; after these follow opdalite and trondhjemite. The crystallization of biotite at such an early stage as that of a gabbroic magma was by Goldschmidt accounted for by the fact that the magma masses in the Caledonian chain intruded between beds of clayey sediments from which large quantities of water emanated by the influence of heat and was absorbed by the magma.

Goldschmidt had earlier (1916) done much work in search of other explanations for the absence of potash in the trondhjemites, e. g. by means of subtraction and removal of potash into the siderocks, but he had found no other explanation. He had also investigated whether there were existing any normal granites connected with the trondhjemites and found that they do occur, though rather sparingly in the Trondheim region. In the Stavanger field trondhjemites are more commonly associated with granites. This is what may be expected. The temperature is not the same in all parts of a big magma reservoir and the water concentration may vary, as indicated by the grading of the rocks into varieties somewhat different in their mineral facies in big igneous masses.

Goldschmidt states that his differentiation diagram of the mica diorite type could as well be applied to the Alpine Klausen diorite-tonalite tribe, or to that of the Andean diorites. Now, it seems to me that as close analogies to them may be found in the differentiated igneous complexes of Fennoscandia connected with the older Archaean granites, in Sweden usually called urgranites, in Finland, again, by SEDERHOLM distinguished as the granites of group I. As mentioned above, apophyses and soda-rich marginal aplitic or felsitic „leptite-like“ varieties frequently occur in connection with the urgranites. Possibly the albite aplites described by SUNDIUS (1926) may be thus explained. The urgranites from which these highly salic and extremely sodic rocks have been immediately derived, include large masses of quartz diorites commonly rich in biotite, and so are as a rule the diorites and many hornblende gabbros which in the Archaean areas mainly represent the gabbro group. Even the hornblendites and peridotites in the Archaean are often biotite-bearing.

The soda leptite eruptions must be supposed to have been fed from the uppermost part of subjacent magma masses. Their lava was the last residual portion of quartz-dioritic or oligoclase-granitic magma, enriched in soda by the removal of potash in the biotite of the deep-lying gneiss. At intervals, and at an increasing rate as the process went on, the eruptions came from deeper-lying portions of the magma or from isolated magma capsulae which had not been equally water-rich originally and therefore had developed the „normal“ liquid line of descent leading to normal granites and a potash-rich last liquid. Perhaps the largest part of the eruptions, when the whole area of the Fennoscandian Archaean is considered, were developed into intermediate leptites which, in their alkali ratios, agree with the most common liparites of today.

From the point of the hypothesis outlined above the connection of the microcline-extreme and the albite-extreme leptites each with a special kind of ores can only be expected. In fact this hypothesis is more elucidative for their understanding than the hypothesis of a mysterious liquation. The metal content of the residual magma, of course, is dependent partly upon that which has been removed earlier and partly upon that which is most easily soluble in it. Thus the fact that manganiferous ores and manganese-rich skarns are often associated with potash-extreme leptites but not with the soda leptites, is explained by assuming that large amounts of manganese in one case concentrated itself into the residual liquid and in the other case had been removed earlier in the biotite of diorites, quartz diorites etc.

The two hypotheses outlined above are not alternative but rather complementary to each other. An early removal of potash is very well demonstrated in many cases, but alone it would hardly have led to such a clean-wash of potash as actually seen in the most typical albite-extreme leptites, the trondhjemites being much less extreme.

The leptite formations are peculiar in showing many features extreme in their kind. From many younger formations they differ, however, rather quantitatively than qualitatively, and there are no really exceptionalistic features in them which could not also form under the conditions now prevailing. But it cannot be disputed that the picture of the conditions during the time when the leptites were originally formed is very different from the present day conditions. Some geologists lay more stress upon the actual features displaced by the rocks, while others emphasize the differences and deduce from these more profound differences in the conditions. As an example of an exposition showing marked tendencies in the latter direction I translate, again, a paragraph from the text book outline of the Archaean of Sweden written by Asklund (1931, p. 173):

„Excepting the limestones, the leptite-hälleflinta complex proper is very completely devoid of differentiated sediments like quartzites, shales etc. which represent residual products of chemical weathering. The richly occurring limestones and intercalations of iron ores cannot be products of enrichment of chemical weathering, as the low proportions of the supplying materials, i. e. lime- resp. iron-rich silicates within the hälleflintas, would involve that enormous masses of those rocks should have been subjected to chemical denudation. Residual products — sandstones and shales — are lacking, and thereby well nigh the only possibility left is to interpret the limestones and iron ores as products deposited from solutions which in one way or another have been freed from the magma of the quartz-feldspar rocks. Especially concerning the peculiar

Archaean limestones — the carbonate rocks of the Archaean in general — the probability of this process of origin has been brougth forth".

