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ON PHENOMENA OF SOLUTION IN FINNISH LIMESTONES AND ON SANDSTONE FILLING CAVITIES

BY

PENTTI ESKOLA

WITH 13 FIGURES IN THE TEXT

HELSINGFORS
FEBRUARY 1913

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Contents.

Preface.

In the course of my geological work in the southwest of Finland, where crystalline limestones are common and numerous quarries afford excellent opportunities of studying them in new sections, I had many occasions of observing the phenomena of solution in these rocks. The phenomena in question began to attract my closer attention, when I found, in the summer of 1911, sandstone in cavities formed by the enlargement of joints due to the dissolving action of water. This discovery was made in the limestone quarry of Illo in the parish of Westanfjärd. It seemed probable that this sandstone might be geologically and stratigraphically analogous with the Lower Cambrian sandstones found as dikes in crystalline rocks at several places in Sweden and Finland. This occurrence suggested several important queries: Could any fossils be found also in this sandstone which would furnish a definite evidence concerning its age? If the Cambrian age of the sandstone could be proved, were there any signs of a later weathering which had occurred in post-Cambrian time, when the denudation had again reached the level of the old sub-Cambrian land-surface? Or were all traces of post-Cambrian (pre-Glacial) weathering lacking, which would mean, that the surface of the Archaean had here been untouched by atmospherical agencies during the whole of the time between the Lower Cambrian and the beginning of the Ice-Age?

For the solution of these questions it was necessary to collect as much evidence as possible, including also observations concerning the post-Glacial phenomena of solution, in order to make it possible to distinguish them from the older signs of weathering. But these later phenomena seemed in themselves to be deserving of more interest, for, so far as I know, they have not yet been studied in detail in any country geologically resembling Finland.

Last summer I therefore revisited most of the limestone quarries in the southwest of Finland in order to examine all the phenomena connected with the weathering and solution of limestone. The results of these studies are given below. The evidence is not so conclusive as I had hoped it would be, especially because, in spite of minute examination, no fossils could be detected in the sandstone. Nevertheless I hope that the facts here discussed may prove to be of sufficient interest to justify the appearance of this article.

I am indebted to Professor J. J. Sederholm, the Director of the Geological Commission of Finland, for the opportunity afforded me of doing the field-work for this treatise as an assistant geologist of the Geological Commission. To Professor Sederholm also are due my warmest thanks for the kind assistance given me in the writing of the English text. — The laboratory work was done at the Mineralogical Institute of the University of Helsingfors.

Solution in Post-Glacial Times.

Ablation of Limestone on the Shores.

The crystalline limestones of southwestern Finland occur as almost perpendicular layers of a thickness varying between a few centimeters and some fifty meters, and of a length often attaining many kilometers. The adjoining rocks are all crystalline and the following are the most common: granites and amphibolites (»metabasites») intersecting the limestones, and finegrained gneisses or »leptites», intercalated between them.

The limestone is commonly more or less corroded on the surface, and the adjoining siliceous rocks therefore form walls protruding some centimeters or decimeters from the surface of the rock. This difference of level shows the amount of ablation of the limestone in post-Glacial time. The wear of the siliceous rocks is entirely inappreciable as compared with the work of ablation in the limestone. Often the Glacial striae are still sharply defined on the surface of the former.

Very rarely the surface of the limestone is on a level with the neighbouring rocks, and the Glacial striae left on it. In this case the limestone has not been worn off at all since the Ice-Age. I have observed but few instances of this kind. It may be seen on the shore of Lake Lohjanjärvi in the parish of Lohja (Lojo), and on the island of Ovensor in the parish of Korpo. In both these instances the rock was until lately covered by the water, in the former place up to about 50 years ago, when the surface of the lake was lowered; in the latter place, which is situated on the sea-shore, the gradual rising of the land has caused the emersion.

In both cases, too, the limestone, when rising from the water, was still covered with a thin layer of gravel. The coincidence of these two conditions seems to be necessary for preserving the limestone from ablation. When it has risen a few meters *above the surface of* *the water*, the rock is always more or less corroded, whether it is bare or covered with a layer of sand or gravel.

In the same way all *naked* surfaces of limestone *on the sea-shores*, which have lately risen above the water, are corroded to a notable degree. Only when covered with soil and water, limestone may occasionally be unaffected by dissolving and denuding agencies. Probably the limestone forming part of the sea-bottom is thus preserved as long as the depth is sufficient to protect it against the action of the waves. In such places the rock-surface must be covered by Glacial or post-Glacial deposits. When the elevation of land has proceeded far enough to expose it to the action of the waves, the soil will in many cases be washed away, and from that moment ablation begins to take place on the bare surface of the limestone. If the rock remains covered, percolating water begins to affect it. A bed of clay, however, protects the rock against solution for a long time, if the rock-surface is nearly horizontal and the soil covers a somewhat extensive area. Such is the case at the vast quarry of Limbergs-gruvan in the parish of Pargas, where the surface of the limestone, at a height of little more than 14 meters, is for the most part untouched by solution. Only on sloping surfaces, near uncovered parts, there is a small amount of solution to be noticed. This phenomenon may be rather common underneath extensive beds of clay, though such rocks are very seldom laid bare. In all other cases where I have seen limestone forming the substratum of clay, the former has been attacked by solution.

This ablation is effected in part by solution, in part by mechanical wear caused by the rolling of pebbles and sand and by the water itself. Of these two agencies, solution is the more important, as is shown by the fact that there is no noticeable difference in the degree of ablation in the limestone which is exposed to the waves of the open sea and that on the sheltered shores of narrow bays and sounds, though the mechanical abrasion caused by the waves is, of course, very much more considerable in the former case, as is shown by its effect on Glacial and post-Glacial deposits.

As a common result of the action of the agencies in question the surface of the limestone, when it has risen above the level of the sea, is eroded to a depth of 3 to 15 centimeters beneath the surface of the adjacent siliceous rocks. Within these limits the amount of ablation varies in the rocks of limestone found on the sea-shores in south-western Finland.

At the same time the limestone often becomes pitted on the surface, a phenomenon peculiar to this rock when corroded by the waves, and also very often seen in the shore-rocks of lakes (fig. 1). On sea-shores the cavities are usually from 5 to 10 cm in diameter and are very shallow, in most cases only 1 to 3 cm deep. Those rock-surfaces, in which the limestone has a non-foliated texture, are especially pitted. Where the limestone is intercalated with numerous small layers of siliceous rocks, this phenomenon is usually absent.

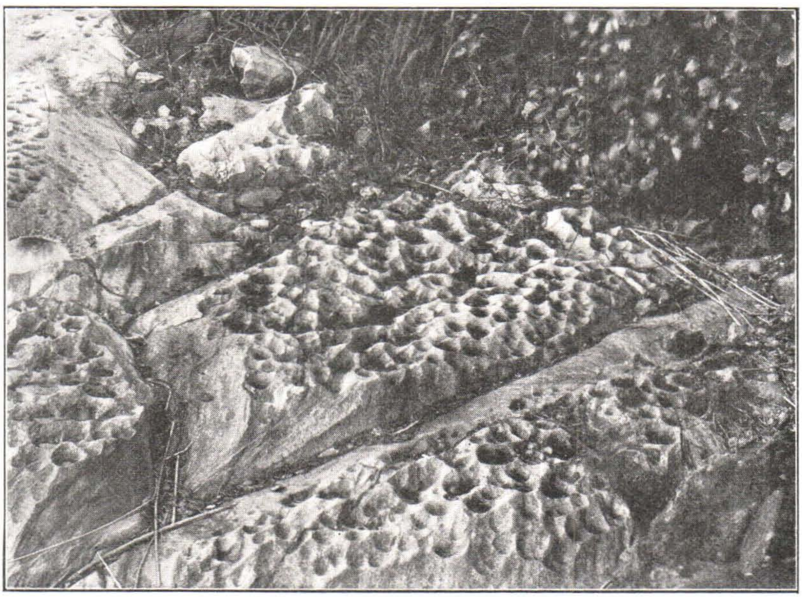

Fig. 1. A pitted surface of limestone. Shore of Lake Määrijärvi in Kisko.

The pitted form of the surface of limestone originated when the rock was within the range of action of the waves. The first reason for it must have been the lack of homogeneousness in the rock, which caused its surface to be worn unequally. The action of the waves aids in giving a rounded form to the cavities. When the rock-surface has risen above the average water-level, the water splashed up by the waves fills the cavities, the surrounding parts remaining drier. Subsequently, when the rock has risen higher, the rain-water stagnates in the cavities and widens them still more. If the surface is inclined, the pitting may, on the other hand, be obliterated by the wash of the surface-water or it may assume new shapes characteristic of the work of the latter (see below page 8).

Undulating water on the lake-shores usually produces much greater results than on the shores of the sea. This is in consequence of the fact that the shore-line of lakes has remained unmoved for a very long time, while on the sea-coast the range of action of the waves is gradually changed by the movement of the land. The pitted surface form of limestone on lake-shores is therefore often more

Fig. 2. Abrasion-cliff at Lake Määrijärvi in Kisko.

developed (fig. 1). The cavities are broader and deeper and often many of them have become joined and form larger holes, and at the joints there are small steeply sloping gullies.

Sometimes true abrasion-cliffs have been formed on lake-shores. In most cases they are of small dimensions, as at Lake Määrijärvi (fig. 2), where the height of the cliff is only about 75 centimeters. The wave-cut terrace is represented by the pitted horizontal rock-surface shown in fig. 1. The slope of the cliff is of a rounded concave form. The cliff at Lohjanjärvi (fig. 3), near the landing place beside the paper-factory, is much higher than that at Määrijärvi. Horizontal fissures, which happened to lie at the level of the terrace, have been so widened as to form low shore-caves (fig. 4). It may

Fig. 3. Abrasion-cliff at Lake Lohjanjärvi in Lohja.

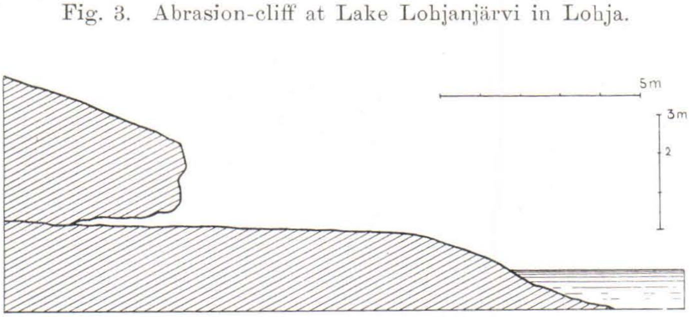

Fig. 4. Cross-section of the abrasion-cliff at Lake Lohjanjärvi in Lohja.

be suggested that the formation of the cliff, too, has been favoured by this circumstance, as the rock has been undermined. Since the lowering of this lake, the high-water level is one meter below the wave-cut terrace.

Ablation of Limestone by Rain-water.

On bare rocks of limestone rising above the level of the sea, rain-water and, in general, surface-water continues the ablation begun by the action of the sea. Also in this case the solution is of greater effect than the mechanical wear. On the whole, the ablation of *bare* limestone by rain-water is very much slower than that by the action of the waves, doubtless because the latter action is more continuous. Therefore, if no special agents have intervened, the surface of limestone on the highest hills has been but little changed in comparison with the shore-rocks.

It might be supposed, that the results of the superficial solution would increase with the height, because the places which are situated at the highest level above the sea have certainly been longest exposed to weathering. Such a deduction, however, can hardly be inferred, owing partly to the fact that the amount of solution by sea-water is in itself very variable, and partly that solution by rain-water is usually much less than by the former. The latter also varies according to the orographical position and the inclination of the surface of the limestone, the thickness of the layer and especially the quantity of humic acids formed by the decay of the vegetation in the immediate vicinity. Thus, the degree of ablation, depending upon so many different factors, varies without any apparent regularity. The greatest amounts of solution, effected by rain-water only, have been observed in the parish of Lohja, at a height of about 40 m above the level of the sea. The height of the protruding walls of the bordering granite attained 45 to 50 cm. Such amounts of solution in bare rocks have not been observed on lower levels.

