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ON ENGINEERING-GEOLOGICAL PROPERTIES OF FINE-GRAINED SEDIMENTS IN FINLAND

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ACADEMICAL DISSERTATION

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PREFACE

Since the mid-1960s, the Geotechnical Laboratory of the Technical Research Centre of Finland has been collecting material, in connection with the studies in its research program, to determine the geotechnical properties of fine-grained sediments. The material of the study came from 80 investigation sites in different parts of Finland. The samples collected were analyzed in the Geotechnical Laboratory to determine their ordinary classification properties and, in addition, their geotechnical properties. In conjunction with the investigations, it was further desired to ascertain the extent to which the properties studied vary according to the geological factors involved. With this in view, 48 of the sites were selected from the total number included in the investigations. The samples were classified on geological grounds into the various types of sediment representing the evolutionary stages of the Baltic Sea. It was then sought by analytic means to determine along general lines the properties of the sedimentary material and the variation in the classification properties as well as in the strength and consolidation properties of the geological types of sediment.

The large-scale collection of research material was initiated by Professor K-H.Korhonen, who was serving as director of the Geotechnical Laboratory and who took charge of the geotechnical treatment of the material. He read the manuscript of the present study, making significant comments and recommending improvements. The author received invaluable assistance in the computerized data processing of the material from Researcher Kari Saari. The pollen analyses were done by Brita Eriksson, Ph.Mag., and Tuulikki Grönlund, Ph.Lic., of whom the latter also did the diatom analyses. Risto Tynni, Ph.D., contributed his services in the interpretation of the microfossils. The manuscript has been translated into English by Mr P. Sjöblom, M.A. Quite a few other persons in addition participated in the processing of the research material over a long period of time.

To all the good people who helped to make the completion of this study possible, the author extends his warmest thanks.

Otaniemi, December 1974

R. Gardemeister

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List of symbols

Li	Littorina sediment type
An	Ancylus sediment type
Yo	Yoldia sediment type
Ba	Baltic Ice Lake sediment type
a	Settlement number
c	Constant
E'_t	Modulus of compressibility, kp/cm^2
E'_{tc}	Modulus of compressibility at consolidation pressure p_c, kp/cm^2
E.T.W.	Epithemia turgida v. westermanni
e	Void ratio
e_0	Natural void ratio
F	Fineness number
H	Halophilous
Hu	Humus content
h_0	Initial sample height
I_p	Plasticity index
k	Settlement exponent
N	Number of determinations or tests
p	Pressure, kp/cm^2
p_0	Effective overburden pressure, kp/cm^2
p_1	1 kp/cm^2
p_c	Consolidation pressure, kp/cm^2
r	Correlation coefficient
Sa	Clay content
S	Salinity, ‰
S_t	Sensitivity
s_v	Shear strength from vane test, Mp/m^2
s_{rv}	Shear strength from vane test, remolded, Mp/m^2
W	Water level observed in borehole
w	Water content, %
w_L	Liquid limit
w_p	Plastic limit
v	Modulus number
V_v	Volume of voids
V_s	Volume of solids
γ	Unit weight of soil, Mp/m^3
γ_d	Dry unit weight of soil, Mp/m^3
γ_s	Unit weight of solid particles, Mp/m^3

γ_w	Unit weight of water, Mp/m^3
ϕ	Angle of internal friction
ω	Modulus exponent

Dimensions used in text	Dimensions of SI-systems
1 kp/cm^2	~ 0,1 MN/m^2
1 Mp/m^2	~ 10 kN/m^2
1 Mp/m^3	~ 10 kN/m^3

Soil symbols in figures

 Peat

 Ooze

 Organic clay

 Clay

 Silt

 Fine sand

 Sand

 Stones

 Till

ABSTRACT

This study deals with soft Finnish fine-grained sediments from the standpoint of engineering geology. The differences between the classification properties and partly the strength and consolidation properties of geological types of sediment are elucidated along general lines. In addition, the interrelations of certain classification properties are briefly examined. The material derives from 48 boreholes; the samples collected have been used to investigate, inter alia, the pH, salinity of the pore water, mineralogical composition, and the classification properties as well as strength and consolidation properties of the deposits. Primarily on the basis of the microfossils occurring in the samples, the material has been divided into types of sediment in accordance with the geological evolution of the Baltic Sea: Littorina, Ancylus, Yoldia and Baltic Ice Lake sediments.

In the light of the large quantity of clay material as well as, to some extent, the content of microfossils, it is evident that the sedimentary material derives, at least in part, from interglacial or interstadial sediments, which underwent new sedimentation at the melting stage of the continental ice sheet and afterward. Mineralogically, the sediments are illite clay. The average pH-values of the fresh sedimentary material vary between about 7,3 and 8,3, increasing with depth. The maximum salinity values of the pore water measured (approximately 8 ‰) occur in the Littorina sediment of southwestern Finland. The salinity of other types of sediment is notably lower. Evidently, the salinity of the pore water has diminished, as a result of, among other things, diffusion and leaching, to nearly a half of its original value.

The classification properties of the deposits analyzed differ on the whole according to the type of sediment in question. The classification properties of the Littorina sediments are closely dependent on the humus content (water content). The classification properties of the other types of sediment are correlated most significantly with the clay content (water content). The sediments are on the whole normally consolidated. Slight over-consolidation occurs, however, fairly generally in all the types of sediment. The over-consolidation is the apparent result of both internal and external factors.

Of the properties of the sedimentary material, its strength and consolidation are affected most significantly by the clay and humus contents and the water content dependent on them. When these properties vary markedly in different types of sediment and do not cancel out the effects of each other, the types of geological sediment based on the evolutionary stages of the Baltic Sea can be differentiated in the light of their engineering-geological properties so as to form different categories.

INTRODUCTION

The soft, fine-grained sediments occurring in Finland were deposited during the final stage of the last Ice Age (late-glacial sediments) or afterward (postglacial sediments). The structure of the sedimentary deposits exhibits variation, which is based primarily on the evolutionary stages of the Baltic Sea [68, 32]. Accordingly, four main developmental stages can be distinguished, representing in structure and properties different types of sediment.

The main part of the oldest sediments were deposited in the Baltic Ice Lake during the late-glacial period some 10 000···12 000 years ago. As the sedimentation of the fine-grained material took place in the close proximity of the continental ice sheet primarily in fresh, cold water, the general structure of the sediments became varved, diatactic [67].

The sediments of the next stage were deposited for the most part in the marine Yoldia Sea. Owing to the salinity of the water, the stratification of the sediments is weak, symmictic. As a consequence of mixing of fresh and saline water, variation in the prominence of the varves nevertheless occurs.

Owing to the land uplift, the connection of the Yoldia Sea with the ocean was broken and there formed the Ancylus Lake, with fresh water. The sediments deposited at this stage are homogeneous in structure.

The youngest sediments were deposited mainly in the marine Littorina Sea. The sediments of this stage are nearly homogeneous in structure. As the warming up of the climate following the Ice Age reached its maximum during the stage of the Littorina Sea, abundant material of organic origin occurs in general in these sediments. The Littorina sediments began to be deposited about 8 000 years ago, the process of sedimentation still continuing in the present basin of the Baltic Sea. Littorina sediments occur primarily in coastal regions (Fig. 1).

The studies dealing with the fine-grained sedimentary deposits originating in conjunction with the evolutionary stages of the Baltic Sea have to a noteworthy extent pursued a chronological line [e.g., 67, 68, 57]. In connection with the studies elucidating the evolutionary stage of the Baltic Sea, attention has frequently been drawn also to microfossils contained in the minerogenic material underlying the organic deposits [e.g., 15, 32, 34, 55, 65, 78, 16]. The studies concentrating on properties of the mineral matter have remained relatively few in number. The most notable of them are the ones published by BRENNER [10, 11, 12], AARNIO [2] and PUROKOSKI [60]. The mineralogical composition of the sediments has been studied most extensively by SOVERI [73, 74].

It is only after the decade of the 1950s that, following Brenner, the geotechnical properties of fine-grained deposits have begun to be studied in a significant way [30, 3, 38]. Quite a few of the studies have concentrated on questions of stability [31, 40, 36, 72]. The deformation and consolidation properties of these deposits have likewise begun to attract wide attention [51, 43, 63].

In the Scandinavian research sector, the largest number of studies dealing with fine-grained sediments have been carried out in Norway and Sweden. The majority of the studies have concentrated on the physico-chemical properties of clays; the object of the investigations has been to bring to light such matters as sensitivity and to look into the stabilization of fine-grained deposits [64, 77, 76, 61, 66, 53].

The purpose of the present study was to investigate the material composing fine-grained sediments in Finland from the standpoint of engineering-geology as well as to ascertain along general lines the differences between geological types of sediment with respect to their classification properties (or so-called index properties) as well as, to a certain extent, their strength and consolidation characteristics. The study further considered, in a general way, the correlations between certain classification properties. The distribution of the properties on the basis of grain size was not dealt with. The study was thus designed to arrive at an overall picture of the engineering-geological properties of the fine-grained sediments occurring in Finland.

The methods of study, research material and separate experimental findings have been published in detail in a separate paper [25], which will be cited in the following pages. The analysis of the material and the engineering-geological conclusions will be dealt with in the present paper.