To this I would only add that in the wide Archaean territory of Fennoscandia outside of the leptite regions proper in western Central Sweden, to which the above outline is applied, differentiation by weathering is generally fairly well recorded by the oldest supracrustal rocks. As pointed out above the most pronouncedly „exceptionalistic" mode of origin is suggested by the sedimentary quartz-banded, or jaspilitic, iron ores.

On the Changes of Composition in Metamorphism and the Principles of Metamorphic Differentiation.

In discussing the record of the conditions during remote geological times exhibited by the Archaean rocks we were repeatedly confronted with the question: Is the composition of the rocks today the same as it was originally, or was it changed later? Even in those cases where well preserved primary structures seem to prove that nothing has been changed, there are usually evidences of recrystallization which in itself means a differentiation in the smallest petrographic units of the structure of the earth's crust, or the individual crystals. This fact involves a feeling of uncertainty in many conclusions. The petrologist often must admit the possibility of a migration of substances and a change of the original composition of rock masses during their metamorphic rearrangement.

During my attempts to interpret the record of the Archaean rocks I was therefore led to ask whether it might not be possible to outline some general physicochemical principles which would help toward an understanding of the cases in which such changes may have occurred and in which direction they may be expected to have gone. A preliminary note on this subject is being published elsewhere (ESKOLA 1932 b). The classification of the metamorphic changes of composition there arrived at is as follows:

1) Metamorphic differentiation within a rock mass, due to:
   a. growth of crystals or aggregates of crystals (the concretion principle),
   b. internal metasomatism leading to concentration of the substances entering into the least soluble minerals (the principle of enrichment in the stablest minerals), or
   c. extraction and re-deposition of the most soluble substances (the solution principle).
2) Transfer of substances into and from a rock mass, effecting:
   a. addition,
   b. metasomatism, or
   c. extraction of substances.

For comparison I quote the classification of the metamorphic processes given by Magnusson (1932) in a recent paper on the metamorphism in the Archaean of Central Sweden:

I Alterations without any considerable chemical changes;
   A. Recrystallization by the influence of high temperature;
   B. Crushing up and shearing;
II Alterations with considerable chemical changes;
   A. Within previously existing materials;
      a. by secondary splitting;
      b. by interchanges of materials;
   B. By addition of materials from outside sources, chiefly from intrusive granites;
      a. forming of pegmatites, feldspathization etc.;
      b. metasomatic replacements.

Referring to the paper of Goldschmidt (1922 b) for the metasomatism and to my recent paper for the metamorphic differentiation in silicate rocks, I shall in what follows briefly discuss a few special cases which are of importance for Archaean geology.

Metamorphic differentiation according to the concretion principle includes the growth of crystals, like porphyroblasts, and of concretions. Relatively big crystals and compact aggregates behave as if they would attract the substances of which they consist. Applied to metamorphic rocks in general the changes following this principle would be expected to result in an accentuation of extreme compositions at the contacts. In varved schists the quartz-rich lighter layers would have become still more siliceous, and the alumina-rich clayey layers still more aluminous. Such changes have actually occurred, as appears for instance from the concentration of staurolite etc. along the upper margin of the clayey layers. On the whole these changes seem to have been rather inconsiderable.

The second principle is applicable to cases in which a crystallization of new minerals has occurred, mostly by means of metasomatic replacement. The products formed are the least soluble ones under the prevailing conditions, and the crystallization continues as circulating solutions bring more material to the place of deposition. This principle is illustrated by the change of kaolinite into sericite inferred by VÄYRYNEN (1929), or by the common pseudomorphs of micas after andalusite or staurolite, described also in the present paper. Potash has migrated to the place of deposition, where its arresting depends upon the forming of the mica. The potash would migrate even under static conditions owing to the concentration gradient in the solution resulting from the crystallization. By this principle a rock may become enriched even by a mineral whose compounds are not originally present in large amounts. The principle of enrichement in the stablest minerals may therefore be expected to act in a direction either the same as or opposite to that of the concretion principle. Differentiation of this kind is probably common, but often difficult to reveal. Most conspicuous is the internal metasomatism at the contacts between non-compatible rocks. Thereby are formed reaction zones, walls, or seams (e. g. the reactions skarns of MAGNUSSON).