When surface water washes the limestone, it often produces a relief which is as peculiar to this action as the pitting is to the work of the waves. This form of ablation is characterized by drills with rounded bottoms (fig. 5), in most cases measuring about 10 cm in breadth and much less in depth. They are a kind of erosion-valleys, being formed when the action of the water is concentrated along certain definite lines. One cause of their origin is an inclination, however slight, of the surface. Gravel, mud and remnants of vegetation which often gather at the bottom of these drills, serve to favour their enlargement. These phenomena of solution are genetically and morphologically related to the »Karrenfelder» of the mountainous regions of limestone rock.

The solution is especially effective on layers, measuring only some decimeters in thickness, and likewise on isolated fragments or lenses of limestone surrounded by siliceous rocks. Such masses become centres of erosion over their whole area, when corroded beneath the adjacent rocks. During rainy periods the cavities formed on their surface serve as reservoirs for stagnant water, or as channels for running water, and vegetable matter often gathers in them. In such cases the ablation often amounts to more than 50 cm, on the coast as also on higher levels.

Fig. 5. »Erosion-valleys» in the surface of limestone. Village of Lohja.

The greater effect of sea-water as compared with rain-water is certainly due to the continuity of its action. The fact, that calcium carbonate is more soluble in water containing sodium chloride than in pure water [1]) is of no importance here, for the difference of solubility is extremely slight in the case of diluted solutions like the water of the Baltic. The variability of the amount of free carbon dioxyde

[1]) F. K. Cameron, J. M. Bell a. W. O. Robinson, *Journ. Phys. Chem. London* 11, 396 (1907), referred to by Leitmeyer in Doelter's *Min. Chem.* I. 314.

in water must indeed be more significant. As stated above, the results of the action of lake-water are, in general, more considerable than those of sea-water, and this fact has been accounted for by the longer continued action of the former. The small quantity of humic acids present in lake-water [1]) also increases its activity, but, in the absence of experimental research, nothing can be said about their relative importance.

Ablation of Limestone covered with Soil.

In limestone which is covered with soil, the surface is always denuded to a certain depth, except when it is lying beneath the water of some basin (cf. above page 4). This ablation is effected by the dissolving action of the water percolating in the ground. The solution is here connected with the weathering of the soil. As it therefore has a certain general importance, these phenomena deserve more detailed treatment.

At the limestone-quarries of Tytyri in Lohja the rock-surface above one of the quarries has been laid bare to some extent. The greatest part of this surface had been covered with a bed of sandy moraine, 0.5 to 1 meter in thickness, thinner at some points, but always comprising thicker layers than those parts which have been exposed to the lixiviation caused by the acids formed by the decay of the vegetation. Thus some unaltered soil, or layer C of the agrogeologists, was lying on the rock-surface. Here the phenomena of solution greatly resemble those on the bare surfaces. The amount of ablation in horizontal surfaces varies from 5 to 15 cm. At the joints there were steep-sided gullies and, in inclined places, drills, very like those which are usually found in bare rocks. Numerous dikes of pegmatite and »metabasite» cutting the rock have been left absolutely untouched by the weathering, the glacial striae being quite sharply defined on their surface. A narrov dike intersects a glacial pot-hole, the bottom of which has been deepened about 10 cm by solution.

At the quarry of Långvik in the parish of Karjalohja a layer of clay of a thickness of one meter or more had been removed from the surface of the limestone and here also the amount of ablation was

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[1]) 20 grams organic matter to 1 m^3 is the average of the water of 7 rivers of Finland according to O. Aschan *(Bidrag till kännedomen om Finlands natur och folk.* 66. Helsingfors. 1908).

about ten centimeters. Drills had been formed in the surface and it was also pitted in the same manner as shore-rocks, though with less regularity.

In several other places, for example, at the quarries of Illo and Lammala in the parish of Westanfjärd, I observed that the limestone, when covered with gravel or clay, had been eroded in the same way as the naked rocks. But this, however cannot be due to the same agencies. In the present case the subaërial solution has worked without the aid of mechanical agencies or sea-water, which has been very effective in the ablation of bare rocks. Consequently, the work of percolating water really is more considerable than that of surface-water, which to some degree may be due to the fact, that the rock-surface gets continually moistened by the water. Carbonic and humic acids dissolved in ground-water are still to be taken into consideration, but we will discuss their action later on. A surprising phenomenon is the occurrence of »erosion-valleys» beneath the layers of soil, for it seems at first sight more probable, that percolating water should moisten the whole surface equally. However, their existence shows that also in this case the action of water tends to be concentrated along certain lines. The water obviously sinks down to the surface of the rock and either flows along its lowest levels or penetrates the most permeable parts of the soil. In this way it forms channels resembling those formed by surface water.

These and many other instances of the same kind prove that the water below the zone of lixiviation has a considerable dissolving effect on the limestone. Probably this effect is much smaller on places where the covering layers are thicker than four meters, but on such places the surface of the limestone is nowhere laid bare.

In the quarry of Tytyri, at a level some meters below the places mentioned above, quite different phenomena of solution were observed. Here the rock had been covered only by a humous layer of soil with a thickness of 30 cm. The amount of ablation effected by solution was much greater than in the former cases, sometimes being as much as 50 cm. The surface also was differently shaped. There were neither drills nor round cavities, but the surface showed irregular hollows resembling the walls of limestone cavities formed through the widening of joints by solution. Apparently the solvent has acted evenly on the whole surface, and the unequal results have been caused by the unhomogeneousness of the rock. — Quite similar phenomena of solution beneath a bed of humous soil have been observed in other places.

The large amount of solution is not accounted for only by the fact, that humous soils are always wet, because then we could not explain, why the solution has been in this case about five times more effective than it is under similar circumstances beneath a bed of unaltered mineral soil. Evidently the humic and carbonic acids formed in the humus play the most important part. In other words, the surface of the rock represents in this case the »eluvial layer» (A2) of the agrogeologists, lying immediately beneath the humous layer (A1).

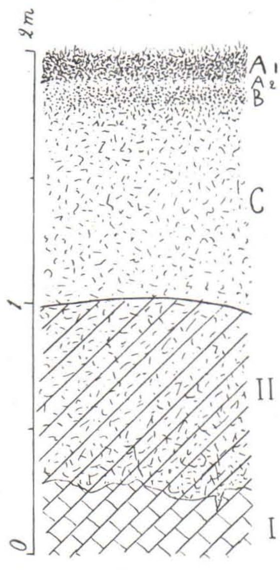

Fig. 6. Section of the weathered limestone in the quarry of Kärkelä in Karjalohja. I=unaltered limestone; II=disintegrated limestone.

A curious phenomenon of weathering was observed at the limestone quarry of Kärkelä in the parish of Karjalohja. In the southern wall of the quarry the limestone, which here is rich in quartz, is covered with a bed of sandy moraine, from 1 to 1.2 meters thick. In the soil the phenomena of lixiviation are well developed (fig. 6), and beneath the illuvial layer there is a thick layer of unaltered moraine (layer C) lying on the rock-surface. The latter has perfectly retained the surface-forms of a rock, which has been polished and striated by glacial exaration, and its surface has not been lowered since. Yet the ock has, to a depth of 70 to 80 cm. become porous and disintegrated in such a way that it can be broken up by hand and the siliceous layers and intersecting veins are likevise weathered. There is also a brown-coloured substance, consisting chiefly of iron hydroxyde, which has been deposited between the remaining grains. The lower part of the weathered zone is especially rich in this substance, wich gives it a dark brown colour.

The limit between the unaltered rock and the zone of weathering is quite well defined and has the same shape as the solution-forms of the limestone beneath the humous soil, as described above. Along the joints the weathering has proceeded deeper than elsewhere and roots of trees have pushed their way into the bottom of the weathered layer. In this case the weathering is effected by solution as usual, but instead of having entirely dissolved the rock, the ground-water has filtered in and acted upon the loosened grains. This phenomenon may be regarded as a consequence of the petrographical character of the limestone. Just along the weathered part the coarse crystalline limestone contains a fine-grained zone, the texture of which I regard as mylonitic. This rock, when unweathered, is composed only of calcite and quartz. By microscopical examination a marked foliation is observed, due partly to the elongation of the calcite grains in the direction of the strike, partly to the alternation of laminae of fine and coarse grain, the longer diameter of the calcite individuals of the latter attaining 0.5 mm. Quartz is found as angular grains, having a fairly uniform size of about 0.06 mm in diameter. Some laminae are richer in quartz than others. This unhomogeneousness seems to be the cause of the rock having been changed by the weathering as described, the coarsest laminae as well as those in which quartz predominates having remained relatively unattacked by solution.

Widening of Joints by Solution.

Water which has filtered into the joints of limestone widens them gradually by means of its dissolving action. This process is effected only by ground-water and superficial water, and thus the widening of joints takes place only when the rock has risen above the level of the sea. If open holes were formed at the sea-bottom, they would soon be filled with sediment which would prevent further enlargement. The opened joints sometimes seen in shore-rocks result from the work of waves and were formed during the time when they lay on the shore-line. Horizontal shore-caves or opened fissures of this kind are rather common and have often been observed at a great distance from the sea. The largest one I have seen is 59 m above the sea in the parish of Kisko near Lake Määrijärvi. The dimensions of this »cave» are: length 9 m, breadth 10 m and height more than 0.7 m. Siliceous layers protrude from the roof, making it evident that the space must have been excavated by the waves. — Similar shore caves have been formed on lake shores as has already been stated (page 7).

Much more usual and important is the excavation of »widened joints» by the water above the level of the sea. As to the local circumstances affecting this action, three cases are to be mentioned: 1) where the rock is naked, 2) where it is covered with humous soil or, in general, with the layer A_1 of the agrogeologists, 3) where the rock is covered with mineral soils comprising the whole series of lixiviation and recementation and unaltered soils. In the first case the widening of joints rarely takes place, but where this has once happened, there the cavities have developed in the same manner as in the second case, because they soon become filled with humous soil. There is an unmistakable connection between the quantity of the vegetable matter and the amount of solution. In the third case the enlargement of joints, though often considerable, is less than in the second.

The widened fissures are mostly nearly perpendicular or horizontal. Their breadth often attains 10 cm or more. Larger holes are formed at the crossing of two joints. If both are perpendicular,

Fig. 7. A net-work of widened joints. The quarry of Hermala in Lohja.

»light holes» will be formed which sometimes are 1 m in diameter. At the crossing of a perpendicular and a horizontal joint larger cavities occur and the widened part of the former often ends abruptly, whilst the horizontal joints may be widened on all sides and send out other perpendicular open joints downwards, which, however, become gradually smaller as the depth increases. Below a certain depth the joints continue downward without showing any effects of solution, though they may be uncemented and permit of a slow circulation of water. Fig. 7 and fig. 8 illustrate the usual type of the network of widened joints.

It is a very striking fact, that these widened joints extend only to an insignificant depth. In the following places the greatest depths attained by post-Glacial cavities are:

In	the	quarry	in	the village of Lohja	3	m
»	»	»	of	Tytyri in Lohja	4	»
»	»	»	»	Hermala in »	3.5	»
»	»	»	»	Mellangård in Westanfjärd	3.0	»
»	»	»	»	Östergård » »	2.7	»
»	»	»	»	Illo, western quarry »	3.3	»
»	»	»	»	Skarpdal, Skräbböle in Pargas	3.5	»
»	»	»	»	Ersby » »	3.0	»
»	»	»	»	Parsby » »	4.1	»

Fig. 8. A net-work of widened joints (dark). The quarry of Lammala Mellangård in Westanfjärd.

These are the greatest depths reached by single open joints. The well developed net-work of cavities, which is seen in the illustrations, ext nds usually to a depth of 2 to 3 m.

Thus in the quarry of Tytyri, where we have the opportunity of studying sections of a length of several hundred meters and a height of more than ten meters, the limestone contains cavities almost everywhere to a d pth of two meters. Very few joints have been enlarged below that level and no cavities exceed the depth of four meters. In other sections similar observations have been made.