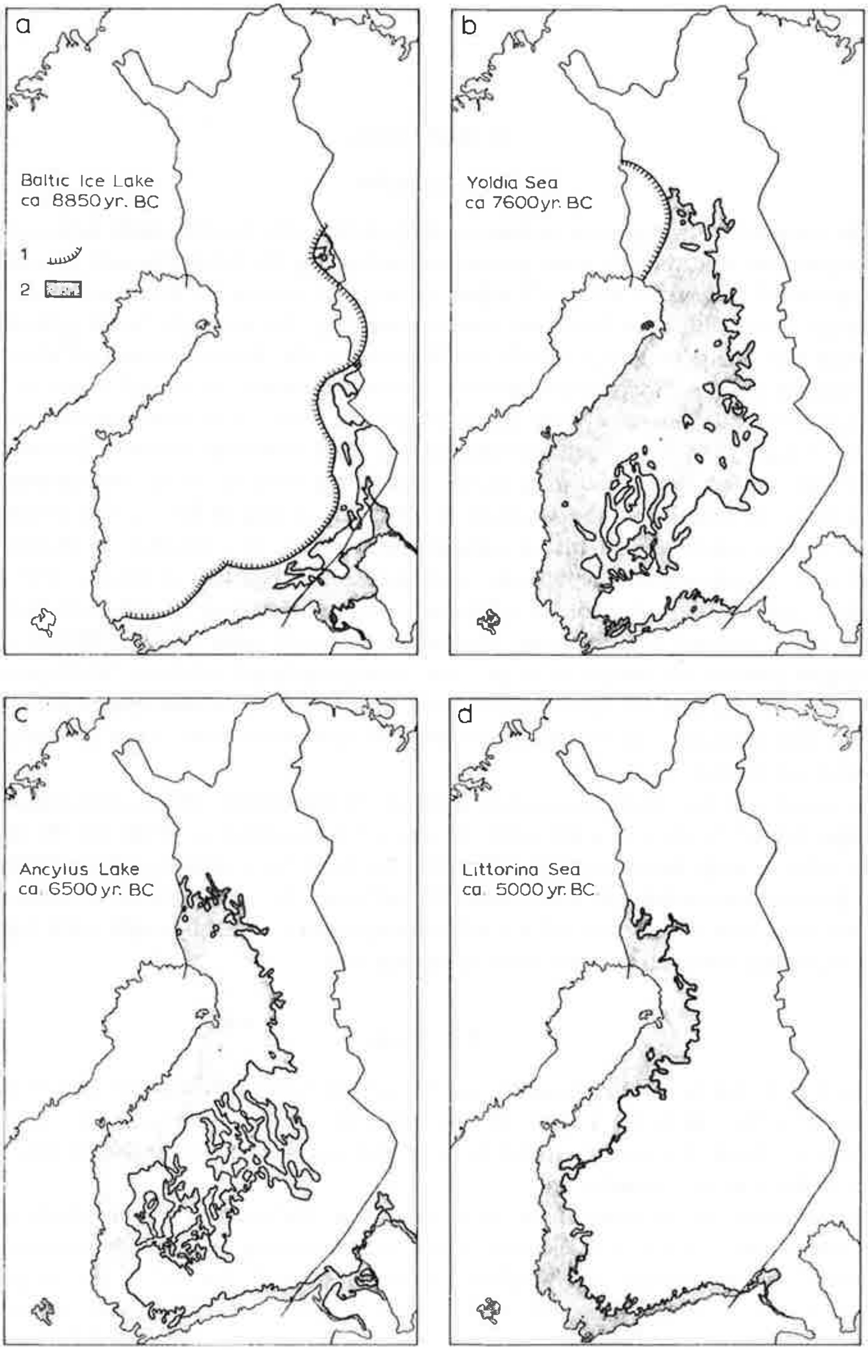

Fig. 1. Main stages in the evolution of the Baltic Sea [33].

1. MATERIAL

1.1 Samples

The samples of fine-grained sediments analyzed for the present study were collected in conjunction with the site investigations carried out by the Geotechnical Laboratory of the Technical Research Center of Finland in response to request from various quarters. Investigations of this kind have been commissioned by, for example, State agencies, like the National Board of Public Roads and Waterways, the National Board of Waters and the National Building Board, municipalities and rural communities as well as private firms. The Geotechnical Laboratory has supplemented the work on its own initiative in those parts of Finland where research material has not been otherwise available. The investigations were carried out in the main in the years from 1966 to 1972. The samples were taken from 48 bore holes, the locations of which are shown in Fig. 2. The undisturbed samples were taken with a piston sampler, with which it is possible to obtain three samples at a time measuring 50 mm in diameter and 170 mm in length. The piston sampling was generally started from the lower part of the dry crust and extended down to the coarse-grained bottom layer. The sampling depths were chosen either to obtain a so-called continuous sample or to produce a sampling length of about 50 cm per meter of depth. In the case of thick deposits, the sampling interval was spaced out to two meters. The samples from the dry crust were generally taken from a test pit and placed in metal containers.

In sampling holes, observations were made of the water level, which in all cases cannot be regarded as the ground-water table. It was not endeavored to determine the ground-water table exactly because of the difficulties involved. In certain exceptional instances, pore-pressure measurements were made. In addition, for the purpose of determining the thickness and the strength of the sedimentary layers, Swedish weight soundings and vane soundings were carried out at the sampling sites.

1.2 Tests

Geological dating of the majority of the sample series studied was carried out by means of pollen analyses. Certain of the series of samples were subjected to diatom analyses to check the dating arrived at by pollen analysis as well as the salinity of the water at the time of sedimentation.

The approximate salinity of the pore water was investigated from a filtrate of the naturally moist sample and distilled water by measuring the electric conductivity. A quantity of the sample was weighed containing 10 g of pore water. The sample was mixed in distilled water in a ratio of 1:4. Half an hour after the mixing, the pH was measured from the suspension. The suspension was then centrifed and filtered with a Membrane sub-pressure filter. The specific conductivity was measured from the clear filtrate with a conductivity equimeter, WTW Type LF54. The measured conductivity

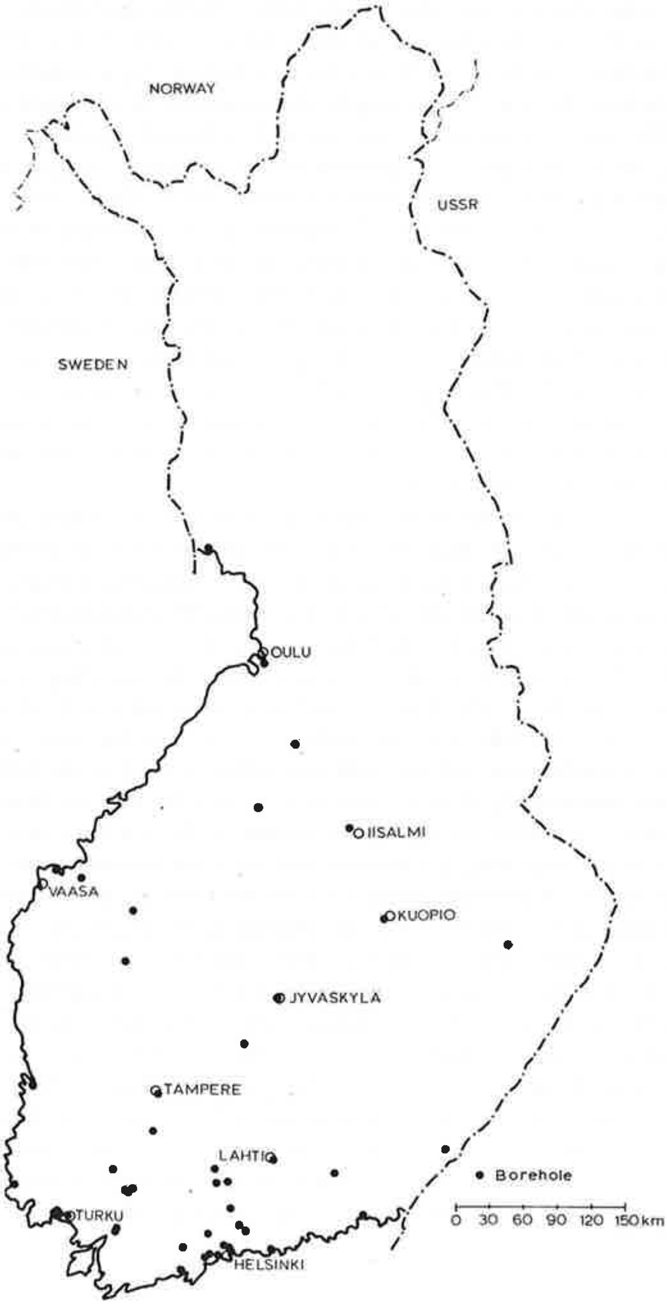

Fig. 2. Locations of the investigation sites.

values were multiplied by five, thereby producing values considered to approximate the original concentration. The salinity was determined by multiplying the conductivity values by a coefficient, the values of which varied from 0,56 to 0,63 [82]. In individual cases, the chloride content of the filtrate was determined. For a comparison of the effect of the preliminary treatment of a sample, the conductivity of certain samples was also determined by squeezing the pore water out with a triaxial apparatus.

To verify the mineralogical composition of the sediments, analyses were carried out at certain sites with an X-ray diffractometer, model PW 1050/30, using CuKα radiation. The velocity of the goniometer was 1° a minute and the velocity of the paper used in the automatic tracer, 80 cm an hour. A grain size of less than 0,02 mm was selected by the aerometric method to prepare slides from the samples. The preparations were made by placing suspension on slides, on which the samples were allowed to dry at room temperature (oriented slides). Some of the mineralogical samples were heated to temperatures of 200°C, 450°C and 550°C. The rise in temperature was about 10°C a minute. The heating was continued for 10 minutes at the temperatures of 200°C and 550°C, but at 450°C the sample was placed in an excitator immediately after this temperature has been reached [74].

The tests consisted for the most part of geotechnical laboratory analyses, done by methods generally used in Finland [79]. The classification properties involved the determination of grain size, humus content, water content, plastic properties, unit weight of solid particles and unit weight of soil. The strength properties were determined in the field by vane sounding and in the laboratory by the unconfined compression test and the Swedish fall-cone test. In conjunction with the vane sounding, a determination of the sensitivity was also made. The consolidation properties were determined by the oedometric device generally used in Finland. It was endeavored to investigate the classification, consolidation and strength properties as well as the pH and salinity of the pore water immediately after the arrival of the samples into the laboratory. The time of investigation was apt in certain cases, however, to be from one to three weeks after the sampling. In the meantime, the samples were stored in a humid room.

In the light of the microfossil analyses and the macroscopic structure of the sediments, the research material was divided into four sediment types: sediments of the Littorina Sea, the Ancylus Lake, the Yoldia Sea and the Baltic Ice Lake. The respective abbreviations used are Li, An, Yo and Ba. This division does not take into consideration all the development of the Baltic Sea in detail but, however, in this connection this has been considered to be sufficient. Further, it shall observed that factors relating to both the climate and the sedimentation basin have been used as basis for this division. The dry-crust layer is separated from the material underlying it primarily by means of the distinct change that takes place in the strength and consolidation properties. The lower boundary of the dry crust cannot, however, be determined unambiguously and objectively in all cases. The statistical analysis of the material was done with a computer.