The solution principle is illustrated by the veined gneisses and rocks traversed by quartz veins. Those veined gneisses to which the term venite (HOLMQUIST) is applicable are believed to have originated by means of a differential fusion of silicate rocks, a migration of the palingeneous magmatic solution, and recrystallization along the paths of the currents. Quartz veins originated in the same way at lower temperatures were almost pure silica only remained in diluted solutions. In both cases the solutions were mobilized by outside energies, mostly by crustal movements, and in many cases the rocks may have been leached by water.

When my note on the metamorphic differentiation was already given to the printer I received the important paper of Goranson (1932) in which the melting of granite is treated on the basis of an experimental investigation. A granitic magma, like that of the Stone Mountain granite used in the experiments by Goranson, with 1 % H_2O, at a depth of 10 kilometres, would begin to crystallize at 1025°. At 700° about 85 % of the magma would be solid. The residual magma would contain about 6.5 % H_2O. About 2/3 of it, or 10 % of the whole, would crystallize as aplite and pegmatite between 700° and 550°, and 1/3, or 5 %, as quartz veins below 500°. There would occur a discontinuity at the moment when a diluted aqueous solution begins to separate instead of a magmatic silicate solution; under certain conditions those two liquids may exist even at the same time. This result explains why transitional types between pegmatitic or aplitic veins and quartz veins are very rare. The occurrence of quartz veins containing variable though mostly small quantities of potash feldspar, however, proves that the siliceous solutions also contain some silicates. In the quartz veins in the Archaean of southwestern Finland I have frequently observed red microcline. In the spilites, greenstones and greenschists there seem to exist rather gradual transitions from pegmatite-like albite-quartz veins often containing magnetite and hematite into quartz-calcite veins containing clinozoisite and sulphide minerals (Eskola 1925).

Goranson's result fixes the temperature limit between the partial fusion and the lower grade metamorphism at about 550°. Above this point veined gneisses originate and below mainly quartz veins. In the former case the rocks from which granitic magma has been squeezed out must have been enriched in those compounds which were originally in excess over the granite proportions. The excess of alumina in clayey sediments may be expected to have increased as well as the excess of silica in quartzitic schists (Eskola 1932 a).

In its effects this metamorphic differentiation is therefore parallel to that according to the concretion principle. The mobilizing of silica at the lower temperatures, again, might be expected to bring forth an impoverishment in quartz of the rocks from which it has been extracted. Owing to the large average amount of quartz in most rock complexes such a decrease can only rarely be stated.

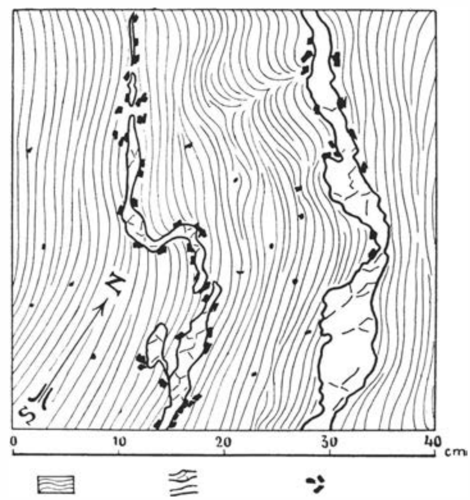

Fig. 5. Porphyroblasts of staurolite in mica-schist, mainly concentrated at the margins of quartz veins. Near the School-house, village of Heinävaara, parish of Kiihtelysvaara in Karelia.

The migration of substances in connection with the deformation of rock-masses, mostly effected by solutions soaking into them, is not by any means limited to silica and the alkali feldspars. The Archaean abounds in instances of differentiation due to the solution and re-deposition of substances. WEGMANN and KRANCK have already studied some phenomena of this kind in the southern archipelago of Finland (1931).

To conclude with an actual example I reproduce a sketch showing the distribution of crystals of staurolite along both sides of quartz veins in a mica-schist (fig. 5). A migration of the compounds of the staurolite is immediately apparent, as also its connection with the quartz veins, but it is hard to see how the substances have moved and what has caused the final placing of the crystals. This figure may be compared with fig. 1 (p. 12) which shows an extreme case in an opposite direction, with no apparent migration. Backlund (1918) was one of the first to interpret the location of porphyroblasts of staurolite in schists as controlled by the rock deformation. A petrologist must not become puzzled if he meets with apparent contradictions in the phenomena of metamorphic differentiation! These phenomena are utterly various and complicated, but they will no doubt offer most interesting problems for the petrologists as well as a useful aid for the geologists in their efforts to interpret the record of the metamorphic rocks.