We are led to the general conclusion that there exists in the limestones a well marked *zone of solution*, and that solution does not take place below the limit of this zone.

There are some exceptions to this rule. Firstly the zone of cavities formed in pre-Glacial times does not show any fixed limit. Originally these cavities were much deeper, having pierced that part of the Archaean crust which is now worn away, and still they often reach deeper than post-Glacial cavities. In special cases also these latter reach a level lower than the ordinary limit. Such an exceptional case occurs in the quarry of Lustikulla near the railway-station of Skogböle. Here are numerous very wide solution-holes, one having a depth of as much as 6 meters. The explanation of the unusually powerful action of solution is given by the fact, that the limestone contains a considerable amount of sulphide minerals, such as sphalerite, chalcopyrite, arsenopyrite and pyrite. The immediate surroundings of the cavities are especially rich in those minerals. When they have begun to weather on the surface, sulphuric acid has been formed which has quickly dissolved great quantities of limestone. For the same reason many deep cavities have been formed in the »copper-mine» of Lapinkylä, in the parish of Kisko, where the limestone contains chalcopyrite.

On the island of Ovensor in Korpo a phenomenon of another kind has been observed. In a certain section at a height of 10.4 meters there is a perpendicular fissure, which has opened on the surface to a width of 10 cm. Further down its width decreases, but it continues still beneath the floor of the quarry. The cavity is filled with sand, containing chiefly quartz and a smaller quantity of feldspar, mica and other rock constituents. It might be supposed that the enlargement of this fissure had partly taken place in pre-Glacial times, but no definite proofs can be brought forward in support of such an hypothesis. There is more rea on for assuming that the sand is a recent alluvial deposit and the phenomenon of widening of post-Glacial origin. The great depth must depend upon the fact that the fissure has been open, allowing the water freely to descend to low levels.

In the quarries of Ovensor, as well as in many other quarries, the zone of open joints is very little developed. In the quarry of Förby in the parish of Finnby only small cavities, not more than one meter from the surface, have been observed [1]). In the quarries of

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[1]) It may be mentioned that in the »marble-mine» of Förby, which is at present worked at a depth of 57 m, no phenomena of solution can be discovered.

Westlax in the parish of Kimito and Pettu in Finnby the zone of solution is entirely absent. The same is the case in the quarry of Bredvik in Westanfjärd, except for a single hole attaining a depth of 4.5 meters, which probably was partly excavated in pre-Glacial times. The absence of the solution-zone in these and some other localities is very likely due to their insignificant height, which never exceeds 20 m above the level of the sea. The height of the surface of the limestone at Westlax and Pettu, where no solution in joints has taken place, is less than 5 m. At the quarries of Illo in Westanfjärd very insignificant zones of solution occur in those sections which are situated near the sea and on low levels, while in the western quarry, where the surface is at a height of about 20 m, the zone of solution is well developed. In the parish of Pargas the connection between the height and the process of solution is still more striking. There are numerous quarries in a bed of limestone striking through the whole island of Ålön. The zone of solution is well developed in the quarries of Skräbböle (at a height of 34 m) and Ersby (h. 32 m) which are situated in the central and higher part of the island, while there are no widened joints in the quarries of Tenböle, Parsby Samhällighetsg uvan (height less than 15 m), Limbergsgruvan (h. 14 m) and Simonby (h. 22 m). The last quarry, like some others, where no solution in joints has taken place, is situated in woods where layers of humous soil are lying on the rock-surface; thus it is evident that the difference of the depths of the cavities does not depend on the different amount of the vegetable matter decaying on the surface, though this factor plays an important part as regards the amount of the limestone dissolved within the zone of solution, i. e. the cubic content of the cavities.

The absence of enlarged joints on low levels can only be explained by the fact that these places have been raised above the sea in a time too short to allow the process of solution to accomplish its work.

Observations have led us to conclude that the enlargement of joints in the limestones of southwestern Finland does not exceed, unless given exceptional conditions, a depth of 3 or 4 m. As this conclusion has been proved in so many cases, it must in general hold good in such areas where the geological agencies and conditions are similar to those prevailing here. Furthermore it seems very probable that the process of solution has reached a certain limit as to the depth attained. The enlargement of the joints does not seem likely to continue to lower levels, or, at least, does so only very slowly. The depth reached by the solution is not at all proportional to the time which the process has lasted, which time has been very variable. Some of the places mentioned on page 15 (Illo, Lammala) are situated only 20 to 30 m above the level of the sea, others (those in the parish of Lohja) 40 to 60 m. Although it is very certain that the length of the time during which certain parts of the earth's surface have been raised above the sea, is not strictly proportional to their height, it is nevertheless evident that the latter places must have been much longer exposed to weathering than the former. Yet there is no difference in the depth reached by the widened joints. The conclusion is that *the enlargement of joints has in a relatively short time reached its present depth, and has not afterwards proceeded downwards to any appreciable extent.*

Let us now consider, what conditions may determine the limit of the zone of solution. A circumstance which must here be given precedence to others, is the jointing. The limestone, like other rocks of Finland, is jointed to a high degree, but the joints which cross the limestone layers are very rarely open. Where this, however, is the case, the opened fissures extend to exceptional depths, as seen above (page 16). For the most part the joints are closed. Although water can percolate through them, it does so only slowly owing to capillarity. It gets saturated with dissolved matter before it reaches any considerable depth and the solution proceeds downward only in the same measure as the cavities are gradually widened.

Consequently this rule holds good only in such regions, where no open cracks or fissures have been developed. Such phenomena being by no means rare in the rokcs of Finland, they may in some places also be found in the limestones. In such places we may expect to find widened joints at low levels, perhaps also small caverns, if water happens to have passed in quantity into the cavities and found channels for its circulation. However, such phenomena have not been observed in the quarries of southwestern Finland.

Also in the Paleozoic and younger limestones the formation of caverns and »honey-combed» areas (Karst-lands), as has been noticed by numerous geologists [1]), is limited to districts, where the litho-

[1]) For instance: Reyer, »Über das Karstrelief», *Mitt. Geogr. Ges.* Wien 1881. H. Stille, »Geologisch-Hydrologische Verhältnisse im Ursprungsgebiet der Paderquellen zu Paderborn». *Abh. preuss. geol. Landesanst.* 1903.

sphere has been broken up by faults and cracks. Abundant water-streams, partly fed by ground-water, partly by superficial creeks and rivers, have gathered in those already open cavities and have enlarged and deepened them to such an extent that they have swallowed up all the surface water. Thus the whole area has been changed to a Karst-land. Where open cracks and fissures are wanting, the drainage remains chiefly superficial, even in limestone-areas.

Although the absence of open fissures explains why the solution proceeds downward only slowly, yet it does not explain the fact that there is a lower limit which the solution does not exceed. Obviously the zone of solution often coincides with that part of the rock-ground which is lying above the upper surface of the zone of ground-water, but often it does not so. Many cases have been observed, f. e. in the quarry of Lammala Östergård, where a layer of peat had been formed on the rock and the ground-water evidently reached above the surface of the rock, yet the process of solution had attained its usual depth. On the other hand, in limestone-rocks with steep and high slopes, as in the quarry of Tytyri in Lohja, the surface of ground-water sinks to lower levels than three or four meters. Consequently we can not explain the zone of infiltration of the surface-water to be identical with the zone of solution of limestone. It is not easy to understand the reason for the existence of the limit of the latter though it seems evident that a process of solution and precipitation, in some way analogous to the changes caused by humic acids in the soil, takes place here. A study of the soils which have been deposited in the cavities gives added strength to this hypothesis.

Where the enlargement of joints has taken place in naked rocks or in such as are covered only with humous soil, the cavities always contain a certain quantity of dark-coloured soil. This has usually been deposited at the bottom of the upper cavities, forming layers, while the rest of the holes often remain empty. This soil is very rich in humous substances produced by the decay of fallen leaves, roots and other vegetable matter which has been washed down into the cavities by rain-water. Mineral substance has found its way in to them in the same way, and there are also not inconsiderable quantities of insoluble siliceous substances produced by the weathering of the limestone. This humous soil fills the lower part of the cavities, but the lowest opened joints often contain a soil of a lighter brown colour. When the cavities are empty at this level, their walls are often incrusted with the brown substance. Below the zone of the cavities, the joints, which do not show any signs of solution, are still incrusted with brown matter.

Samples of these soils from the quarry of Parsby in Pargas have been analysed in order to determine their chemical composition. Sample I, which represents the dark soil, was taken from a cavity 1.8 m below the surface; sample II, the light brown soil, had been deposited at a depth of 2.7 m from the surface. Both contained certain amounts of unaltered calcite in small fragments. After drying at 110° C the powders were treated five times with ammonium nitrate in order to remove the humus, and then the soluble substances were dissolved by means of hydrochloric acid:

	I	II
Loss by heating to 110° (H_2O)	13.48 %	6.78 %
Loss by treatment with NH_4NO_3	19.01 »	3.49 »
Soluble in HCl	18.85 »	27.74 »
Residue	48.66 »	61.99 »
	100.00 %	100.00 %

The percentage of calcium oxyde and other basic oxydes in the soluble part were determined. Carbon dioxyde, which was determined in a separate portion, is calculated as calcium carbonate:

	I	II
$SiO_2 + Al_2O_3$	31.85 %[1]	26.67 %
Fe_2O_3	34.55 »	24.96 »
CaO	14.76 »	21.71 »
$CaCO_3$	1.80 »	7.65 »
MgO	11.20 »	9.93 »
Deficit (alkalies)	5.84 »	9.08 »
	100.00 %	100.00 %

As shown by these figures, the dark soil is characterized by a high percentage of humus, while in the soil from the lower level an unusually high percentage of calcium is the most striking feature. Probably this element is here present partly in the form of organic compounds (or »humates»). The analyses prove sufficiently that a

[1]) With some MnO.

precipitation of calcium really takes place in the deepest parts of the cavities. This fact suggests the following theory as an attempt to explain the limit of the solution.

Humic and carbonic acids, which have been formed by the gradual oxydation of the humus in the upper soil, act on the limestone as strong dissolving agents. Evidently the considerable enlargement of joints in the zone of solution is effected by their action. This soil corresponds to the humous layer A1, whilst the eluvial layer (A2) is represented by the rock surface of that part of the cavity where the solution is more active. As is the case in the soils lixiviated by humic acids, the eluvial layer is also here resting on the illuvial layer (B) or the layer of deposition and recementation, which is represented by the brown-coloured soil, found in the lower parts of the cavities, and by the incrustation of the joints. When the water descends from the level of layer A to layer B, it is already saturated with salts of calcium and its dissolving action has been much reduced. The precipitation of the dissolved matter in layer B being due to the presence of oxygen, this layer will have a constant level, if anything, more likely to rise than to descend, owing to the gradual thickening of the upper layer of soil. When once the solution has proceeded so far downwards that the atmospheric gases only penetrate with difficulty to the lower part of the cavities, the process of deepening ceases and the water only widens the cavities in the upper part of the zone of solution. At the same time the capillary cavities beneath the widened joints become filled with precipitated matter and thus closed; consequently the circulation of water is still more hindered.

Yet, when the limestone is covered with so much soil that it comprises more than the layers in which the processes of lixiviation and recementation commonly take place, the rock can still be attacked by dissolving agents, as we have stated above (page 4). This fact seems to be in conflict with our theory, but it may perhaps be assumed that the water which has passed these zones of a siliceous soil is still capable of dissolving calcium carbonate, so that a renewed lixiviation takes place on the surface of the limestone.