2. STRATIGRAPHY AND ORIGIN OF THE SEDIMENTS

2.1 General stratigraphy

In the light of the results of the study, the deposits of fine-grained sediment are seen in general to comprise the stratigraphic strata that could be expected on the basis of the geological development of the area investigated. Local hiatuses occur, however, in the strata. In certain instances, some type of sediment is apt to have occurred so thinly that the analytical interval used in the study could not indicate its existence reliably. An Ancylus sediment must be involved, for the type has not been detected for sure in certain occurrence, mainly in the surroundings of Helsinki.

In the district of Raisio, in southwestern Finland, Littorina sediment has been found to be lacking or to be present only locally as a thin layer. Raisio represents an area where the Littorina type of sediment ought to occur fairly prominently compared with other corresponding areas. Moreover, the amount of water during the time of sedimentation ought to have been sufficient, for the height of Littorina I in the area is about +49 m [4] and the maximum height of the surface of the clay deposits approximately +25 m.

The occurrence of hiatuses in the strata is due to, among other things, the fact that the primary sedimentation does not, owing to bottom currents, always take place as uniform layers but is probably concentrated in calm depressions at the bottom. Another significant factor is probably erosion caused by bottom currents in deep waters and wave action in shallow waters; such erosion can remove deposits of sedimentary material. Bottom erosion of this kind still takes place in the Gulf of Bothnia and the Gulf of Finland [80, 28]. In certain cases, also the brevity of the local water stage probably contributes to the smallness of the amount of sedimentary material.

Besides the sedimentation connected with the various evolutionary stages of the Baltic Sea, abundant sedimentation that took place after the contraction of the basin can also be observed locally. In the upper portion of the sample series from Iisalmi, there are seven or eight meters of organic clay with a humus content of between two and six per cent. The pollen content indicates that the sediment was deposited for the most part during the Littorina stage. Both the approximate salinity of the pore water and individual diatom analyses point to a fresh-water lake basin. A corresponding type of ooze layer that had been deposited in a lake basin during the Littorina stage occurs at Nurmijärvi, where the three meters of the upper portion of the sample series investigated are composed of clayey ooze with a humus content of between 7 and 8 per cent.

The youngest sediments, mainly Littorina deposits, are generally situated in valleys and depressions in the terrain. The occurrence of Littorina sediment is a random phenomenon, however, for late-glacial sediments are apt to reach surface of the ground even in valleys. This has been observed by NIEMELÄ as well [57]. The partial lack of the youngest sediments is revealed by, for instance, GRIPENBERG's [26] studies dealing with the basin of the Baltic Sea. In connection with the present study, the most complete series of strata were observed in the cases where the sedimentary area forms a relatively small depression in the terrain. The sedimentation in a bottom depression of this kind is likely to have taken place in peaceful conditions. On the other hand, in connection with long valleys, there occur in certain cases incomplete series of strata difficult to interpret. The reasons for this are probably the afore-mentioned erosion caused by bottom currents and waves and random sedimentation.

2.2 Structure and microfossils of the sediments

The structure of the sedimentary deposits was studied with the unaided eye from half-dry or dry fragments left over from samples subjected to other investigations. In certain instances, samples were taken for the specific purpose of studying structural features.

Littorina sediments are homogeneous in their fundamental structure. However, in many instances, they contain fragmentary remains of, among other things, shells. Tiny shells and their remnants have been found in greatest abundance in samples from the areas of Koivulahti and Vöyri in the region of Pohjanmaa (Finnish Bothnia). In the Salo area, remains of perch (Perca fluviatilis) have been met with in the boundary zone between Littorina and Ancylus sediments [22]. When fresh, Littorina sediment is dark of color – greenish gray or nearly black. Dark, sulphide-bearing sediment occurs quite commonly. In the coastal region at the far end of the Gulf of Bothnia, the color of the sedimentary material is pitch black. The sulphide-bearing black material oxidizes rapidly after sampling and turns gray. Oxidation in a natural state takes place in the dry-crust layer as well as in open, hairlike cracks, which occur deep below the dry crust in situ (Fig. 3). This

Fig. 3. Oxidized cracks (in situ) in Littorina sediment, Sipoo.

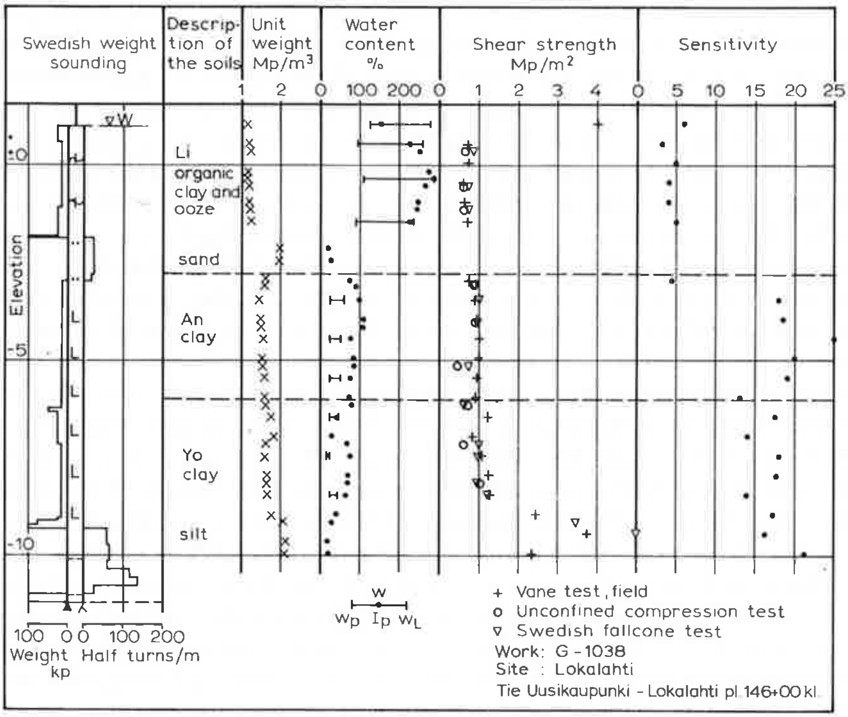

Fig. 4. Classification and strength properties, Lokalahti.

breakage in a natural state has often hampered the investigation of, for example, the strength properties of samples.

Between the Littorina and Ancylus layers, there occurs in many places a coarse-grained layer indicating the regression stage (Fig. 4). The grain size is of the order of sand and fine sand, and the thickness of the layer is in many places from a half to one meter. This layer is at its most typical when the sample series has been taken from the proximity of the edge of a clay deposit or when coarse-grained deposits occur in the near surroundings. The formation of such a layer has depended on the extent to which coarse-grained material has been washed into the sedimentation basin. This coarse layer situated between Littorina and Ancylus sediments occurs also in the Baltic marine areas of the present day [80, 28].

Ancylus sediment is homogeneous in structure or contains only slight microvarving. When fresh, it is generally dark gray in color. From the environs of Oulu to Haapajärvi, however, the color of the sediment is reddish. In southern and southwestern Finland, Ancylus sediment usually contains sulphide bands and spots, which have not been observed in the sediments of the interior.

Yoldia sediments are to some extent homogeneous in general structure and to a certain extent slightly varved, symmictic. This varved structure is in many places in the coastal regions relatively distinct. In the interior, as, for example, in the Jyväskylä–Jämsä area, the varves are exceedingly faint. The variations in structure are probably based primarily on variations in the salinity of the sedimentation basin as well as, in the interior of the country, possibly on the coarseness of grain of the material in shallow-water areas. When fresh, the sedimentary material is generally dark gray. In places, there occur in the upper part of the deposit dark sulphide spots. The Yoldia sediment has been frequently observed to be reddish from the environs of Oulu to Haapajärvi. In the Somero and Loimaa areas, the clay deposited during the Yoldia stage exhibits a brecciated character. The clay is also apt to contain scattered »coarse fragments», an example of which is a sandstone fragment about three centimeters in diameter found in Yoldia clay in the Raisio area (Fig. 5). Coarse material of this kind probably derives from icebergs.

The sediments of the Baltic Ice Lake are in the main distinctly varved in structure. In the portions at the bottom, the varves are in many cases symmictic in type while the upper portion is diatactic. In the coastal region of southern Finland, the lower portion of the deposit has often been observed to have a reddish tinge. In many places, the varves can been seen to have been disturbed. The varves are apt to occur at a slant or to be folded owing to sliding. The structure thus corresponds to the results of the studies of, among others, Niemelä [57]. The sediment of the Baltic Ice Lake at Kouvola exhibits quite distinct layers of a shallow water stage. The fractions are sand and fine sand, and the thickness varies from about 0,5 to 3 meters. The thickness lessens from the edge of the clay area toward the center. These layers representing the discharge stages of the Baltic Ice Lake have been met with as uniform horizons over an area of several square kilometers as well as quite a few kilometers to the north from the investigation site [49]. The exceptional thickness can probably be attributed to the proximity of predominantly sandy material in the marginal portion of Salpausselkä I.

The structure of the sediments has been used, together with investigations of microfossils, in demarcating geological types of sediments. Of the microfossil investigations, pollen analyses constituted the predominant part. On the basis of these analyses, it was ascertained that the amount of pollen in the postglacial deposits, with the exception of the beginning of the Yoldia stage, is fairly high. By contrast, the late-glacial deposits are generally poor in pollen, containing secondary pollen in greater abundance than postglacial sediments [35]. For this reason, the pollen contained in the varved late-glacial sediments has been approached with caution. The boundary between the sediments of the Baltic Ice Lake and the Yoldia stage has therefore been drawn mainly on the basis of the sedimentary structure as well as the variations in the proportional contents of arboreal and nonarboreal pollens.

Diatom analyses were made primarily for the purpose of estimating the original salinity of the sedimentation basin. The determinations were concentrated on sediments dating from the Littorina stage, for few or no diatoms have been met with in older deposits. The period of the Ancylus Lake is clearly reflected, however, in the diatom contents. Yoldia sediments yield in general only slight amounts of diatoms. There are quite a few reasons for the lack of diatoms. According to Niemelä [57], the coldness and turbidness of the water are among the factors that explain this condition. In spite of certain difficulties attending the interpretation of microfossils, they provided a useful criterion, together with the structure of the sediments, in setting the boundaries between different types of sediment for the purposes of the present study.