Internal differentiation and addition, interchange, or extraction of substances are often connected with each other. Especially numerous cases of metasomatism due to addition of substances have been described, such as soda, potash (most important in the Archaean!), iron, magnesia, silica, carbon, and sulphur.

Some special attention may be directed to the problem of the magnesia metasomatism in the leptitic rocks.

The Magnesia Metasomatism.

C. E. Tilley and Sir John S. Flett (1930) described hornfelses from Kenidjack, Cornwall, including anthophyllite-cordierite hornfelses, anthophyllite-cordierite-plagioclase hornfelses and anthophyllite-plagioclase hornfelses (in which cummingtonite may take the place of the anthophyllite). These rocks resemble very much many examples from the Orijärvi region (Eskola 1914), as well as those occurring in numerous fields in the leptite regions of Sweden. Concerning the metasomatism the authors write i. a. (p. 37):

„Extensive metasomatic changes in sediments or siliceous leptites, involving large-scale introductions of magnesia and iron oxides from an adjacent igneous intrusion, have been claimed by Eskola for the somewhat similar anthophyllite-cordierite rocks of the Orijärvi area". — — „Without entering into, or discussing, the evidence given by Eskola for the rocks of the Orijärvi field, we may state that the evidence for metasomatic processes of this nature is wholly wanting at Kenidjack. Apart from the inherent difficulty in believing that such magnesia-rich solutions are available in the residual liquids of granitic magma, it is seen that the normal sediments at the immediate contact with the granite have suffered no metasomatism of this nature, anthophyllite-cordierite rocks being developed distant from the contact".

Among several possible ways of explaining the genesis of the Kenidjack hornfelses TILLEY and FLETT have accepted the following as the most probable one:

„There remains the fourth hypothesis which we believe to be responsible for the nature and the relationships of these peculiar rocks. Briefly it is considered that the original doleritic intrusions were subject to intense atmospheric weathering whereby calcite, chlorite, serpentine and iron oxides were developed from the plagioclase, pyroxene and possibly olivine. The formation of calcite from basic plagioclase resulted in the freeing of alumina possibly as bauxite or other hydrous oxide. As a result of these processes, and the ready migration of lime and alkalis (soda), the dolerites were largely leached of these constituents The whole was then subjected to intense shearing whereby the lime-rich areas gave rise on contact metamorphism to hornblende, and the chlorite and aluminous recidues gave rise to the cordierite-anthophyllite rocks. A cordierite-anthophyllite rock would represent the extreme stage of leaching, but intermediate stages would be represented by those transition rocks in which plagioclase is present in significant proportions".

In the present paper rather much has been said about the „actualistic method". Applied to the present case it would involve the inquiry whether extremely magnesia-rich rocks like the cordierite-anthophyllite rocks are found among the recent sediments. So far as I know no such sediments are known to exist, a fact which certainly is not good for the hypothesis of TILLEY and FLETT.

For several reasons, nevertheless, I would like to consider seriously the hypothesis of TILLEY FLETT, also in connection with the Archaean of Fennoscandia. In the first place, being responsible for having first advanced the hypothesis of magnesia metasomatism which has found a widely extended application in Sweden, I am rather sensitive obout it and would be glad to have it corrected, if it is wrong. Furthermore, the idea of TILLEY and

FLETT seems to me very attractive. As they say, one has difficulty in believing that magnesia-rich solutions are available as liquids associated with acid granites. I know from my own experiments on hydrothermal synthesis in steel bombs that magnesia is practically insoluble when the amount of silica present exceeds the metasilicate ratio, although the orthosilicate and still more basic silicates of magnesia are rather easily soluble in overheated water under high vapor pressures. Finally, if any hypothesis related to that of TILLEY and FLETT would account for the widely spread magnesia-enriched rocks in the Fennoscandian Archaean, we would have here an eloquent instance of the effects of a thorough weathering indicating a comparatively warm climate. This would be what I have been looking for most eagerly, but so far in vain.

I hope that the geologists working in the Archaean areas of Finland and Sweden will consider this hypothesis. Meanwhile I give the reasons why I must still indulge the hypothesis of magnesia metasomatism with regard to the Orijärvi region.