When comparing the insignificant results of solution observed in the Archaean limestones of Finland with the magnificent caves of the »honeycombed» areas of Carniola and other Karst-lands we must also consider other circumstances which affect them. In the

Karst-lands, wide areas consist of pure limestone, and insoluble products of weathering therefore remain only in small quantities which are mostly washed away by underground water, the cavities being left open. In Finland the limestone occurs in relatively thin layers, which may consist entirely of pure calcite, but nevertheless the cavities will soon be filled with the products of weathering of siliceous rocks as well as by other soils gathered from the surroundings by surface water. Thus the free circulation of water in the cavities will be impeded. Another circumstance to be considered is the difference in solubility of the limestones. Unaltered sedimentary limestones are more soluble than metamorphic marbles. The difference in solubility of these varieties, however, is in itself very insignificant[1]. Certainly much more important is the degree of porosity which is generally greater in sedimentary limestones than in marble. Finally a third factor is climate. No quantitative estimates have been made regarding the difference of solubility in limestones, for instance between any part of Central Europe and this country, but surely this difference must be rather considerable. The downward action of the solution is still more dependant on the phenomena of lixiviation by humic acids, being, of course, very much quicker, if the climate is warm enough to cause complete oxydation of the vegetable matter.

[1]) F. Kohlraush and F. Rose (*Z. f. phys. Chem. 12*, 239) have determined the solubility of precipitated $CaCO_3$ and calcite according to the conductibility of electricity, obtaining at 18° C for the former k=27 for the latter k=26.

Solution in Pre-Glacial Times.

Sandstone found in Limestone in Cavities formed by Solution.

In the parish of Westanfjärd on the large island of Kimitolandet two occurrences of sandstone in limestone have been found, one in the limestone-quarry of Illo, another in the quarry of Mellangård in the village of Lammala.

The Quarry of Illo.

This quarry is situated two kilometers south of the village of Illo, on the western shore of a little bay, Illo-viken. Limestone occurs here as two parallel, perpendicular layers. The adjacent rock is a fine-grained gneiss (»leptite»), but among the surrounding rocks a granite predominates which is younger than the limestone and intersects the latter in several places. Five quarries are situated in these beds of limestone. The sandstone occurs in the northernmost and largest which is called Storgruvan. The whole bed, which has a strike of N. 52° E. and a thickness of 19 m, consists of a very pure coarsely crystalline white limestone, which is quarried to a depth of 4 to 7 meters. To the northeast the rock passes, in the direction of the bay, under a bed of clay. The floor of the quarry is here about 4 m above the level of the sea.

In the walls of this quarry there is a zone of solution which, however, is not well developed. The deepest open joints do not reach more than 2 m beneath the rock-surface. On lower levels, I have only found cavities forming geodes and containing beautiful crystals of calcite, barite and fluorite with a reddish powdery deposit (hematite?) on their surfaces. Furthermore, pyrite and marcasite occur as very small crystals. These minerals must certainly be of very ancient origin. Probably it is due to the pneumatolytic action of the Archaean granite. At any rate, they have nothing to do with the phenomena of solution here discussed.

On the floor of the quarry some isolated outcrops of sandstone occur (fig. 9).

Three of these outcrops (marked on the sketch-map 1, 2 and 3) are situated at the entrance (at the N.E. end) of the quarry, where the limestone was covered by clay which has now been removed.

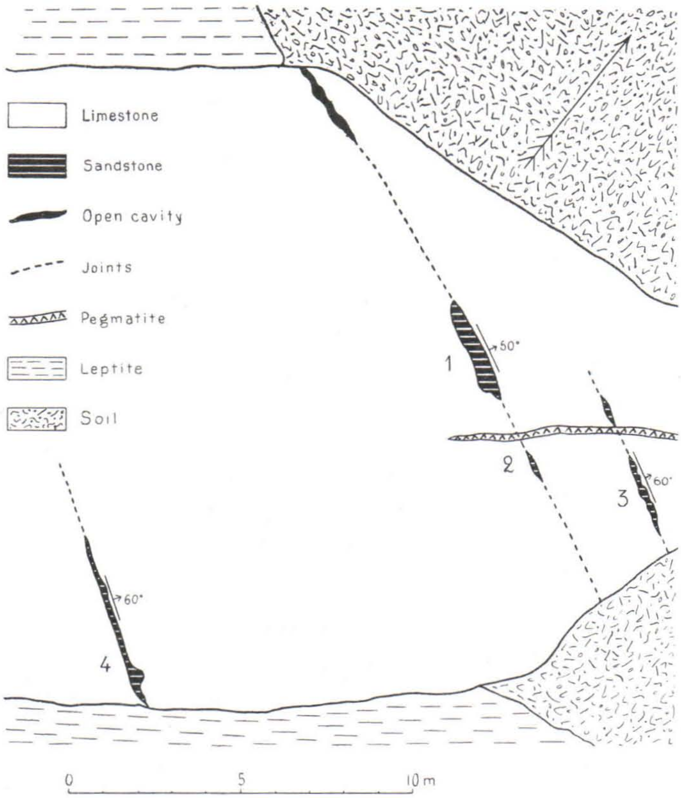

Fig. 9. Plan of the sandstone-casts of the quarry of Illo in Westanfjärd.

At the time of my visit, the quarrying had proceeded to a depth of about 1.5 m. The fourth outcrop of sandstone lies in the inner part of the quarry, where the walls attain a height of 4.2 m. All the sandstone-masses or *casts*[1]), as we will call them, fill cavities which

[1]) It seems incorrect to use the term dike for such occurrences of sandstone as those in question. This term covers the sheet-formed rock-masses in

are formed by the enlargement of rectilinear joints. Their strike is constantly N. 60° W., the dip of casts 1 and 2 is 50° N.E. and that of the others is 60° N.E. Thus the casts are nearly parallel.

The joint in which occur casts 1 and 2 crosses the whole bed of limestone and continues in both directions from the casts remaining open to a breadth of about 1 cm. In the northwest side of the quarry it has been enlarged still further and attains a breadth of 20 cm, being partly empty, partly filled with glacial clay (fig. 15 page 34). The horizontal section of cast 1 is 280 cm long and its greatest breadth is 45 cm. Cast 2 is only 3 cm thick. The joint in which he cavity of cast 3 has been enlarged, continues in a northwesterly direction to a distance of only one meter from the cast and there ends. The greatest breadth of this cast is 15 cm. It is interrupted by a dike of pegmatite going parallel with the strike of the limestone and also crossing the joint of casts 1 and 2. — The joint of cast 4 ends abruptly in both directions. The breadth of this dike-shaped cast is about 1 cm, except near the southeastern wall of the quarry, where it widens to 35 cm.

There is no doubt about the origin of the sandstone. Its manner of occurrence and the forms it has assumed, the surface being of that irregularly curved type which is characteristic of limestone cavities formed by solution, make it evident that *tectonic joints have been enlarged by solution; sand has crept from the earth-surface into the cavities thus formed and been afterwards cemented to a sandstone.*

As regards the original constituents of the sediment, the sandstone shows very little variation in different parts of the casts. Its colour is uniformly brownish yellow and it consists almost exclusively of quartz in well rounded grains of all sizes from 0.1 to 1.2 mm in diameter. A characteristic feature of this sandstone is the occasional occurrence of larger pebbles of quartz in the ground-mass. These pebbles sometimes attain 20 mm in diameter. Muscovite occurs rarely in the form of very small flakes; rounded grains of tourmaline

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nearly perpendicular positions, which have originated through the filling of fissures with material of any kind. Thus the »sandstone-dikes» found in rectilinear fissures intersecting various rocks are true dikes in this sense of the word. But the masses of sandstone now in question, though in the case of Illo they happen to be nearly dike-shaped, may occur in many other forms, as will be seen below. Therefore, because their form is variable, it is preferable to use the term »cast» for indicating them, the sandstone having been cast in the limestone cavities in the same way as gypsum is cast in forms.

and magnetite have also been observed. In the four slides which were made of this sandstone only one grain of feldspar was detected which was unal ered microcline. Megascopically, single grains of weathered red feldspar were found.

The quartz-grains have been enlarged by recrystallisation, but the zone of secondary quartz has rarely a breadth of more than about 0.05 mm. The original contour-line is marked by a brownish gray pigment. The original quartz shows usually an undulatory extinction. This phenomenon is also observed in the additional quartz recrystallized around the original grains. This fact, however, does not prove that the sandstone has undergone pressure after its cementation. It is quite natural that the substance which has recrystallized later should follow the arrangement of the previously existing quartz. — On the other hand, the grains are often corroded, causing the original outlines to be broken up (fig. 10).

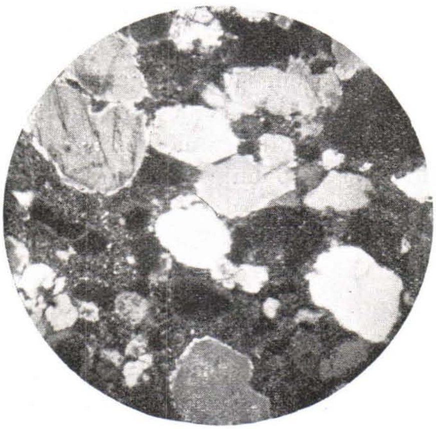

Fig. 10. Secondary growth and corrosion of quartz in the sandstone of Illo in Westanfjärd. + Nicols. Magn. 24 diam.

The greatest part of the cement of the sandstone consists of a quartz-like mineral, the individuals of which measure only 0.02 mm or less in diameter. Most of them show an irregular, wandering extinction, and single grains show an ill developed spherulitic structure with a positive character of the elongation of the fibres. Because of the extreme minuteness of the grains they could not be studied in convergent light. However, the mineral has in its microscopical character more resemblance to chalcedony than to quartz. Another part of the fine-grained ground-mass evidently consists of normal quartz. Furthermore, limonite and a colorless chloritic substance, with a birefringence somewhat lower than that of quartz, occur in the ground-mass. Calcite, too, occurs in large individuals, which sometimes contain several quartz-grains. The quantity of this mineral varies greatly and in some parts it is totally absent. When adjacent to the ground mass of chalcedony, the calcite shows corroded forms, as if it had been replaced by the former, only small remnants being left. Open spaces are very common in the cement. — The sandstone is of variable hardness owing to the varying character of the cement. Especially in the thin, dike-shaped parts of the casts the rock is very hard, megascopically almost quartzitic. Some parts of cast 1 are also hard, but other parts softer and more brittle.

In cast 1 there are numerous pieces of shale of a size varying between 1 and 10 cm in diameter. They are light gray, aphanitic and more or less soft bodies, often containing cavities, formed by solution of limestone-fragments which originally were embedded in them. Traces of the structure of limestone have often been left on the walls of those cavities; in some cases also the twinning of calcite has left its marks on the walls. This circumstance is interesting, because it shows that solution has taken place after the hardening of the sand. At present the shale is free from carbon dioxyde, causing no effervescence when tested with hydrochloric acid. Microscopically the fragments show variable characteristics. In the soft fragments there is an amorphous groundmass of clayey substance, containing grains of quartz and flakes of muscovite measuring only 0.05 mm or less in length. Another harder fragment which showed laminated texture and small cavities where calcite had been dissolved, was composed of chalcedony of the same kind as the cement of the sandstone, and small flakes of mica. This fine ground-mass contains grains of quartz and crystals of pyrite, 0.04 to 0.09 mm in diameter. Still there are numerous extremely small grains of a colourless substance showing a high refringence and a low birefringence, which I suppose to be some phosphate mineral. The presence of rather considerable amounts of phosphates was stated by a qualitative test. Limonite and a black, opaque substance occur as pigment. In a thin section, which was cut perpendicularly to the lamination (fig. 11), this opaque substance occurs abundantly along certain laminae which are, however, often discontinued and curved. It is insoluble in hydrochloric acid, but by treatment with sulphuric acid and potassium bi-

Fig. 11. Bands of carbon in the shale. Illo, Westanfjärd. Magn. 24 diam.

chromate it disappears, generating at the same time bubbles of gas, a reaction which proves it to be carbon. Its presence is very interesting, because the circumstances of its occurrence show that it must be of organic origin; yet no traces of any organic structure can be detected. It may be noted that the phosphate mineral occurs most abundantly among these masses of carbon.

The Quarry of Lammala Mellangård.

This quarry is situated in a very extensive continuous bed of limestone, the adjacent rock on both sides being »leptite». This layer also is perpendicular, with a strike of N. 85° E. In the immediate neighbourhood of this quarry towards the east is the quarry of Lammala Östergård, and to the west of it there are some smaller quarries. In all of them the limestone is white, coarsely crystalline and penetrated by numerous dikes of »metabasite» in the direction of the strike. Layers or lenses of dolomite are intercalated with the limestone.