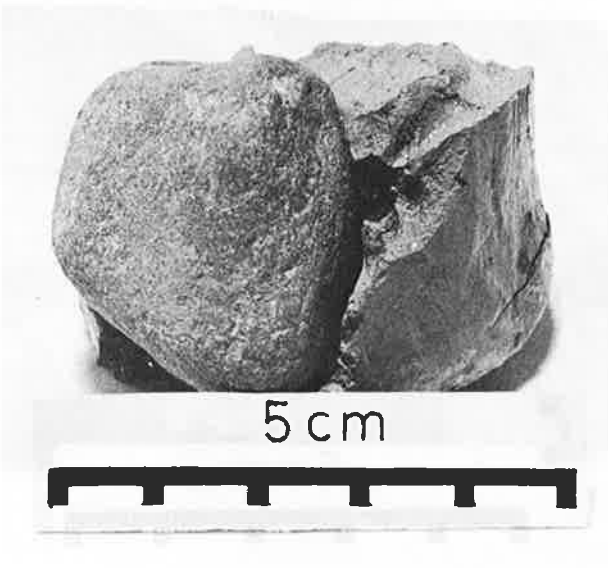

Fig. 5. Fragment of sandstone found in Yoldia clay, Raisio, Siirinpelto, depth 6 m.

2.3 Origin of the sedimentary material

According to the oldest views [e.g., 67] the fine-grained sedimentary material derived from the fine constituents of till, which were washed into the sedimentation basin during the melting stage of the continental ice sheet. The fine-grained material is believed to have eroded off the weathering crust of the bedrock and worked loose off rocks crushed by the ice. Still, taking into consideration the large quantity of clays and the low clay content of the till, such an origin of the sedimentary material is not possible by itself. Consequently, assumptions have been made in favor of a preglacial or interglacial origin of the clay material [e.g., 81, 74, 21, 23].

No interglacial clay deposits have been met with in Finland in situ. On the eastern side of the present national border, however, clayey material has been found that has been identified as of interglacial origin. The most widely known find was made by BRANDER [8] at Rouhiala – a detached chunk of clay dating from the Eemian stage. DONNER and GARDEMEISTER [16] have regarded the clayey material occurring at Somero, in southwestern Finland, as of interglacial origin. Characteristic of the Somero clay is its rather high Corylus and Alnus content, with the diatoms representing at many points a marine stage. In many places, the clay exhibits a brecciated structure. The clayey material has been viewed as being re-deposited Eemian sediment, representing in the main the f and g zones of the Eemian interglacial [16].

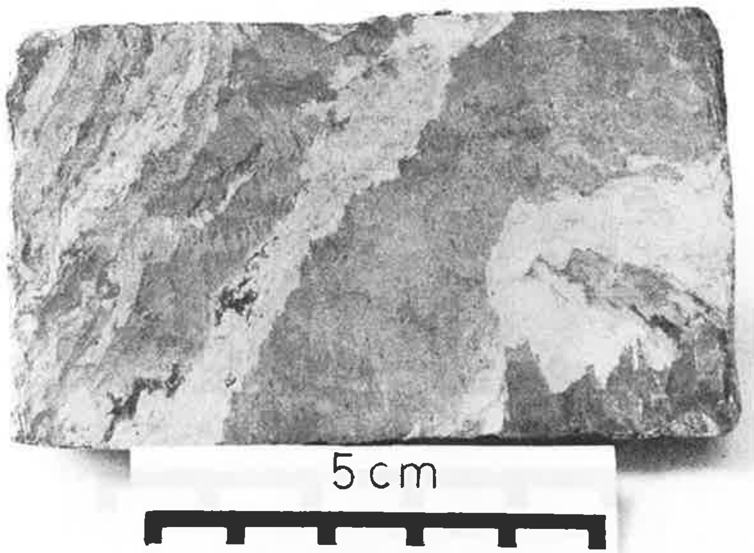

Fig. 6. Brecciated structure in clay, Loimaa, depth 3,8 m.

Of the rest of the sample material included in the present study, a distinct brecciated structure has been met with at, for instance, Loimaa (Fig. 6). This feature cannot be regarded merely as the result of a disturbance caused by sliding. In the light of the results of the investigation made at Somero, the Corylus and Alnus pollen might evidently be taken as an index of Eemian stage clay material in the sediments of the Baltic Ice Lake and the Yoldia Sea. Unmistakable Corylus and Alnus contents would indicate that part of the sedimentary material might date from the Eemian stage or possibly even some older stages.

Of the pollen contents of the sediments studied, Corylus generally accounts for between 2 and 7 per cent. In certain areas, such as Loimaa, Nurmijärvi, Riihimäki, Somero and Vihti, the highest Corylus contents rise to about 10 per cent. The sample series from the parish center of Somero contain between 20 and 30 per cent of Corylus. Some five per cent Corylus contents occur at, among other places, Haapajärvi, Jämsä, Kouvola, Lahti and Tampere. The Alnus contents range correspondingly from five to twenty per cent [25]. The rather large amounts of Corylus and Alnus in these cases were probably not brought about by long-distance flights alone. If the amounts of these pollens are used as indices of old sedimentary material, the majority of the sediments of the Baltic Ice Lake and the Yoldia Sea would consist of interglacial clay material.

This view is supported by, for instance, observations of submorainic clay, which has been regarded as interglacial or interstadial [e.g., 9, 5, 54]. The author has made similar observations in the Pohjanmaa region (Finnish Bothnia). In connection with the investigations of the man-made lake of Hautaperä at Haapajärvi, clay and silt to a minimum thickness of about 0,5 m were found inside the moraine. Overlying these deposits was a till cover about five meters thick. A clay-silt layer of a corresponding type was brought to light at Kestilä in connection with construction work on the Uljua basin. Two meters thick, it was met with under a till bed approximately five meters thick. The till deposit recurred underneath it. A sample taken afterward from the sedimentary layer contained the following pollens: Betula 76 %, Pinus 11 %, Alnus 9 %, Corylus 2 % and Picea 2 %. The pollens yielded by the sample agree with the research findings of, among others, Mölder [54], Aario [1] and Korpela [47].

In the light of the foregoing, it appears as if the material of fine-grained Finnish sediments might to a substantial extent be derived from interglacial or interstadial sediments. The sedimentary material would thereby be involved in a kind of »rotational» process, being redeposited from time to time, at least in part. The latest stage, as of now, would have been the formation of the Ancylus and Littorina sediments from the antecedent deposits of the Baltic Ice Lake and the Yoldia Sea.

The possible preservation of the ancient sedimentary deposits during the advance of the ice sheet cannot be unambiguously explained. The following may be stated as a certain hypothesis: During the interglacial and interstadial stages, the fine-grained sediments were located, as at present, in the lowest places in the terrain. During the advance of the continental ice sheet, the abrasive action of the ice affected the rises in the ground most, while the sheltered parts of valleys sustained less abrasion. In low-lying regions, the ice sheet could have pushed over the sedimentary deposits while they were in a frozen state, and this could have ensured their preservation underneath the glacier throughout the stage of the advance. During the stage of the recession of the ice, the meltwaters flowed into the valleys, soaking the deposits of sediment. Fine-grained material washed out of the till deposits at the same time. This hypothesis agrees in the main with Virkkala's views [81]. The type of sediment richest in clay in southern Finland is the Yoldia sediment, which would thus contain the most old clay material. This might be due to the fact that the clay beds that underlay the ice sheet were not washed by meltwaters to a significant extent until this stage. Taking into account the interstadial stage of the Peräpohjola region [47], the clayey material would have been deposited as sediment before the Yoldia stage at least twice. The assumption about the preservation of the ancient sedimentary deposits underneath the ice sheet is not, however, flawless, which means that the resolution of the question must await the findings of future investigations.

3. MINERALOGICAL COMPOSITION

In view of SOVERI's rather extensive mineralogical material [73, 74], the present study was limited to certain investigations designed to check the data. Their purpose was primarily to compare the mineralogical composition of various areas and various types of sediment qualitatively. For this study, six series of samples were selected, being taken from the following localities: Iisalmi, Joensuu, Jämsä, the rural commune of Kemi, Kouvola and Vöyri. From each series, two samples were studied in the manner mentioned in Section 1.2, involving heating at different temperatures. The X-ray diagrams of the samples are presented in Figs. 7···12, with the exception of one of the samples from Iisalmi, the high humus content of which significantly hampered interpretation.

From the samples from Ohikulkutie, in the municipality of Salo, and the parish center of Somero, the mineralogical composition was investigated more closely in depth than in the case of the other samples mentioned in the foregoing. Three of the samples were heated to temperatures of 200°, 450° and 550°C. The purpose of investigating these samples was to look for possible mineralogical variation in a thick sedimentary deposit and to compare the mineralogical differences between two different types of sample series. The X-ray diagrams of the samples are reproduced in Figs. 13···16.

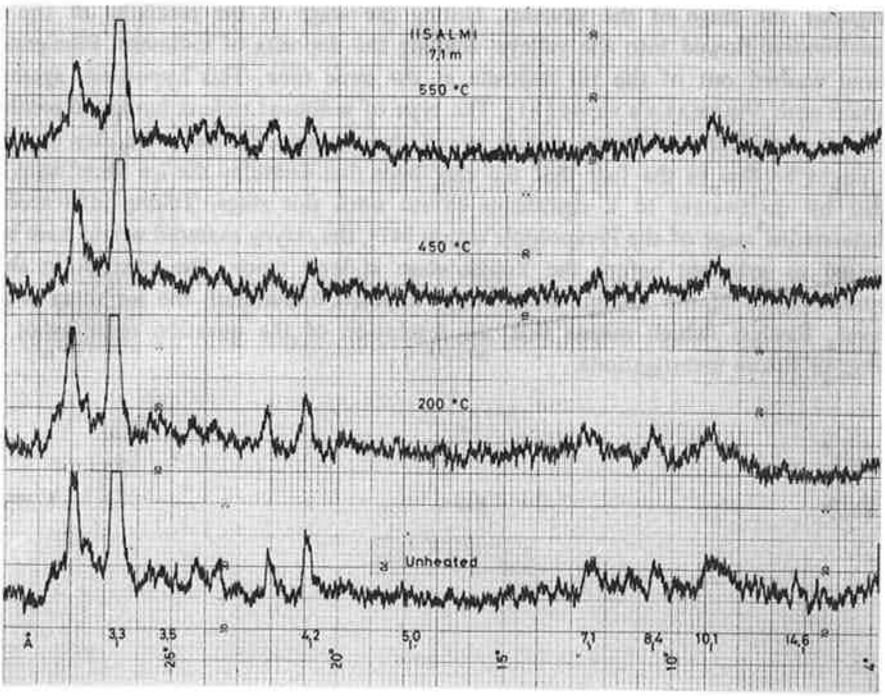

Fig. 7. X-ray diagrams, Iisalmi.