Concerning the ore-bearing zone around the Orijärvi granite there seems to be no escape from the conclusion that metasomatism has been the main process in the genesis of the sulphide ores and the „ore quartzites" as well as of the skarn rocks. The hypothesis of TILLEY and FLETT, if applied in this case, would involve the further assumption that the cordierite- and anthophyllite-rocks and the ore quartzites were rich in magnesia and poor in lime ages before the metasomatism set in. It may be impossible to find any direct evidence against this assumption, but neither does it seem to be necessary. A look at the pictures of the big cordierite crystals in the Orijärvi field (e. g. p. 204) is sufficient to convey the idea that magnesia had a certain solubility and power of migrating. The same appears from the remarkable replacement of the leptite minerals by the cordierite in the fragments at Kurksaari (p. 208) where only grains of quartz and apatite have been left intact and enclosed in the cordierite. In the Orijärvi copper ore the sulphides and the silicate minerals seem to be closely connected genetically with each other, and the process does not seem to consist merely of a recrystallization of cordierite, but also of an introduction of most of the materials present. There are among other things beautiful crystals of cordierite whose ends are surrounded by the ore and which evidently have crystallized in miarolithic cavities. Neither can I see how the replacement of the limestone by the tremolite skarn could possibly be accounted for except by a migration of a magnesia-bearing solution. Many further evidences of this migration have been brought forth by Geijer and others in Sweden.

The association of sulphidic ores and magnesia-rich (sometimes iron-rich) silicates is widely distributed. A great number of occurrences might be mentioned; I refer to the works of Geijer on the Falu (1917) and Riddarhytte (1923) fields. It would be strange indeed if this repeated coincidence was the result of a mere change. It may be noted, however, that there are also many occurrences of similar „magnesia-extreme“ rocks not accompanied by sulphide ores. — Quartz veins show a positive evidence of the existence of magnesia in the siliceous solutions remaining after the pegmatitic crystallization, as they often contain chlorite.

It would of course be desirable to know exactly in what form magnesia has migrated, but there seems little to give any hint in this respect. Perhaps the solutions have contained some other substances which were able to keep magnesia in solution but escaped as the minerals crystallized. In the treatment of the phenomena of metasomatism it is often necessary to assume some such a „carrier“ substance (cf. above p. 49) which has disappeared when its work was complete. In the case of hedenbergite or andradite skarn, for instance, it seems almost unavoidable to assume the presence of some element like fluorine or chlorine in those cases also where this is not indicated by the occurrence of fluorspar or scapolite. With the aid of the carriers iron may escape the whole process of magmatic crystallization and separate only at a later stage as replacement ores or skarns, or as ore veins, while the carriers themselves, in the form of soluble salts, continue still farther and may reach the earth's surface in thermal springs. Some of the carrier elements are arrested in minerals, as boron in tourmaline or axinite, and fluorine in fluorspar. If these elements did not happen to have such poorly soluble compounds, we would hardly have known that they played a rôle in the metasomatism.

In the case of the magnesia metasomatism, however, the hypothesis of the carrier elements is of little value if it is not possible to tell which it has been and how it has worked. As an alternative hypothesis it might be assumed that magnesia was added in the form of extremely diluted solutions and the metasomatism took place according to the principle of enrichment in the stablest minerals.

Small as the concentration of magnesia in the solutions added must have been, it was sufficent to cause replacement of the feldspar owing to the still smaller solubility of the newly forming magnesium silicate, cordierite and anthophyllite. The solutions soaked into the leptite in great quantities carrying iron and sulphur which combined themselves probably already in the solutions and were deposited as sulphides. Iron in the rocks and their magmas is as a rule accompanied by magnesium: so was also the iron which eventually combined itself with sulphur. In a way, therefore, iron may in this case be spoken of as a carrier. In the skarn rocks replacing limestone, iron and magnesia were in fact deposited together, and more or less iron also enters into the anthophyllite, cordierite and garnet which are found in the replacement products. This reasoning seems to offer the most probable solution of the problem of magnesia metasomatism.

The Problem of the Beginning.

In his theoretic study of the condensation of water on the cooling earth Niini (1932) assumed that the quantity of water on the earth has been the same as it now, or about $1400 \cdot 10^{18}$ kilograms. Before the condensation the athmospheric pressure therefore was 275 kg/qcm. As this exceeds the critical pressure of water, the condensation should have begun at the critical temperature which, due to certain amounts of salts dissolved in the overcritical water vapor, was somewhat higher than that of pure water, according to NIINI at 380° or 390° C. The earth's crust, under the influence of this overheated vapor, should have contained on its surface pneumatolytic or hydrothermal minerals. The condensation starts with the forming of a phase boundary surface between the lower liquid sphere, the Ocean, or the hydrosphere, and the upper gaseous sphere, the athmosphere, and not primarily as a „first rain". The condensation proceeds continually as temperature falls, the Ocean growing thicker and the atmospheric pressure decreasing. Owing to the decrease of the density of water at the rise of temperature the Ocean level, in spite of the evaporation of the water would, from a temperature of about 290° C downwards, stand higher than at present, at 180°—220° about 300 metres above the present sea level. NIINI points out that at that early stage the heat gradient in the lithosphere should have been very much steeper than at present and the earth's crust consequently much thinner, perhaps only a few hundred metres. Therefore the isostatic adjustment should have been highly perfect and no high mountains could have existed; therefore probably for a time the Ocean covered almost the whole surface of the earth.