The sandstone in this quarry was first observed by Sustschinsky, who in his treatise on the contact-phenomena of limestones of southwestern Finland gives a short account of sandstone occurring in limestone in the eastern end of the quarry.[1]) After the visit of Sustschinsky the quarry seems to have been much enlarged, and there are now two outcrops of sandstone in the eastern part of the quarry.

The position of the sandstone-casts is shown in the plan (fig. 12). When compared with the casts described above a notable difference in form is at once apparent. The horizontal sections do not here resemble the cross-sections of dikes or lenses, as in the case of Illo, but are more rounded, in one case (cast 6) forming almost a semicircle. The horizontal section of cast 5 (fig. 13), which is situated on the northern side of the quarry, is 420 cm in length and 90 cm in breadth. It strikes N 40° W and its sides are perfectly perpendicular. At its nor hern end an unwidened joint begins, but ends within a meter of its commencement. Several perpendicular joints are observed going in the same direction. In fig 8 (page 15) are seen some of those joints; in the upper part of the wall, the widening by solution in post-Glacial times is visible. The occurrence of so many joints

[1]) P. P. Sustschinsky, *Travaux de la Soc. Imp. des Naturalistes de St. Pétersbourg*, vol. XXXVI, livr. 5. Section de Géol. et de Min. 1912, page 82. (In Russian, with a German summary).

parallel with the strike of the cast makes it evident, that this cast, too was formed in a widened joint. There are also joints in nearly horizontal positions (dipping about 10° E), which have also been widened to some extent. One of these cavities is connected with the sandstone-cast (seen in fig. 13), and others are seen on lower le-

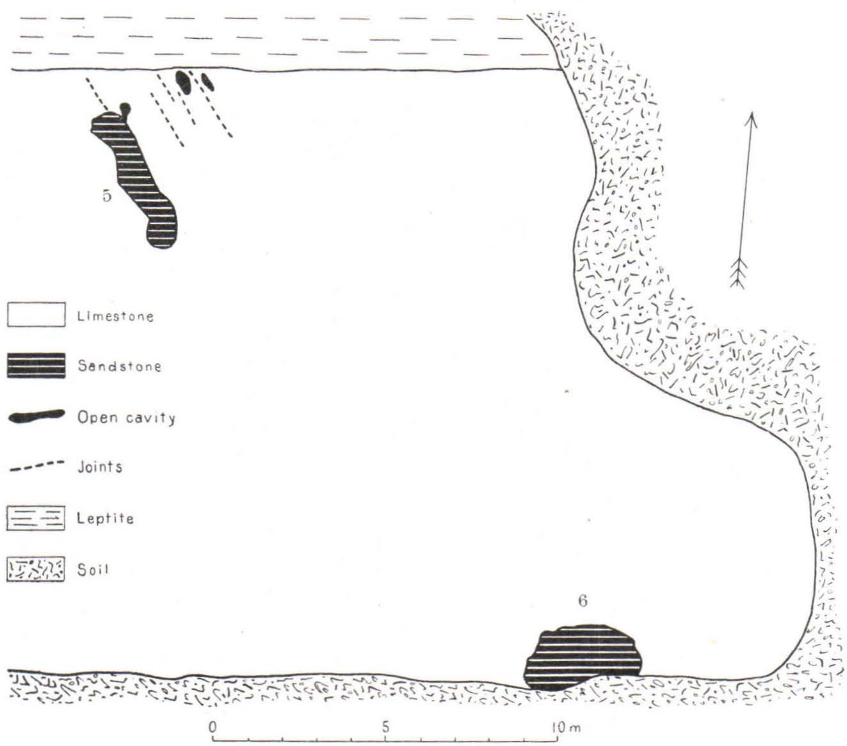

Fig. 12. Plan of the sandstone-casts in the quarry of Lammala Mellangård, Westanfjärd.

vels, to a depth of 4 meters (cf. fig. 8 page 15). As they are situated below the limit of post-Glacial solution and are in part connected with those cavities, in which the casts have been formed, they were probably formed at the same time as the cavities which are now filled with sandstone, but as they were horizontal, no sand could creep in.

The sandstone-cast 6 (fig. 14) found at the southern side of the quarry, has in its horizontal section a length of 3.4 m and a breadth of 1.8 m. It differs from all other casts, its extention being parallel with the strike of the limestone. During the quarrying of the limestone, the sandstone-mass had been left unbroken (cf. fig. 14). It shows the smooth striated surface resulting from glacial exaration. Being very soft, it had been somewhat hollowed by the ice. The sides are perpendicular, and evidently in this direction the cast assumes its

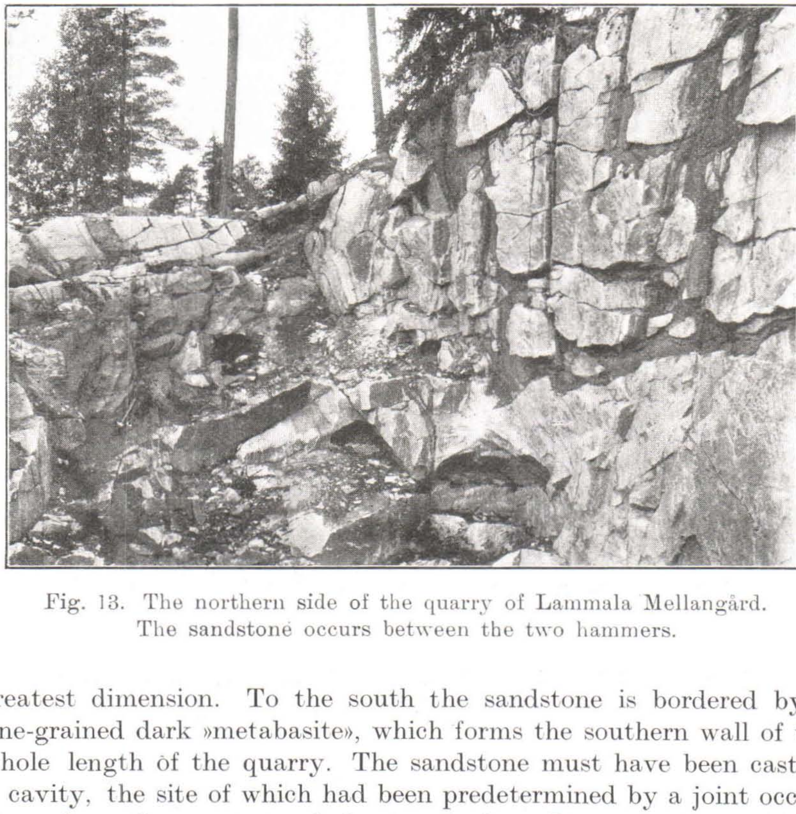

Fig. 13. The northern side of the quarry of Lammala Mellangård. The sandstone occurs between the two hammers.

greatest dimension. To the south the sandstone is bordered by a fine-grained dark »metabasite», which forms the southern wall of the whole length of the quarry. The sandstone must have been cast in a cavity, the site of which had been predetermined by a joint occurring along the contact of the two rocks. It was not possible to examine the jointing in the floor of the quarry, because it was covered by water and blocks of limestone.

The sandstone of cast 5 resembles very closely, in its original composition, that of Illo, being a homogeneous quartz-sandstone of a brownish yellow color. The well-rounded grains measure from 0.1 to 0.9 mm in diameter, and are mixed with occasional larger pebbles, the biggest measuring 8 mm. Most of them show an undulatory extinction which continues also outside of the original outline. The diagenesis of the sediment has proceeded farther than in Illo, and

Fig. 14. The sandstone-cast (6) at the southern side of the quarry of Lammala Mellangård, Westanfjärd.

the rock is a typical crystal-sandstone, the grains having been enlarged by secondary growth until the interstices were almost filled. The limits of the individuals show a decided tendency towards rectilinearity. Only quartz is met with, but in the recrystallised part it is impregnated with an abundant brown pigment. Open spaces are frequent. Gray and occasionally bluish fragments of shale are very common; most of them measure less than 1 cm, but some 3 cm in diameter. They consist of an aphanitic clayey substance containing small flakes of muscovite. Usually, the substance has become hard, but in some pieces it is quite soft and becomes plastic when moistened with water.

The constituents and the average grain of the rock of cast 6 are the same as in cast 5. The biggest pebbles of quartz reach a size of 25 mm in diameter. The sediment was originally quite similar to that in the former case, but it has undergone a different diagenesis and alteration. In the largest part of the cast the rock is porous and so soft that it can be easily broken into small pieces with a hammer. The grains are very imperfectly cemented with small quantities of a clayey substance, rich in limonite. It is of a brownish yellow color except in the western part of the cast where the rock is speckled, like the so called »tiger-sandstone», with dark-brown patches, measuring 1 to 2 cm in diameter; whereas some parts have a uniform dark-brown colour. An interesting feature is the occurrence of spheroidal surfaces resembling joints, these being marked by the same dark-brown matter which has impregnated the patches. This substance contains much manganese; it being treated with hydrochloric acid, chlorine is evolved. All these phenomena were explained by the discovery of some globular pieces of calcite-sandstone within the loose rock. This interesting sandstone consists of rounded grains of quartz, measuring from 0.1 to 1 mm in diameter, which were embedded in coarsely crystalline calcite, the individuals of which sometimes attain as great a size as 10 mm. In this very pure mass of calcite, the quartz-grains lay separated from each other, often at a distance of 0.18 mm. The predominating colour of the calcite is white, but there are also brownish violet manganiferous patches, in form and size identical with the dark-brown patches of the loose sandstone. An analysis of the calcite-sandstone gave the following result [1]).

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[1]) The analysis was made by Mr A. Salmi with the exception of the determination of manganese which was made by the writer.

		Carbonates, recalculated to 100 %	Molecular proportions	
CaO	19.70 %	53.43 %	0.954	0.994
MnO	0.39 »	1.06 »	0.015	
FeO	0.30 »	0.81 »	0.011	
MgO	0.21 »	0.57 »	0.014	
CO_2 (with H_2O, loss on ignition)	16.27 »	44.13 »	1.003	1.003
Insoluble	63.40 »	— »		
	100.27 %	100.00 %		

This calcite-sandstone was the original rock in the whole cast. But the calcite had been afterwards dissolved, and manganese was a part of the residue, being oxydised to the tetravalent stage. The spheroidal zones of impregnation mark the former limits of unweathered portions. In the same way, much manganese has concentrated around the remaining parts of the unaltered calcite-sandstone. I have determined colorimetrically the manganese in the patches as well as in the ground-mass of the calcite-sandstone and the weathered sandstone:

Patch of calcite-sandstone	MnO	0.56 %
» » weathered sandstone	»	0.28 »
Ground-mass of calcite-sandstone	»	0.20 »
» » weathered sandstone	»	0.01 »

As at first seemed probable, considerable amounts of manganese have been dissolved together with calcium carbonate, and now the ground-mass is almost devoid of this compound.

Only a few fragments of shale occur in this sandstone-cast. Instead of shale, there are numerous light green fragments of loose consistency which evidently are weathered pieces of metabasite, for near its contact with sandstone this rock has quite the same appearance as in the fragments.

Empty Cavities from Pre-Glacial Times.

It has already been mentioned that empty cavities are found in the quarries of Illo and Lammala Mellangård which probably were formed simultaneously with the cavities filled with sandstone. There is, howerer, no definite evidence about their contemporaneous formation. In Illo (fig. 15) the uppermost part of the cavity has been filled with glacial clay which was probably deposited there during the Ice-Age. If this fact should be established beyond all doubt, the pre-Glacial age of this cavity would be proved. But the bedding of the clay is doubtful, and as the rock-surface above the cavity is also covered with clay, it may possibly have crept in at a later epoch.