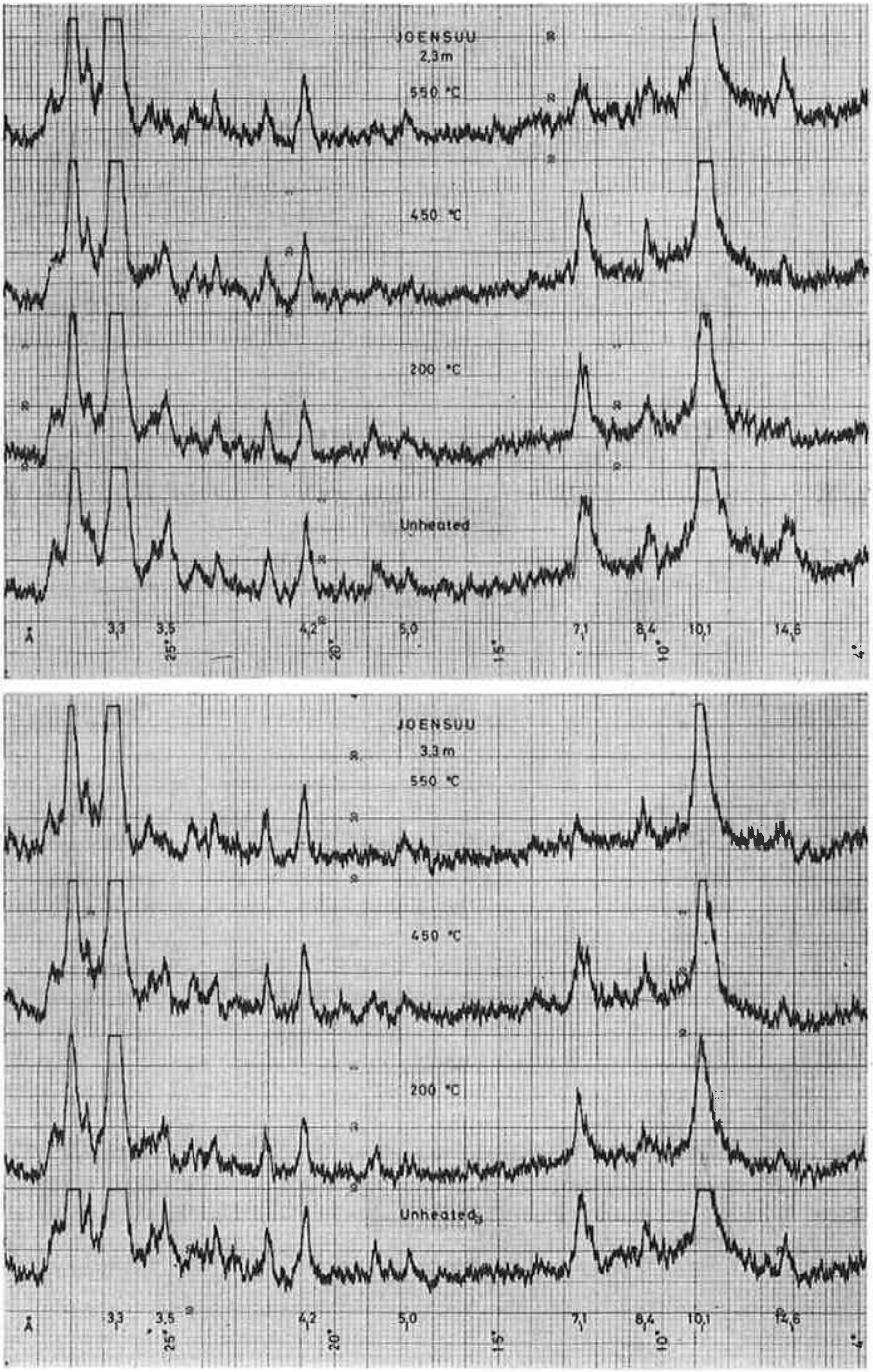

Fig. 8. X-ray diagrams, Joensuu.