NIINI also tries to calculate the rate of the decrease of temperature of the earth's surface, on the basis of the radiation law of STEFAN-BOLTZMANN. Owing to the uncertainty of certain premises the results are rather indefinite, but, on the most probable premises, the time of the temperature fall presupposed by the condensation of the water would have been surprisingly short, only about 20,000 years from 400° to 16° C. NIINI points out, that the chief difficulty in this calculation is due to the fact that the „effective temperature" of the radiating earth globe cannot be inferred, as it depends upon the absorption of the vapor-filled athmosphere and the doubtless very thick cloud cover of that time. The assumption regarded as most probable by Niini and applied in the calculation of the above figure, 20,000 years, is that the effective temperature at a time when the average temperature on the surface of the lithosphere was 400° C was about 30° C higher than at present. If it had been higher, then the time of the cooling would have been shorter while, in the opposite case, i. e. if the shield effect of the cloudy athmosphere was greater, the time of cooling would have been longer. Considering that the conditions probably prevailing during the period of condensation upon the earth actually seem to prevail at present on the planet Venus, upon which the shield effect of the clouds seems to be very great, the latter alternative seems somewhat more probable. We may thus conclude that the time required for the fall of temperature from 400° C to the present degree would probably have been over rather than under 20,000 years.

Compared with the geological time scale with its thousand millions and more of years the period of condensation, at ay rate, probably was exceedingly short. Nevertheless the action of the athmosphere upon the lithosphere during the interval from the first consolidation of the earth's crust to that time when the present temperature was reached should have been long-continued enough to cause a thorough alteration of the surface of the lithosphere. During the first time, before the start of condensation, the products should have been „pneumatolytic“ and from the passing of the critical point onward hydrothermal products grading over into products of weathering wich would gradually change in character with the fall of temperature. When the average temperature of the earth's surface had fallen to 100° C the athmospheric pressure was still considerably higher than at present and consequently the boiling-point of water above 100° C. This temperature therefore had no special significance in the process of cooling.

Returning to the conditions during the earliest geological time we have the picture of an earth with a vivid volcanic activity but a cool climate and no trace of the results of weathering that should have been formed during the „period of condensation“, when land areas had been laid bare and the exogenic agencies had begun their work on the growing continents. Under those conditions — high temperature, from nearly 400° C downward, an athmosphere saturated with water vapor — chemical decomposition of the rocks should have been exceedingly intense. During the latter part of the condensation period it should have been essentially similar to weathering in the tropical zones of the present earth, only far more thorough.

This picture is not in harmony with HADDING's (1929) idea that the leptites, representing stratified tuffs of the oldest Archaean, would be the first water-laid sediments, originating shortly after the „first rain“ had fallen on the earth.

I shall consider three different possible ways to account for the absence of traces from the period of the earth's cooling:

1. The earth has never been liquid altogether and no first condensation of water has ever taken place.

2. The earth was once liquid; its cooling and the condensation of the water took place approximately in the way outlined; the products of hydrothermal alteration and high-temperature weathering, however, have been obliterated by volcanic eruptions, mountain building, and denudation.

3. The cooling took place as supposed under 2 but the quantity of free water was at that time much smaller, having increased since by supply from the crystallizing magma. All the water now existing in the Ocean would have been freed, if a 17 kilometres thick mantle of granitic magma all around the globe crystallized and thereby gave off 4 % water. Even if the amount of water given off was only a half of that quantity, the process of condensation would yet have been considerably shorter, as the quantity of water in the early athmosphere would have been smaller and its shield effect correspondingly slighter. The hydrothermal

and subaerial changes during the condensation period were therefore inconsiderable.

The majority of geophysicists at present agree with Jeffreys (1929) that the earth has been at one time liquid altogether. To me the absence of traces of the first condensation of water has seemed rather strongly to favour the idea of Chamberlin (1926) that the earth never was entirely molten, although the argument of the latter is no doubt open to criticism from the view-point of modern tectonical geology. I shall, however, as fruitless omit the discussion which I have written on this topic and suspend the question which of the three assumptions proposed above is right, or whether they are wrong alltogether. Instead of these speculations I shall, in the summary below, outline a sketch of the earliest events traceable in the geologic history from the Archaean rocks.