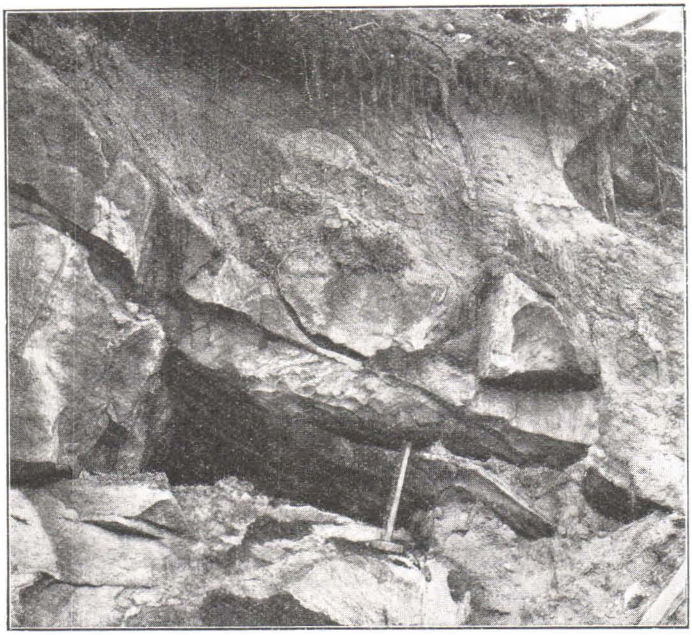

Fig. 15. Empty cavities in the northeastern side of the quarry of Storgruvan, Illo, Westanfjärd.

The rounded form of the upper edges of the cavity shows that solving agents have also been at work since the time, when the rock-surface was smoothed by Glacial exaration; on the other hand it is evident that the strata of the sediment deposited in the cavity ought to have been disturbed also if a cavity existed already before the times of the deposit of the Glacial clays.

The pre-Glacial age of a cavity might be proved, if indisputably Glacial deposits were found in it although they did not cover the surface of the rock. This has been the case in the western quarry of Lammala Östergård, about 300 m to the East of the quarry of Mellangård. Here the southern wall reaches a height of 7 m, and the rock-surface above it is smooth and bare at a height of 32 m above the level of the sea, according to the topographical map. In the upper part of the wall there is a well-marked net-work of post-Glacial cavities reaching a depth of 2.7 m. Occasional cylindrical holes, measuring 0.5 m or less in diameter, extend beyond the limit of this zone of solution and continue beneath the floor of the quarry.

In one of them, laminated Glacial clay was found 6.7 m below the surface, underlaid by a layer of sand consisting of well-assorted quartz and feldspar about 1 mm in diameter. The sand as well as the clay is doubtless a true Late-Glacial deposit, and consequently the cavities must have existed when the land became freed from its ice-cover. This is the only case I have observed, where the existence of empty cavities formed by solution in pre-Glacial times is quite proved. Being situated in the neighbourhood of the sandstone-casts it seems most probable that they have been formed at the same time as the latter, though they may have been widened by solution in later pre- and post-Glacial times.

Another occurrence of Glacial clay in a cavity of limestone may still be mentioned, though this cavity has not been made by solution. It occurs on the island of Niksor in the parish of Finnby. In the most north-westerly of the 7 quarries situated on this little island, the limestone is cut by a vein of pegmatite and at the plane of contact there is a vast cavity which is incrusted with large and very transparent crystals of calcite containing radial aggregates af manganite. The cavity is open at the naked rock-surface and consequently the calcite crystals have been obliterated by solution in its upper part, so that the hole has the form of a solution-cavity. At the bottom, however, 4.2 m from the surface, the crystals are embedded in a layer of laminated clay, which has protected them from weathering. The sediment has the typical appearance of Glacial clay, though in part the lamellae are extremely thin, being sometimes only 0.15 mm in thickness. This phenomenon is interesting because it affords an evidence that the cavity has not been open nor exposed to weathering in pre-Glacial times; for if this had been the case, the crystals, now preserved by the clay, would also have been destroyed.

The Geological Age of the Sandstone.

The question concerning the geological age of the sandstone and the cavities in which the sandstone has been cast is of the greatest importance, because of the conclusions which can be drawn from the facts described above. As the search for fossils has not given any positive result, it is necessary to rely on general geological and petrographical evidence. The arguments in favor of the Lower Cambrian age of the sandstone seem, however, to be very strong, as shown by the following considerations.

1) *Analogy with Lower Cambrian Sandstone in general.* The whole South and Centre of Sweden and the sea-regions north of the Åland and Åbo archipelago, known as the North-Baltic Silurian district, were continental areas during the last pre-Cambrian or sub-Cambrian times. A denudation of very long duration had reached the old pre-Cambrian rock-crust and levelled the landsurface to a peneplain on which a large part of the weathered rock lay in situ. In the beginning of the Paleozoic era a transgression of the ocean took place. The greatest part of the weathered rock was abraded away and deposited as ordinary sediments (sandstone). A smaller part of the weathered crust, but a few meters in thickness, was still left undisturbed and covered by the sandstone. In many places, where the contact between the Cambrian and the Archaean is exposed, it is visible as a rock brecciated by weathering, graduating downwards into an altered gneiss (Lugnås, Kinnekulle and Norra Billingen in Westgothland). These phenomena, and still more the fact that the widely distributed Cambrian sandstone [1]) consists chiefly of quartz with a small amount of feldspar, are proofs of advanced chemical weathering. It is obvious that the denudation and the subsequent transgression have extended also to the region where the sandstone-casts occur. — But also the cavities formed by solution and the sandstone which fills them are in themselves reliable proofs of the same processes.

2) *Analogy with the Sandstone-dikes.* We have exact evidences that in many parts of southeastern Fenno-Scandia the present landsurface has been but very little denuded below the level of the Lower Cambrian plain. It has been known for a long time that the surface

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[1]) The sandstone-facies has developed without exception in all the North-Baltic, Middle- and South-Swedish Cambrian areas. Equivalent Lower Cambrian sandstone still occurs in the Baltic Provinces where it overlies the »Blue Clay».

of the Archaean in the vicinity of the Central Swedish Silurian areas still retains the flat land-form of an abraded plain. But also in areas which are now more uneven and are situated at long distances from the remaining outcrops of Silurian, the ancient plain can be recognized by the uniform level of the highest hills, although the land has been broken up by faults and made rugged by the influence of Glacial exaration. That it really has existed as a plain from the Early Cambrian time and not been levelled during any later period, is shown by the occurrence of sandstone-dikes. In two cases, Lower Cambrian fossils have been found in these dikes: in those intersecting a foliated diorite near Vingershamn on certain islands on the western coast of Lake Väner [1]) and in other dikes occurring in the rapakivi-granite in the parish of Saltvik on Åland [2]). Sandstone-dikes not containing fossils, but geologically and petrographically resembling the former, occur on small rocky islands (Skarvkyrkan, Örnen etc.) in the archipelago of Tvärminne, East of Hangö [3]), near Loftahammar on the Eastern coast of Sweden [4]), and on the island of Bornholm [5]). The »sandstone-casts» are to be considered as on a parallel with these dikes. As regards their geological importance, the dikes and the casts are equivalent in as much as they prove that the denudation effected after their formation has been insignificant. — It may be inferred that dikes of sandstone ought to occur in the vicinity of the casts, but though I paid particular attention to this circumstance during my excursions in this region, especially on bare rocky islands in Westanfjärd, Hiittis, Bromarf and Finnby, I discovered no dikes whatever. This, of course, does not invalidate the arguments for an analogy.

3) *Petrographical Analogy.* In early Cambrian times the geological and meteorological conditions must have been very uniform over wide areas of Northern Europe, as is proved by the uniform char-

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[1]) A. Gavelin, »Om underkambriska sandstensgångar vid västra stranden af Vänern», *S. G. U.* Ser. C, N:o 217. (1907).

[2]) V. Tanner, »Über eine Gangformation von fossilienführendem Sandstein auf der Halbinsel Långbergsöda-Öjen im Kirchspiel Saltvik, Åland. inseln», *Bull. Comm. Géol. de Finlande*, 25, 1911.

[3]) These dikes were found by Sederholm (in 1907).

[4]) A. Gavelin, »Beskrifning till kartbladet Loftahammar», *S. G. U.* Ser. A, page 63 (1904).

[5]) N. V. Ussing, »Sandstensgange i Granit paa Bornholm», *Danmarks geoogiske Undersögelse,* II Raekke, N:o 10.

acter of the Lower Cambrian sandstone in all areas where it has been found. Greyish yellow and grey are the predominating colours, whilst reddish tints are very rare. Quartz is always the chief constituent, feldspars being insignificant in quantity and, on the whole, characteristic mainly of the bottom layers. In many localities, larger pebbles of quartz of various sizes occur amid the finer-grained groundmass. This circumstance is, in my opinion, a consequence of the fact that, while the chemical weathering was very complete, the mechanical wear and assortment of the matter was less important than in many other periods of sandstone formation. We may take the Jotnian sandstone or the Devonian »Old Red» as examples. All these features depend on such conditions as are uniform over wide areas, while the coarseness of the grain and the accessory compounds or the quality of the cement may vary according to local conditions. Those uniform features are common to all sandstone-dikes and are characteristic of the sandstone-casts in question.

By reason of these analogies it seems to be permissible to correlate the sandstone-casts with the Lower Cambrian series. Other possibilities, however, must also be taken into account. Above all we have to consider the Jotnian, which geologically shows many analogies with the Cambrian. The Jotnian time, like the Cambrian, was preceded by a denudation of long duration, and the sub-Cambrian denudation has apparently not proceeded very far below the sub-Jotnian land-surface, nor has the actual land-surface been very much degraded since the Jotnian time. In some areas the Jotnian sediments are still preserved in »Gräben», formed in pre-Cambrian times [1]). Thus it would be only in keeping with well known facts,

[1]) It is not quite impossible that Jotnian beds might still exist or, at least, might have existed until the beginning of the Ice-Age in southwestern Finland, south of the sandstone area of Satakunta. The very common but unequal distribution of red Jotnian sandstone in the form of boulders throughout southwestern Finland suggests such an assumption. In the area in question the amount of sandstone in the drift varies from 1 to 9 %, except in the parish of Bromarf where I found as much as 28 %. But this high percentage may be explained by the fact that a large terminal ose occurs here (the Northern Parallel Ridge running parallel with the Salpausselkä). In such deposits the greater part of the boulders have been carried much farther than in other Glacial drift. This consideration and still more the extent of the area, where this sandstone occurs (cf. for instance H. Hausen, »Data beträffande frekvensen af jotniska sandstensblock i de mellanbaltiska trakternas istidsaflagringar», *G. F. F.* 34, p. 495. 1912), make it more probable that all the Jotnian sandstone has been transported from large Jotnian areas in Satakunta and on the bed of the Gulf of Bothnia.

if remnants of Jotnian sediments were found as dikes or casts. The relation of our casts to the Jotnian is rendered less probable by general petrographical differences, for reddish tints and a uniform size of the grains are predominant in the Jotnian quartz-sandstones.

There is still the possibility that the sandstone-casts were formed at some period between the Cambrian and the Ice-Age, their pre-Glacial age being proved by the occurrence of Glacial striae on the surface of one of the casts (fig. 14, page 31). As it is evident that the Cambro-Silurian transgression has reached these areas, the solution of the cavities in the limestone and the formation of the sandstone could only have taken place during another elevation of land, when the Archaean rock-surface had once more been laid bare and weathered. The formation of the cavities must coincide with some period of regression of the sea.