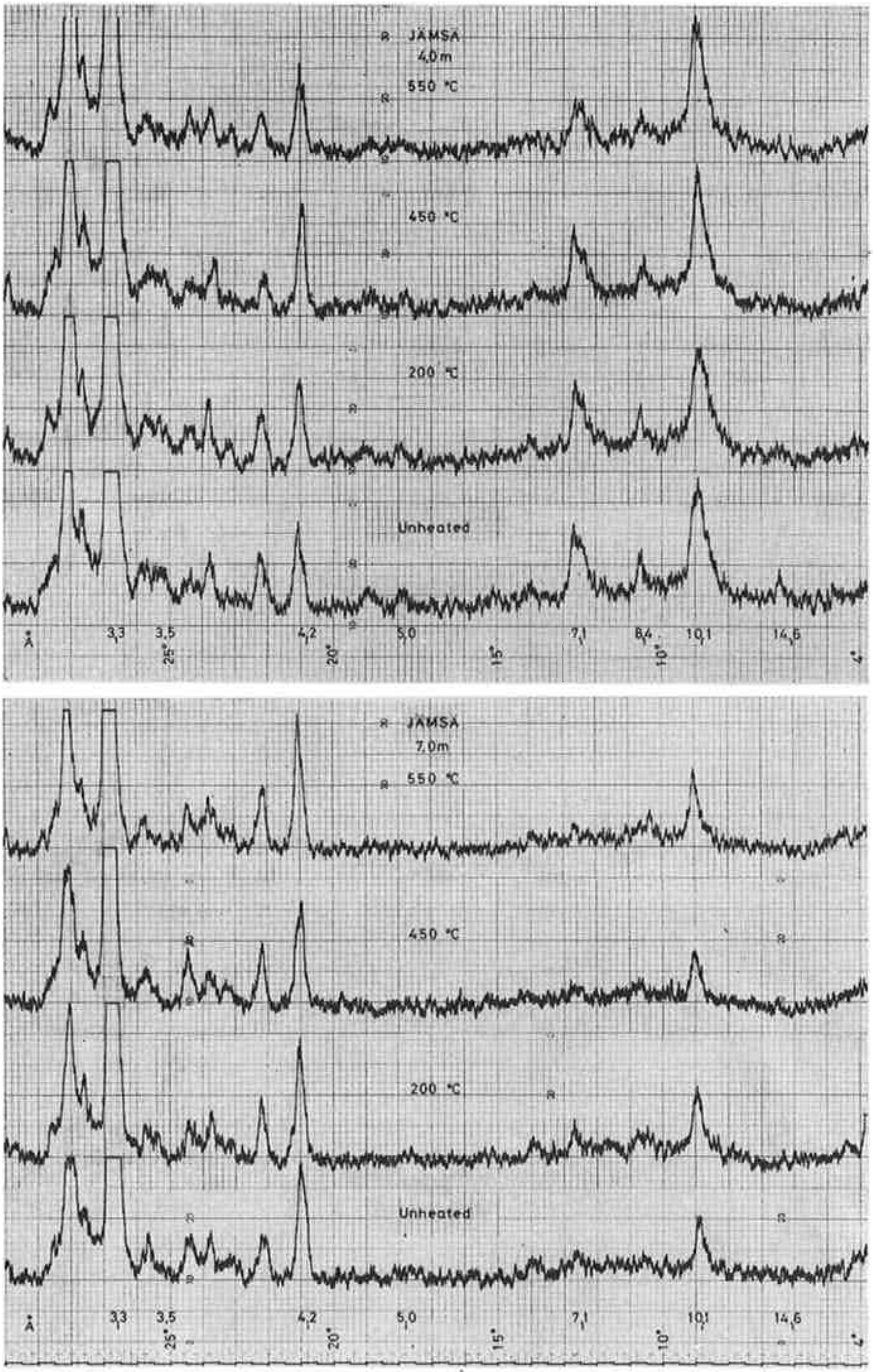

Fig. 9. X-ray diagrams. Jämsä

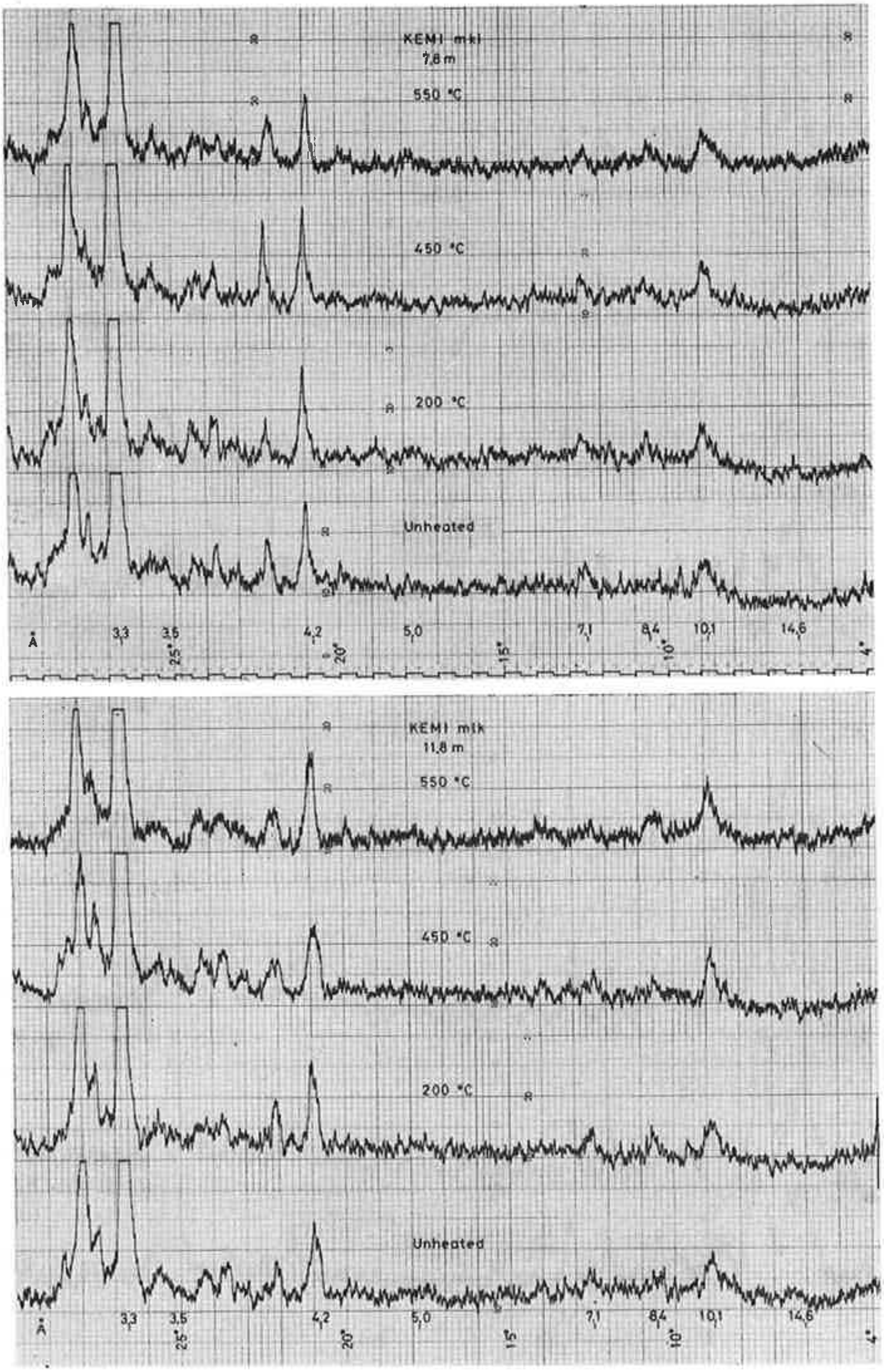

Fig. 10. X-ray diagrams, Kemi (rural commune).

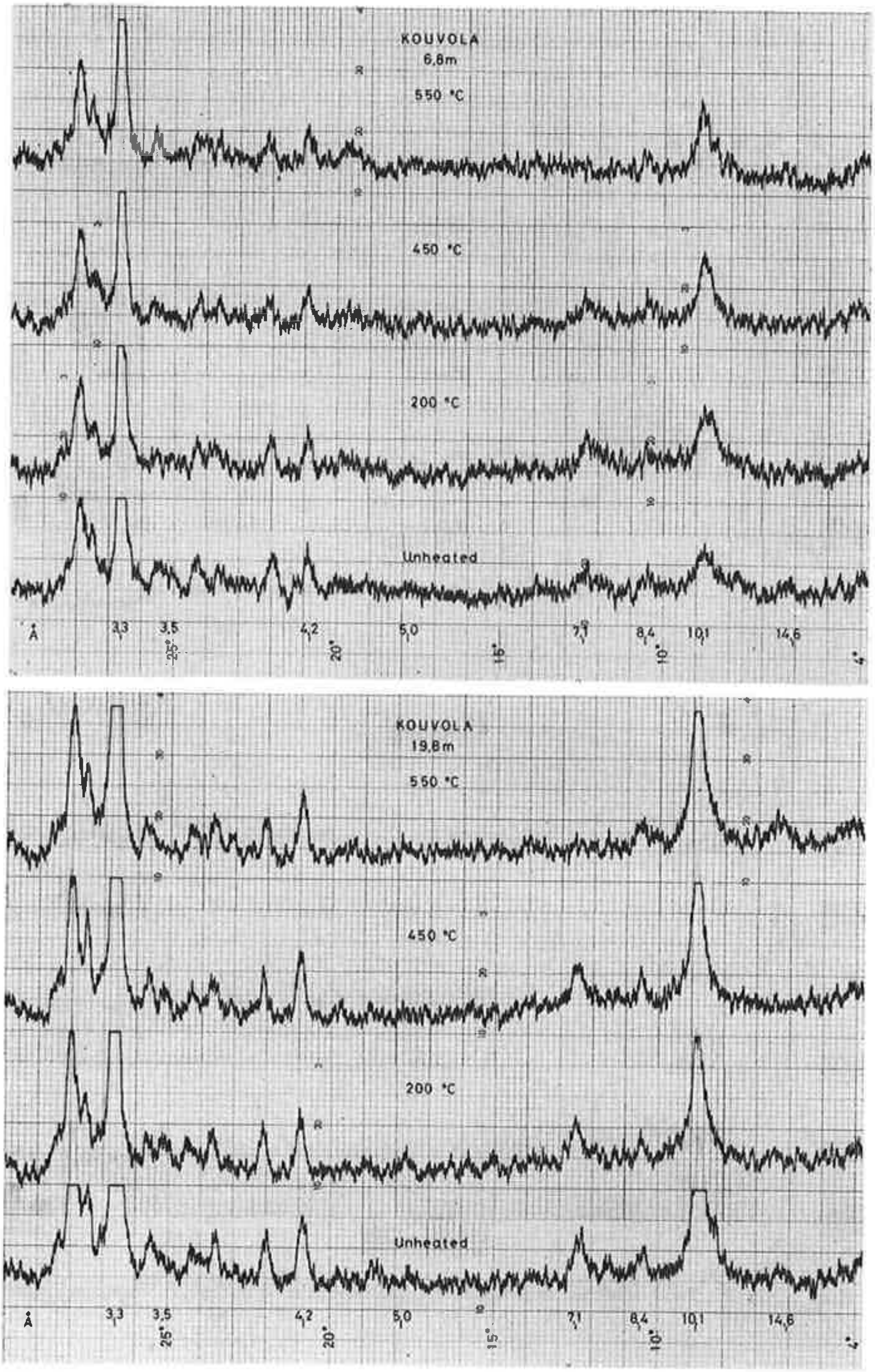

Fig. 11. X-ray diagrams, Kouvola.

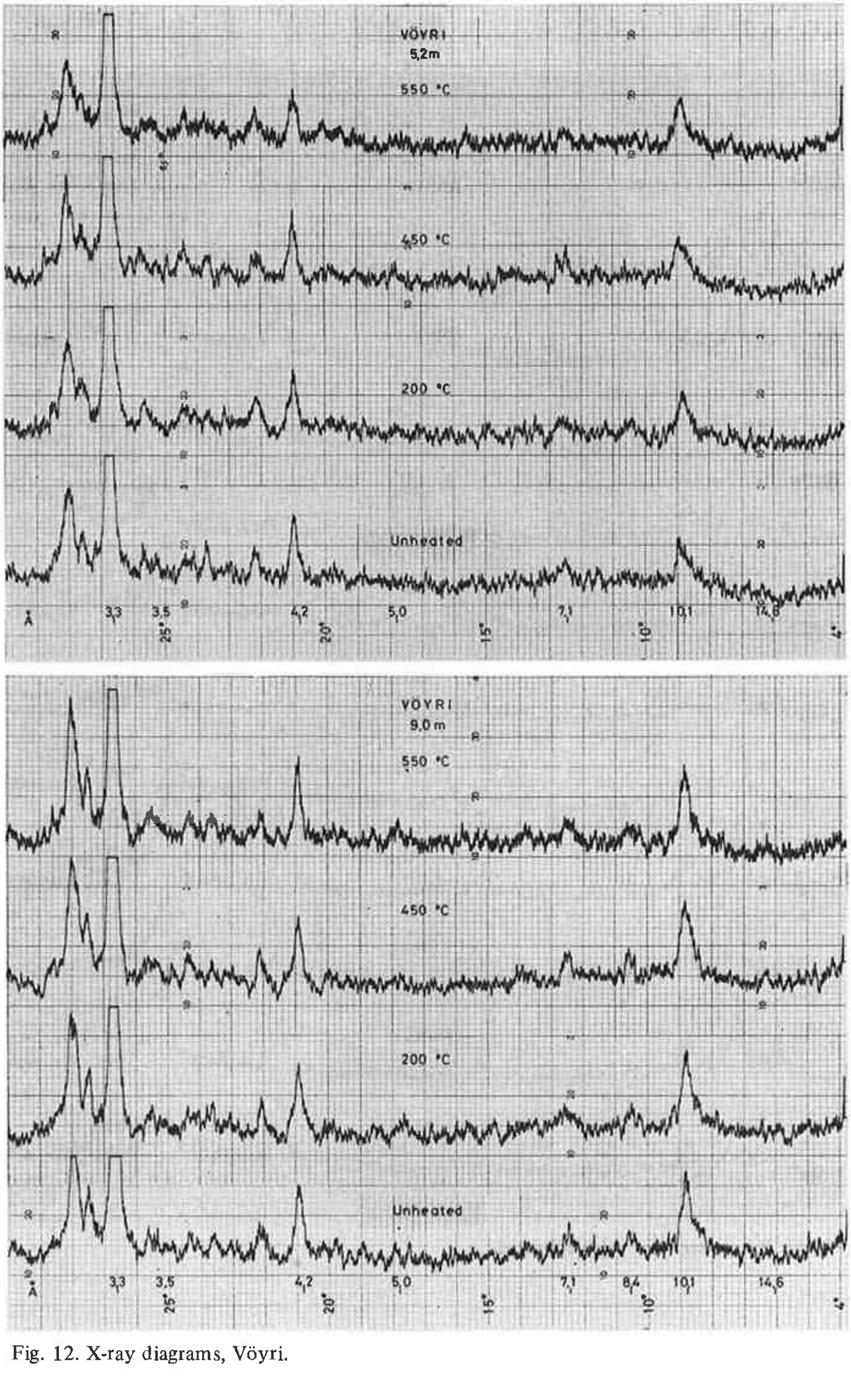

Fig. 12. X-ray diagrams, Vöyri.

Fig. 13. X-ray diagrams, Salo, unheated.