Summary.

The Archaean includes many metamorphic rocks whose relict primary features prove them to have been originally similar to recent sediments, such as drift, gravels, sand, silt, mud, or clay. The writer especially describes some varved schists from the Archaean of Finland and publishes analyses made separately of the lighter (coarser) and the darker (finer) layers of the varves of these and of late-Glacial varved clays (p. 14). The varved schists contain lime-rich nodules, in composition and mode of occurrence agreeing with calcareous concretions in the varved clays (analyses p. 20). These Archaean sediments exhibit such close similarities to analogous Pleistocene sediments that similar conditions of origin, i. e. weathering and deposition in temperate or cold climates must be inferred. Many graphite-bearing schists similar to bituminous shales from later periods, or recent muds containing organic remains, occur in various sections of the Archaean. Sederholm has described brecciated rocks which he interprets as autochtonous weathering soils. Though not quite conclusive in the opinion of the writer,

the indication of these occurrences accords with that of all the other Archaean climate witnesses. Important is the negative evidence that no indications of weathering in warm climates, such as the laterites of the tropical regions of the present, have ever been met with in the Archaean of Fennoscandia.

Varved sediments, regarded as the most reliable climate witnesses, have not been found in those sections which are believed to represent the oldest Archaean in Fennoscandia, or the so-called leptite complexes, though even these include clayey sediments similar to them in composition. In general the leptite complexes as well as the Bothnian formations differ from younger Archaean series in the larger proportion of volcanogeneous rocks. The quartz-banded or jaspilitic ores, occurring in formations which are supposed to belong to the Middle and Lower Archaean, are referred to as formations indicating a most exceptionalistic mode of origin.

The genesis of the „microcline-extreme" and „albite-extreme" leptites occurring especially in many ore fields of western Central Sweden (Bergslagen) is discussed from the view-point of the crystallization differentiation theory. As they have been described, by SUNDIUS, MAGNUSSON, GEIJER and others, as volcanogeneous rocks with a nearly unchanged composition, they should represent late stages of the residual liquids. The microcline-extreme leptites may be regarded as normal products on the „liquid line of descent" (BOWEN), but the albite-extreme leptites require some other explanation. The writer proposes two possible hypotheses which are believed to be complementary to each other: (1) the relative absence of potash in the leptites, as in the trondhjemites, is accounted for by their derivation from a series in which much biotite had crystallized at relatively early stages, and (2) soda has escaped crystallization at the earlier stages in the form of carbonate and finally replaced lime and potash by means of autometasomatism.

The writer attempts to outline some general principles which would help towards an understanding of the changes of composition so frequently inferred in the Archaean rocks. Among phenomena of metamorphic differentiation (Eskola 1932 b) the genesis of veined gneisses (venites) and quartz veins is discussed on the basis of the results of Goranson (1932). The problem of magnesia metasomatism in silicate rocks in discussed in connection with the explanation of magnesia-rich rocks from Kenidjack, Cornwall, by Tilley and Flett, and some views are presented to explain this metasomatism from the general principles of metamorphic changes.

The problem of the beginning of the earth's geological history is discussed with reference to the study of Niini (1932) on the supposed first condensation of water. The absence of all such products of hydrothermal alteration and intense weathering which should have been formed during the condensation period would seem to indicate that the earth has never been liquid altogether. As alternative explanations, however, is considered the possibility that these products have been obliterated, or also that no such products were formed in any considerable amount, as a large part of the water of our globe may have been dissolved in the magma and been freed later during its crystallization.

In the leptite regions the supracrustal leptitic rocks appear to be the very oldest rocks. Their advanced stage of differentiation, however, indicates that crystallization of magmas prior to their extrusion had occurred on an enormous scale. Next before the leptites, which are chemically equivalent to aplites, there are in the differentiation series the ordinary granites or granite gneisses. Their existence is thus concluded from the chemical character of the leptitic rocks. They may or may not be exposed somewhere. It were close at hand to look for them in the vast granite gneiss areas of western Sweden and eastern Karelia. In many leptite areas, e. g. in southwestern Finland, the leptites are seen to be invaded by granitic gneisses, while the latter frequently pass gradually over into leptite-like rocks. All what we know of the structure of the Archaean territories, where granitic rocks seem, on the whole, to underly the supra-crustal rock complexes, would suggest the following idea: In remote Archaean periods widely spread subjacent granitic magma masses existed at rather shallow depths beneath the crust which was largely built up of leptitic rocks. Crystalline materials may have already existed at greater depths, as inferred e. g. by GORANSON (1931), and it may well be imagined that the subjacent granitic magma was generated by the partial refusion of such materials. The solid crust was growing thicker from the extrusions fed by the crystallizing granitic magma. During periods of mountain folding liquid magma from the subjacent basins was pressed into the folded leptite complex. As these processes had continued during long times, it is conceivable that leptites always are seen pierced by granites. This picture of the conditions during the oldest geological times would seem to rest upon a somewhat safer foundation of observation than all that can be said about the existence or non-existence of a „first consolidation crust".