The first regression of any considerable extent in the Paleozoic era probably took place during the change of the Silurian to the Devonian period [1]), at the same time as the folding of the Scandinavian mountains. The unconformity between the Silurian and the Devonian strata of the Baltic provinces shows that the elevation has increased from south to north. In southern Esthonia the Old Red lies on the upper Gotlandian, but towards the north it is lying on lower groups of the Silurian and finally, south of Lake Ladoga, on the Blue Clay. If the Devonian were still present in Finland, it would be found resting on the pre-Cambrian rocks, which must have been laid bare here at the time of the Late Silurian denudation. The sandstone of Westanfjärd, if formed at this time, would perhaps be equivalent to the sandstones of Orsa in Dalecarlia or Öfved in Scania. But there are several difficulties in the way of the assumption of a Devonian age. Petrographically this sandstone differs from most Devonian, as it does also from the Jotnian sandstones. Another objection is, that the plain which forms the bottom of the Devonian of Russia, supposing it continued over the Gulf of Finland, would cut the level of the Lower Cambrian plain somewhere near the southern coast of Finland. Thus the area of Westanfjärd seems to be within the belt, where the Late Silurian denudation has just reached the pre-Cambrian rock-crust, but not degraded it. Consequently no considerable weathering, such as is necessary for the ex-

[1]) Wilhelm Ramsay, »Le golfe de Finlande et le lac Ladoga», *Atlas de Finlande 1910.*

cavation of deep holes by solution, is likely to have taken place here at this time.

In the Devonian period, a new transgression began, proceeding from Russia in a northwesterly direction. During the time from Carboniferous to Tertiary one or more periods of regression have taken place. It is very improbable that the sandstone-casts belonged to any of these systems because of the perfect cementation of the sandstone. Then, although the degree of diagenesis of a clastic sediment is of itself by no means a measure of its age, it is obvious that a quartz cement can be formed only on low levels beneath the surface, in the zone of cementation. Evidently the sandstone cannot have been formed during the last period of denudation, for since this time the surface of the pre-Cambrian rock has never been overlaid by sedimentary beds of any considerable thickness. If two or more periods of denudation, interrupted by sedimentation of thick formations, have taken place in post-Devonian times, the sandstone might belong to one of the earlier periods; but the lack of any traces of sediments from these times makes it far more probable that no such thick series of strata ever existed in Finland in post-Devonian times. To this question we will return later.

We shall now discuss some conclusions which can be drawn from the observations mentioned above, assuming that the sandstone-casts of Westanfjärd belong to the Lower Cambrian. These conclusions would be greatly modified, if the further investigations should prove that the sandstone were younger, whilst a more remote origin would not invalidate these conclusions.

The Original Depth of the Cavities formed by Solution.

It is not possible to determine exactly the depth originally reached by the solution which has formed the cavities during sub-Cambrian times; yet, at the same time, using other similar occurrences as a criterion, it may be admissible to form some opinions about certain possibilities in this connection.

The deepest excavation known in Karst-lands, i. e. the cave of Trebic or Lindner-höhle, belonging to the cave-complex of Adelsberg, reaches a depth of 322 meters [1]). This cave is situated in a region, where the conditions for deep-reaching solution are extremely

[1]) W. v. Knebel, »Höhlenkunde», *Die Wissenschaft* 15, page 43, 1906.

favorable: The limestone-beds are wide and thick, the rock consists of pure carbonates, the area has been broken up by tectonic movements and elevated to form a plateau, so that the deepest parts of the caves are still far above the level of the sea. In the limestone here in question the conditions are very different and must have been so also in sub-Cambrian times. The most essential condition, i. e. the existence of open cracks and fissures, is here lacking. It might be supposed that the jointing was perhaps more developed in sub-Cambrian times and that the joints were re-cemented later. But the rounded form of the casts and the open holes prove the contrary. And because the area had been degraded to the stage of peneplain, it cannot have attained any considerable height above the level of the sea. Thus there is sufficient evidence that the sub-Cambrian cavities in the Archaean limestone must have been very much shallower than the caves of the Karst-lands.

As we have learnt from the phenomena of solution in post-Glacial times, the progress of solution is very slow under the conditions which now prevail in this country. We must assume that the conditions were identical in sub-Cambrian time with regard to the height, the composition of the rock and its jointing.

Agencies which have varied are the climate, which may have been warmer than now, and the time during which the weathering was active, which must have been much longer than the time covered by the post-Glacial epoch. These are certainly the chief reasons, why the solution in sub-Cambrian times reached to such depths that there are still parts of the cavities left after a considerable denudation. We may assume, that the limestone was excavated below the zone of weathering of the siliceous rocks, and that these depressions became recipients for water which proceeded slowly downwards forming by solution cylindrical holes, thereby making use of the joints only when these were open.

The highest granite-hill in the neighbourhood of the quarry of Illo reaches a height of 36 m above the level of the sandstone-casts. Its summit is nearly on a level with the tangential plane of all the highest hills. If we should assume that this level is about 10 meters or a little more below the sub-Cambrian plain, supposing that the estimate of Swedish geologists with regard to the flat country of Westgothland [1]) could be applied here also,

[1]) Sten De Geer, »Explanation of Map of Land-forms in the Surroundings of the Great Swedish Lakes», S. G. U. Ser. Ba, 7, 1910, page 12.

we should arrive at the conclusion that the original depth of the sub-Cambrian solution of limestone may have been about 50 m. This figure cannot be regarded as being very much too low, considering the above mentioned possibilities of the downward action of the solution.

Conclusions regarding the Geological Evolution of Southwestern Finland in Post-Cambrian Times.

The phenomena of weathering, which have been observed in the sandstone of Westanfjärd, have happened in pre-Glacial times. The best evidence of this conclusion is furnished by the sandstone occurring on the southern side of the limestone quarry of Lammala Mellangård (cast 6, fig. 12). The surface of this cast has been hollowed by the exaration of the ice (fig. 14). Because the calcitic sandstone is, in its original form, quite as hard as the adjacent crystalline limestone, the excavation by the ice would have been impossible, if the sandstone had not been previously made porous and softened by the weathering. The partial destruction of the calcitic cement in the sandstone of Illo and the solution of the fragments of limestone contained in the shale may also have happened in pre-Glacial times, for that part of the cast, which is now exposed, was 1.5 m under the surface of the rock, and had been covered by a layer of soil of sufficient thickness to prevent the lixiviation penetrating it; under such circumstances the post-Glacial phenomena of solution in the rocks generally reach only an inconsiderable depth.

As the sandstone had been cemented by calcite before it was weathered, this weathering must have taken place during some subsequent period of elevation of the land, when the series of Paleozoic sediments, which had covered the surface of the Archaean, had been removed.

The degree of disintegration of the sandstone must be regarded as very imperfect, much calcitic cement having still been left in the sandstone. It is a very striking fact that these almost unnoticeable phenomena are the only positive traces of weathering during pre-Glacial times after the formation of the sandstone-casts. No cavities in limestone formed during these times have been found in any of the limestone-quarries, so far as my investigations have proceeded. The majority of the cavities belong to the zone of solution which certainly has been effected by the work of weathering in post-Glacial times. In single cases, where cavities reach below the limit of this zone, it is evidently due to some exceptional causes, such as the presence of sulphides in the rock or the pre-existence of open fissures. Some empty cavities, as those in Illo, Lammala and Bredvik, either evidently or probably of pre-Glacial age, might perhaps be supposed to be post-Cambrian, but because their occurrence is limited to the vicinity of sub-Cambrian cavities, it is far more probable that they were originally formed at the same time as the latter, though they may, of course, have been widened in later pre-Glacial times.

The absence of cavities in the limestone formed during the period in question proves that the surface of the pre-Cambrian rocks of Southwestern Finland has not been exposed to an advanced secular weathering in any post-Cambrian period. This conclusion becomes more obvious, if we try to assume the contrary. In this case the dissolving agencies should have worked on the limestone during a warm period, when the vegetation was tropical, i. e. under conditions which must have prevailed here in pre-Glacial times. Because there were numerous deep cavities, a great number of which were certainly empty, abundant water must have had free entrance to deep levels of the rock. The solution must have proceeded relatively quickly, the cavities must have been enlarged and deepened, and insoluble products of the weathering have entered. Cavities and casts of sediments formed at this time would therefore occur frequently in the neigbourhood of the Lower Cambrian sandstone-casts and also in other limestones where actually no such phenomena have been observed.

It does not seem likely that all traces of such a weathering could have been destroyed by a subsequent denudation, for the difference in level between the Lower Cambrian plain and the actual rock-surface must have been inconsiderable, certainly in no case as much as a hundred meters, but in most places much less. In the highest hills it cannot be much above twenty or thirty meters. If weathering and erosion had acted on the rock after the Cambrian period, the difference would have been still further diminished. Where the sandstone occurs in the quarry of Lammala Mellangård, the height of the rock-surface is about 30 m above the level of the sea, at a level only five or six meters below the common tangential plane of the hill-tops. Consequently, it must be very near the level of the ancient plain. On the other hand, the secular weathering reaches at the present time in many parts of the warm and temperate zones to a depth of much more than a hundred meters. If such a process had affected the surface of the old crystalline rocks, it would certainly have made such an impression that marks of it would be visible in every rock. The absence of cavities in the limestone is especially important because the process of solution reaches lower levels in limestone than any other kind of weathering in crystalline rocks [1]).

The study of the phenomena of weathering of the sandstone of Westanfjärd leads us to the conclusion that *the surface of the Archaean rocks of this area has been laid bare and to a certain extent weathered in pre-Glacial times.*

From the absence of limestone-cavities and casts of sediments formed during the periods between the Early Cambrian and the Ice-Age, it may be inferred, that *the Archaean rocks in this area during the above-mentioned periods were never affected by secular weathering during any considerable length of time.*

As to the first conclusion, there are certain circumstances which permit us to determine with some accuracy the epoch when the weathering probably was effected. The fact that the weathered sandstone has not been recemented, shows that the rock was not afterwards covered by sedimentary beds of any considerable thickness. The solution of the calcitic cement must have occurred during the last elevation of the land, i. e. in the Tertiary period. As has been stated above, the secular weathering cannot have been very advanced, and therefore it seems probable that the process in question may have taken place during the last epochs of the Tertiary period, when, on the approach of the Ice-Age, the climate was less genial and the superficial lixiviation was slower than in earlier times when the temperature was more favorable [2]); but this is better discussed in more detail.

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[1]) A. G. Högbom (*G. F. F.* XXI, page 201) reasons that the secular weathering may probably affect deeper parts in crystalline siliceous rocks than in limestone rocks, so that the latter form hills rising above the surface of the former in an area which has been denuded by weathering and erosion. This may be true as regards the disintegration and loosening of the rocks by means of weathering, but it seems that we may, depending on our knowledge of the physicochemical properties of the rocks, assume that the formation of cavities in limestone by solution reaches lower levels than the weathering of siliceous rocks which is also caused by the action of dissolving agencies. In the formation of the sandstone-casts of Westanfjärd we have a convincing evidence that this was the case.

[2]) These ideas have partly been suggested by the theory of A. E. Törnebohm concerning the genesis of the rock-basins (»Grunddragen af Sveriges

All geologists agree on the point that the surface of the old pre-Cambrian rock in the South of Finland was laid bare before the land became covered with ice. In fact, the scarcity of boulders of Paleozoic [1]) or later sediments in the Glacial drift, cannot be explained in any other way. How can this be kept in harmony with the indisputable fact that no advanced secular weathering of the old rocks has taken place? Only by assuming that denudation had in these regions reached the ancient land-surface shortly before the beginning of the Ice-Age. This hypothesis is quite in accordance with the fact that the pre-Glacial elevation of the land attained its highest point during the last epochs of the Tertiary period [2]).

It may be added that this was in all likelihood not the only time when, in these areas, denudation reached the ancient land-

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geologi», 2 upplaga, 1884, also in *G. F. F.* VIII, 346). According to this theory, much disintegrated rock had in Tertiary times been lying in situ, protected by tropical vegetation. These weathered products were for the most part removed under the rough climatic conditions at the beginning of the Ice-Age, when the protecting vegetation had already disappeared. In the old rocks, the erosion was greatest along the lines of tectonic faults and cracks which had been formed in previous times. Such a theory seems very feasible, yet it must, of course, be somewhat modified, because at present we know that in these areas any thick layer of weathered Archaean rock never existed in post-Cambrian times; instead of this there were sedimentary beds. Especially the loosening of broken up rock may be easily imagined to be the result of weathering and erosion under an arctic climate where the action of frost plays a very important part. Finally, the land-ice has completed the outlining of the actual topography of the rock-surface.