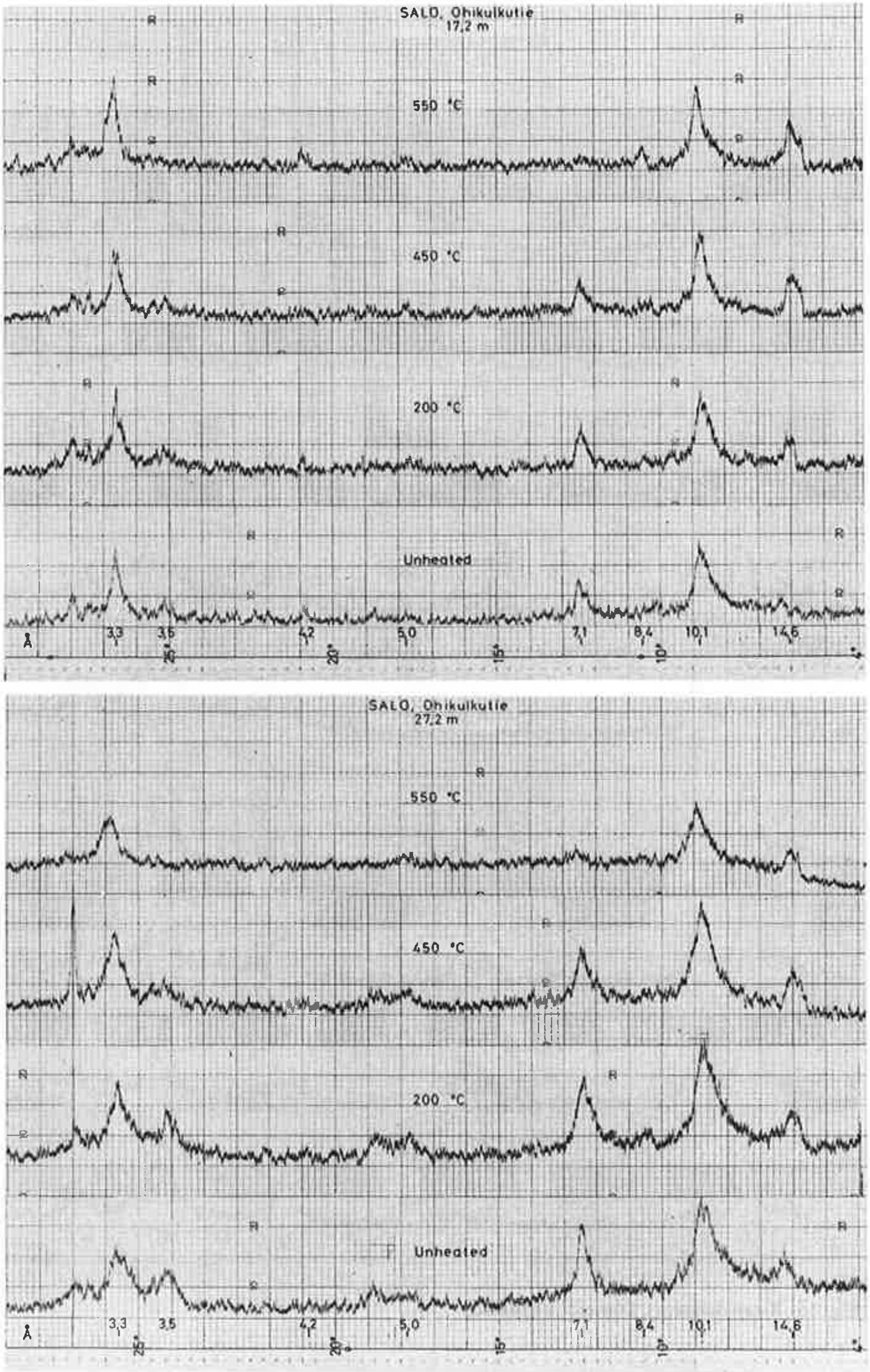

Fig. 14. X-ray diagrams, Salo, heated.

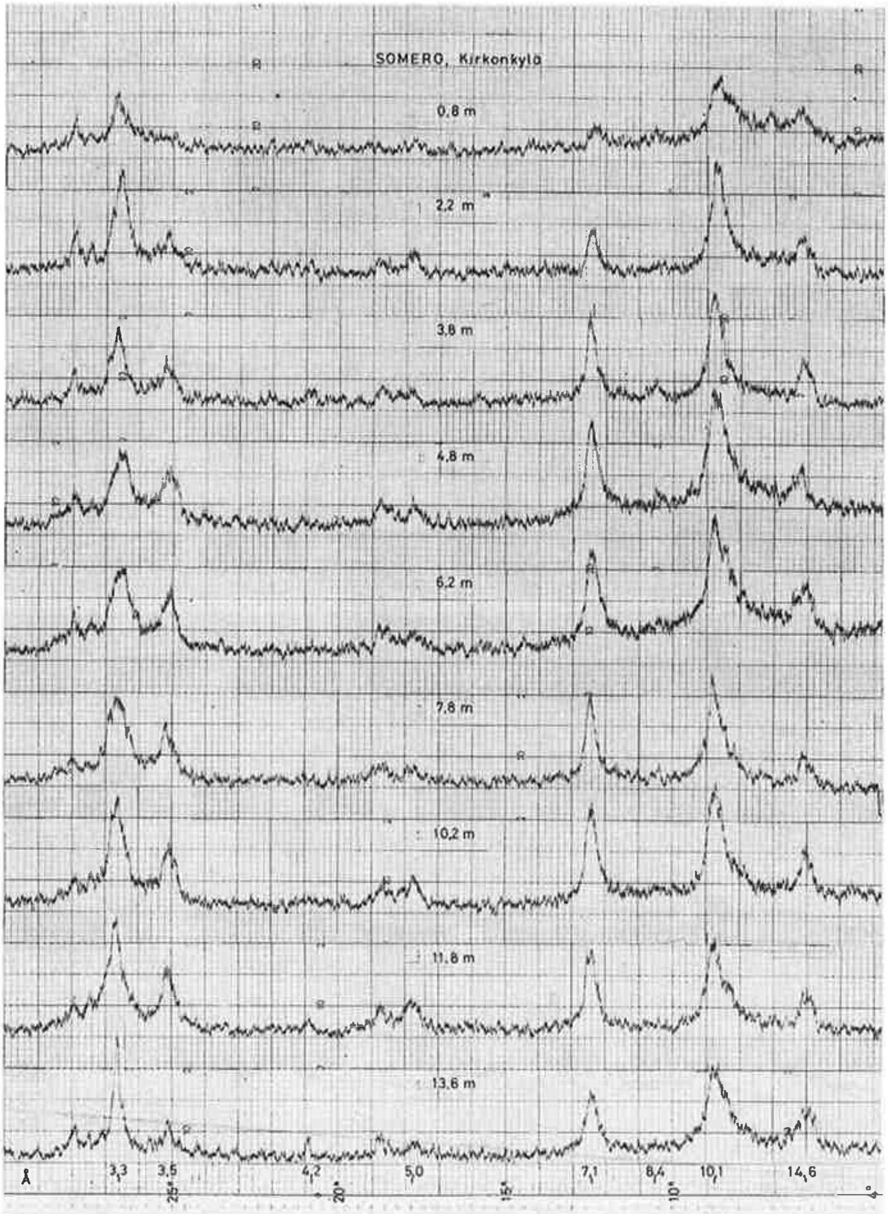

Fig. 15. X-ray diagrams, Somero, unheated.

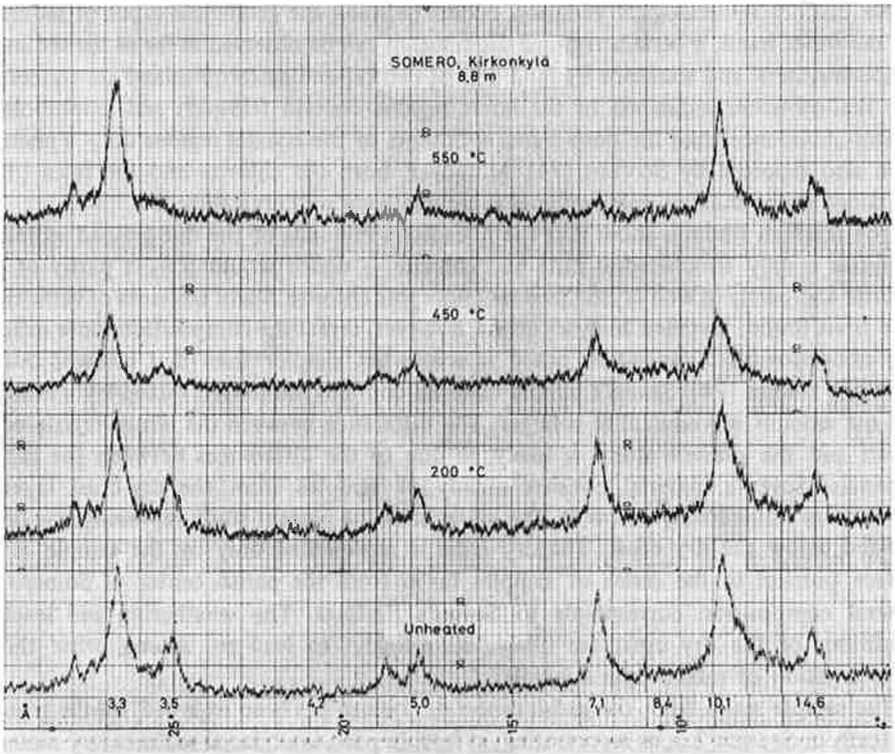

Fig. 16. X-ray diagrams, Somero, heated.

The principal reflections of the prevailing minerals occur approximately with the following Ångström values:

illite	10,1; 5,0 Å
chlorite	14,6; 7,1 Å
vermiculite	13,8···14,5 Å
quartz	4,2; 3,3 Å
feldspars	3,5; 3,25; 3,2 Å
amphibole	8,4 Å

The grainy minerals contained in the samples studied are predominantly quartz and feldspars and to a slight extent minerals of the amphibole group. The main group of micaceous minerals consists of mica and/or illite minerals as well as, in many instances, chlorite. The last-mentioned is often seen to be so-called clay chlorite; but well-crystallized metamorphic chlorite occurs primarily in the shallow-water sediments of central and eastern Finland. Some vermiculite also occurs in small amounts in these sediments. Well-crystallized mixed-layer minerals are not present at all from the practical standpoint in the samples investigated. An isolated exception is the dry-crust sample from the parish center of Somero.