The beginning of the history of the earth's crust is not yet within touch for geological research. To a certain extent the actualistic method is applicable even to the very oldest rocks known, and all that can be said is that volcanism and plutonism in the earliest geological times acted on a larger scale than ever in later times. This gradual difference, however, conveys the idea that the beginning was not for back.

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Explanation of the Plates.

The longer side of the compass box serving as a scale measures 15 cm. It is in all the photographs of outcrops placed so that the compass end points to the North.

Plate I.

Fig. 1. Varved schist near the Keihäskoski rapids, Ignoila, Suojärvi. The rock shows a transverse shearing and many small faults along shearing planes, the eastern side of each fault having moved relatively in a northerly direction.

Fig. 2. A specimen from the outcrop shown in fig. 1, loosened along shearing planes. $^3/_4$ natural size. The west side of the faulted slab, showing a concave rounded groove along each varve, is turned upwards, while the downward turned east side shows pod-like swellings on the varves.

Fig. 3. Varved and contorted schist with a quartz vein. South of the road between the railroad crossing and the Välimäki mine, Impilahti.

Plate II.

Fig. 4. Varved schist, each varve being composed of several thinner layers. Railroad cut east of the road crossing near Välimäki, Impilahti.

Fig. 5. Varved schist with calcareous concretions in a quartzitic „giant varve". Railroad cut near Välimäki Station, Impilahti.

Fig. 1.

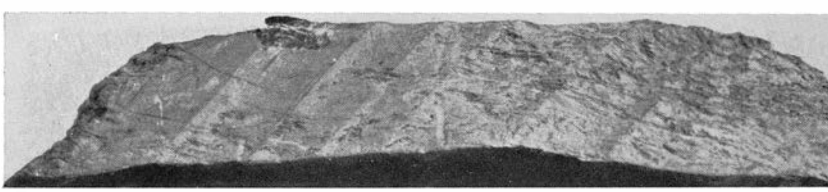

Fig. 2.

Fig. 3.

PLATE II.

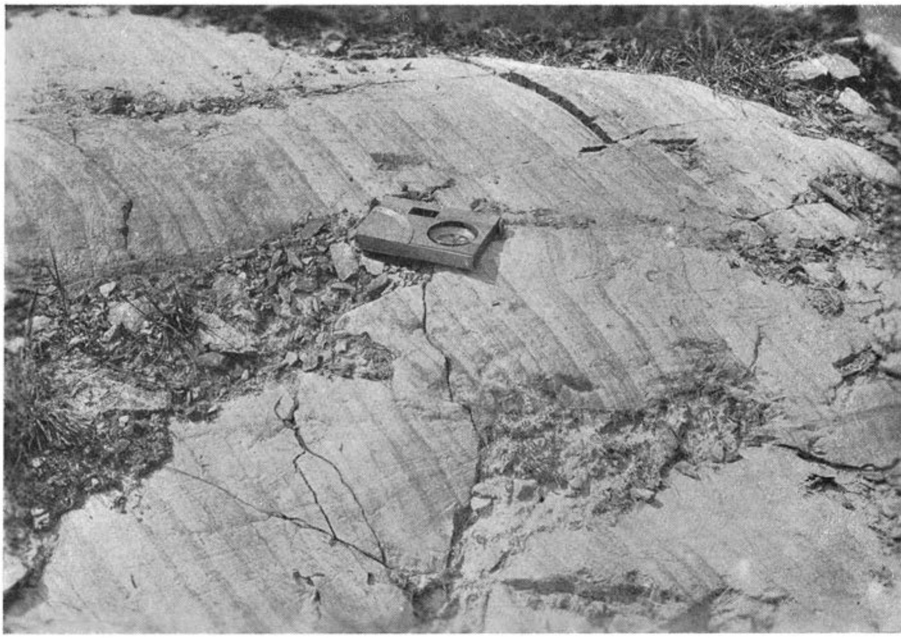

Fig. 4.

Fig. 5.