[1]) In this connection it may be mentioned that in the district of Åbo, especially West of Lake Pyhäjärvi, there occurs in the drift a pale gray, sometimes yellowish, finegrained sandstone, the existence of which here seems to have escaped the attention of the geologists hitherto. This sandstone consists of slightly round-edged or angular grains of quartz of 0.07 to 0.1 mm in diameter, and of muscovite as a lesser constituent. It is very soft and porous. cemented only with limonite, and resembles closely the apparently Cambrian sandstone found as boulders on Åland (H. Hausen, »Stenräkningar på Åland», *G. F. F.* 33, p. 502). The latter was originally cemented by calcite, which has been dissolved by weathering in post-Glacial times. In its original form it may be identical with the »bluish calcitic sandstone» of C. Wiman (»Studien über das Nordbaltische Silurgebiet», *Bull. Geol. Soc. of Upsala*, VI, p. 42). The sandstone in question also was probably a calcitic sandstone originally, though I have never found remains of unweathered stone in the boulders. Blocks of this sandstone which is called »sierakivi», are used by the farmers as grindstones.

[2]) According to Wilhelm Ramsay the cooling of the atmosphere was simply a consequence of the breaking up of the earth's surface-forms during Late Tertiary times. (»Orogenesis und Klima», Öfvers. F. Vet.-Soc. Förh. 1910).

surface, without acting much on the pre-Cambrian rock. As already stated (page 39) the Silurian strata were probably already removed in the Late Silurian time. Devonian sediments were deposited, but it seems probable that these also were worn off during the Late Paleozoic or Mesozoic era. For, if they had formed the substratum of such younger deposits, as probably existed here during Early Tertiary time, some remains of them would probably have still existed at the beginning of the Ice-Age, and boulders of them ought to be found in the Glacial drift. As there are no Devonian rocks among the latter, the conclusion seems feasible that all those sediments had been removed during Paleozoic or Mesozoic times and that all sedimentary formations which were washed away during the Tertiary period, had been formed during Late Mesozoic or Early Tertiary times. Because these sediments never reached any considerable thickness or were overlaid by other thick layers, they remained in the state of loose clays and sands and gravels which could not be preserved in the form af boulders, supposing anything of them had been left after the preceding erosion.

As to the way in which these earlier processes of denudation probably happened, we are able to make certain suppositions. Chemical weathering and erosion may have taken place, but their action must have been only of short duration. More likely, weathering was mainly caused by physical forces, f. i. in such forms as occur when arid climatic conditions prevail. It is quite possible that in Fenno-Scandia the climate may have been arid during different post-Cambrian epochs, just as it was in the neighbouring countries, where the previous existence of deserts is proved by the occurrence of deposits of salts. We may mention the Devonian of northern Russia, which comprises deposits of gypsum and rock-salt, and the Permian of Middle-Germany with its thick beds of salts. But, admitting that such conditions existed, it is hardly possible that weathering and denudation could have been very effective in such a district as that of southern Finland which must have been low and flat during all post-Cambrian ages. It seems far more probable that the Archaean may have been attacked by marine denudation during one or several periods of transgression. In this case no appreciable weathering of the Archaean ought to have taken place, because it was either covered with sediments or with the water of the sea. The degradation of the Archaean ought to have been very slight, for the waves could only with difficulty attack the hard and smooth rock-surface after having removed the sediments.

As a matter of fact, weathering and denudation have happened in the countries around the Baltic in several of the earlier pre-Glacial epochs as is proved by observation in many cases. The unconformity between the Gotlandian and the Devonian in the Baltic provinces has already been mentioned. In Sweden phenomena of weathering have been observed in the Upper Gotlandian, underneath the diabase beds of the table-mountains of Westgothland. In Scania the conglomerates of the Keuper contain pebbles of Archaean rocks, and the Visingsö-formation, which, according to some Swedish geologists, also belongs to the Keuper, lies on a weathered surface of the Archaean. Of later systems, the Cretaceous of Scania is deposited on weathered Archaean rock.

Most of the theories which try to explain the topography of the rock-surface of Sweden and Finland, admit, besides the influence of the tectonic movements, a vigorous weathering in Late pre-Glacial times. There has been, among Fenno-Scandian geologists, no doubt as to the existence of such a process, although in later years it has become evident that it cannot have disintegrated the rock-crust to any considerable depth. The phenomena of weathering in the sandstone of Westanfjärd are probably the only positive traces of this weathering observed up to the present day. Their occurrence here is, as stated above, explained by the circumstance that the process of solution in limestone usually reaches lower levels than weathering of any other kind.

The second conclusion, viz. that the pre-Cambrian rocks have not been appreciably attacked by weathering in any post-Cambrian age, is, of course, applicable only to the adjacent part of the earth's surface, which has not been separated by faulting in post-Cambrian times from that part where the sandstone occurs. For, other portions of the Archaean crust may have risen higher and been levelled by denudation before the Ice-Age. The peninsula of Westanfjärd is evidently bordered by faults to the west and the east, and in the south the open bay of Klobbfjärd may be a sunken part.

Thus, this area probably forms a continuous part of the Lower Cambrian plain. As it is impossible to determine with certainty which parts of the surrounding areas are sunken or raised, the theory can be applied to them only in as much as they can be shown to be parts of the same ancient plain.

Two facts seem especially to justify a more extended application of the above theory. Firstly the occurrence of sandstone-dikes in other parts of soutwestern Finland, which proves that the degradation of the pre-Cambrian since the Early Paleozoic time has been insignificant, and secondly the absence of signs of pre-Glacial weathering in the rock-masses as well as in the pebbles and boulders contained in the Glacial drift, or even of cavities in the limestone [1]). This fact indicates that no thick masses of weathered pre-Cambrian rocks existed in the territory in question shortly before the Ice-Age. The absence of weathered rocks being a striking feature of the whole of southwestern Finland, the occurrence of Cambrian sandstone as dikes and casts is an exceptional occurrence, limited to a few areas. Consequently we do not know whether the difference in level between the former plain of Lower Cambrian age and the present rock-surface is in the whole region so inconsiderable as it is in certain areas. Therefore the theory cannot be generalized with certainty so as to be applicable to the whole of southwestern Finland.

In any case, it is evident that this conclusion cannot be applicable to northern and central Finland. It has already been mentioned that an elevation of Fenno-Scandia, probably during several different epochs, took place in the Paleozoic times, whereby the land was raised more in the centre than in the peripheral areas, just as has happened in later times. One such epoch of elevation took place at the end of the Silurian period. In southern Finland the pre-Cambrian rocks were probably laid bare without being much denuded, but in central and northern Finland, in the vicinity of the caledonian chain, this denudation must have degraded the pre-Cambrian rocks also to a certain depth, as is proved by the inclined old pe-

[1]) Another very important instance is the absence of any signs of weathering in the ores, causing what Krusch calls »sekundäre Teufenunterschiede». With the exception of some very insignificant phenomena relating to the formation of gossan, which are evidently of a post-Glacial age, such as the occurrence of native copper in Outokumpu in Kuopio Län and of pyrargyrite in Aijala in Kisko, all ore-minerals of Finland are of primary origin. Beyschlag, Krusch and Vogt (»Die Lagerstätten der Nutzbaren Mineralien und Gesteine» I, p. 206) note the absence of any secondary changes common to territories which have been glaciated. In the case of southern Finland this fact, however, cannot be due only to the denuding action of the land-ice. The authors quoted (l. c.) mention areas with conditions favourable to weathering where the oxydation of the ores has attained such depths as 15 to 40 m and more. If any weathering of similar intensity had taken place in the naked Archaean rocks during post-Cambrian times, traces of it would still be visible. In Finnish Lappland the gossan and other phenomena of weathering have really been observed (cf. p. 49).

neplains which can be traced in the Scandinavian mountains. During later phases of the elevation the older rocks have apparently been degraded still more in the Centre of Fenno-Scandia, f. i. in the Tertiary period, as shown by the occurrence of unmistakable pre-Glacial erosion-valleys in several districts of northern Finland and Sweden, and by the phenomena of rock-weathering, as for instance those observed during the course of prospecting-works in the gold-fields of Finnish Lappland. Here the rock is at present weathered to a depth of some twenty meters or more. Sederholm [1]) thinks that this is owing to the proximity of this region to the ice-shed, where therefore exaration has been inconsiderable and insufficient to remove the weathered rocks. But in view of the fact that large masses of the altered rock are still quite solid, it seems evident that such a thick zone could not have been destroyed by the work of the ice, in whatever part of the glaciated area it might have occurred. It appears, that we have here those signs of an advanced secular weathering, which are lacking in Southern Finland.

In central Sweden where the land-forms and their genesis have been studied in great detail [2]) the actual rock-surface is in several pre-Cambrian areas but little below the level of the Lower Cambrian plain. The flat Archaean expanses in the neighbourhood of the Silurian areas offer the best instance of this kind. Many of these areas show a gradual change to hilly districts, the amount of the post-Cambrian denudation increasing gradually. The raised sides of the inclined sections of the Archaean crust, which have been cut by faults, are at times degraded to a depth of some twenty or thirty meters, while the lowest sides are still covered with Silurian beds. The occurrence of sandstone near Loftahammar is an evidence of the fact, that the post-Cambrian denudation has been insignificant also in a broken area at a long distance from any Cambrian field. On the other hand, there are in Central Sweden many horst-shaped areas, where the post-Cambrian denudation has had considerably more effect, a circumstance which shows that the theory by which we have tried to explain the geomorphological evolution of certain portions of south-western Finland, cannot be generalized too far.

[1]) J. J. Sederholm »Om granit och gneis», *Bull. Comm. Géol. de Finlande* N:o 23, page 5, footnote.

[2]) G. De Geer. »Über die Beziehungen unserer Seenplateaus zu den einstmaligen Abrasionsflächen (*Förh. vid Nord. Naturf. o. Läkaremötet i Helsingfors* 1902). S. De Geer, Land-forms in the Surroundings of the Great Swedish Lakes». (*Sveriges. Geol. Und.* Ser. Ba n:o 7, 1910).

Summary.

As to the surroundings of the sandstone of Westanfjärd, the following conclusions may be arrived at:

Denudation in post-Cambrian times has degraded the area only to an insignificant amount under the Lower Cambrian plain.

There has never been any advanced chemical weathering in the pre-Cambrian rocks of this area during post-Cambrian periods.

During a period preceding the Ice-Age the pre-Cambrian rock has been laid bare and weathered to a certain degree.

As a corollary to these conclusions we may add that *in post-Cambrian times the area has never been raised to any considerable height above the level of the sea* [1]).

Other geological evidences make it probable that denudation here has reached the pre-Cambrian rock in the Devonian period also and perhaps once or several times in later periods, too. Across southern Finland and central and southern Sweden there exists a belt of areas, where denudation since the early Paleozoic ages has repeatedly reached the same plain, but never exceeded it. In central Fenno-Scandia elevation and degradation of the land have been the predominating factors, whilst in the neighbouring countries outside the limits of Fenno-Scandia aggradation has prevailed in post-Cambrian times. It is a very interesting fact that, along the southeastern boundary of the Fenno-Scandian territory of elevation, there has existed a »belt of balance» during such long ages.

[1]) Furthermore, the fact that there are cavities in the limestone which seem to have remained open since the Lower Cambrian time makes it probable that in post-Cambrian times the area has never been covered by very thick beds of sedimentary formations. However, the evidence of this is not quite indisputable. The objection may be offered that the cavities were formerly perhaps filled with calcite, which has been dissolved during the period of weathering which occurred in later pre-Glacial times, in the same way as calcite which had formed the cement of the sandstone of Westanfjärd. Sederholm (*Compte Rendu Congr. Géol.* Stockholm p. 866) has mentioned two other facts which permit such a conclusion to be drawn with more certainty, regarding the surroundings of the Finnish Gulf. Firstly the fissures in which the sandstone-dikes occur on the islands near Tvärminne (as well as in the region S. of Westervik in Sweden), are partly open and evidently have been so since the Cambrian age; secondly, the sub-Cambrian blue clay of southeastern Finland and Ingermanland is still quite uncemented and plastic, closely resembling the Quarternary clays.

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