No distinct mineralogical variation occurs between the geological types of sediment. On the other hand, a certain regional distribution can be observed as far as the sediments of southwestern and southern Finland and of central and eastern Finland are concerned. The shallow-water sediments of the latter regions contain feldspars and amphiboles in greater abundance than the deep-water sediments of the coastal regions do – a phenomenon also reported by SOVERI [74]. Moreover, both the chlorite and the mica (illite) contained in the shallow-water sediments are relatively well crystallized.

The research findings show that the micaceous minerals of the fine-grained sediments comprise mainly trioctahedral illite and chlorite – which would consist partly of clay chlorite and partly of well crystallized metamorphic chlorite. Slight amounts of vermiculite have been found. Detailed analyses might, however, reveal the composition more exactly. The mineralogical composition noted is somewhat simpler than that brought out by SOVERI's studies [74]. Soveri's sample material contains, moreover, mixed-layer minerals and the amount of vermiculite is larger. The difference between the results registered by Soveri and the present study is likely to due to the differences between the sample materials. Soveri's material consists mainly of samples from the dry-crust layer or the stratum immediately below it. The material of the present study represents the layers situated below the dry crust. The dry crust is represented only by the sample of the surface portion in the series of samples taken from the parish center of Somero; its mineral composition corresponds to Soveri's findings. The weathering and leaching conditions of the dry crust are likely, accordingly, to lead to, among other things, the formation of mixed-layer minerals.

The sample series from the parish center of Somero has been regarded, on the grounds set forth in Section 2.3, as representing, at least in part, interglacial sedimentary material. Its mineralogical composition, however, is approximately the same as that of the youngest Littorina clay occurring in, for instance, the Salo area. From this the conclusion might be drawn that as early as the interglacial stage the mineralogical composition of the clay material was probably nearly the same as it is now and that at different sedimentation stages only slight changes at most take place. In the climatically cool conditions prevailing in the Nordic countries, a kind of near »mineralogical state of equilibrium» would thus occur, leading at a fairly early stage to the formation of clays of the illite type. If the material of the deep-water sediments of the coastal regions can be regarded as having derived at least in part from interglacial material, then it may be affirmed on mineralogical grounds that in the shallow-water sediments of the interior of the country is reflected the preglacial weathering crust. This is indicated by, for example, the moderately well crystallized chlorite and illite. SOVERI [74] has observed, furthermore, that the sediments occurring in the mica-bearing bedrock areas of eastern Finland contain mica and illite in greater abundance than the sediments of granite areas do.

In the light of the foregoing, it may be stated that the mineralogical composition of the fine-grained Finnish sediments is likely to have been significantly affected by, among other things, the following factors: the interglacial sedimentary material, the preglacial weathering crust, the glacial rock powder, the underlying bedrock, and the leaching and crystallization of the mineral constituents under varying sedimentation conditions.

4. ACIDITY

The acidity (pH) of the fresh sedimentary material beneath the dry crust is in the majority of cases over 7, increasing fairly evenly with depth. In the part at the bottom, diminishing pH-values are often registered, which is probably due to the flow of acid ground water in the coarser material. A clear oxidation is observable in the dry crust when the pH is approximately 0,5···2 units below that underneath the dry crust.

The most basic material beneath the dry crust occurs in sediments of the Baltic Ice Lake, the highest pH-values of which are 9,4 (Fig. 17). About 70 % of the observations reveal the pH in this type of sediment to be over 8, the mean of the measurement results being 8,3 (Table 1). In Yoldia sediment, the pH-values are appreciably lower, the mean value being 7,4. The Ancylus and Littorina sediments do not deviate significantly from the Yoldia sediment with respect to their pH mean values. The variation in the results

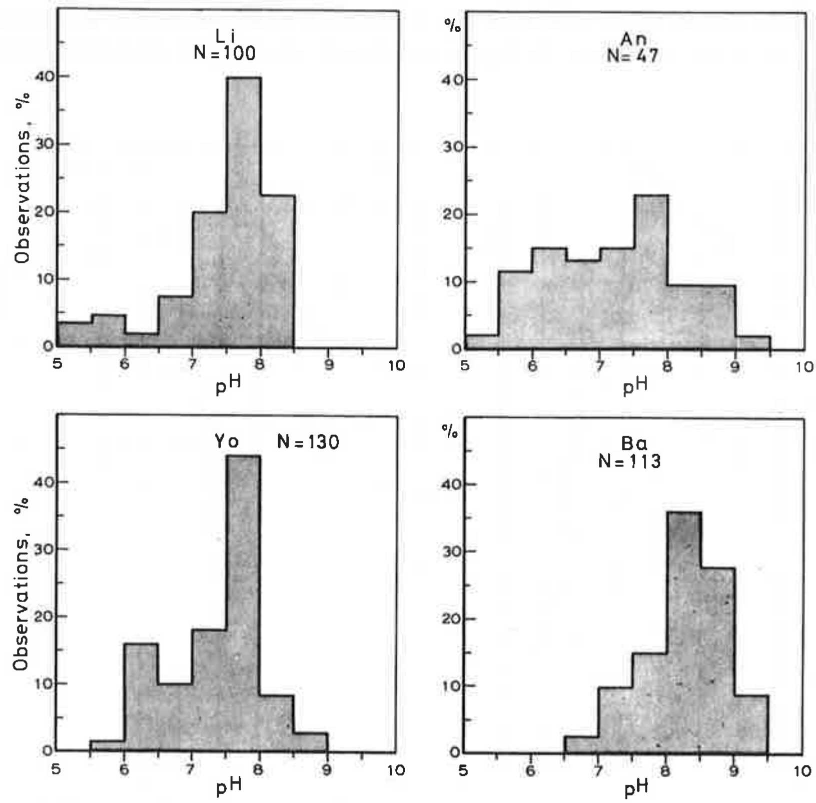

Fig. 17. Acidity distribution in different types of sediment beneath dry crust.

yielded by the Ancylus sediment is significant. The variation is explained by the fact, among other things, that the material composing the Ancylus sediment consists of both the rich clays of the coastal regions and an abundance of silt-dominated shallow-water materials characteristic of the interior of the country. In the latter, owing to the coarseness of the material, more acid conditions prevail than in the rich clays. This is indicated by the measurement observations, for the lowest pH-values in the Ancylus sediments have been measured in the silty deposits of the interior and the highest in the clays of the coastal regions.

The variation in the pH-values of the Littorina sediment is affected by, besides the regional differences, apparently also the oxidation of the samples after they have been collected. The Littorina sediments, which contain saline pore water, are more susceptible to oxidation than the other sediments are. This comes to light when, for instance, the mean acidity values of the different types of sediment in the dry crust and underneath it are compared (Table 1).

The oxidation in different sediment types after the sampling is revealed by Fig. 18, which gives the results of the sample series from Degerby, Inkoo commune. At the initial stage, the pH was measured after the arrival of the samples in the laboratory. A re-measurement was performed about five months after the sampling. In the meantime, the samples were carefully stored in closed containers in a humid room. The new measurement reveals strong oxidation (2···3 pH-units) in the layers in which the salinity of the pore water is highest. In layers with lower salinity, the oxidation during this

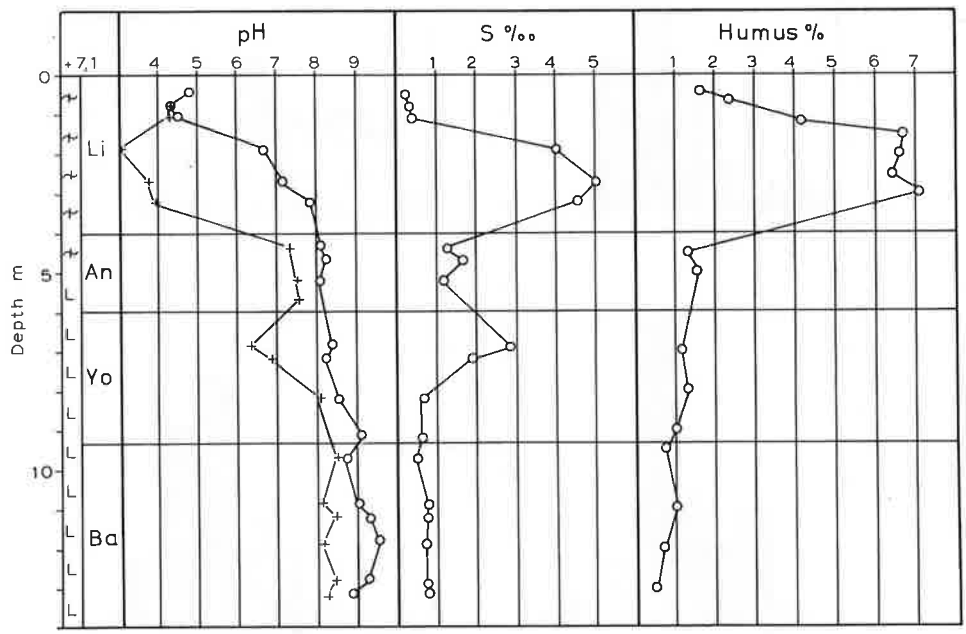

Fig. 18. Change in acidity in connection with storage of sample, Inkoo, Degerby. Smaller pH-curve (judged by its numerical value) was measured about 5 months after the sampling.

Table 1. Acidity means and standard deviations in different types of sediment.

Acidity	Sediment type			
	Li	An	Yo	Ba
pH in dry crust	5,4 ± 1,0 N = 20	6,6 ± 0,7 N = 12	7,1 ± 0,4 N = 16	7,3 ± 0,5 N = 12
pH beneath dry crust	7,6 ± 0,6 N = 100	7,3 ± 1,0 N = 47	7,4 ± 0,7 N = 130	8,3 ± 0,6 N = 113

interval was about 0,5···1,5 pH-units. The change in pH-values was on the same order in JERBO's investigations [35].

It is not possible on the basis of the pH-values registered by fresh sedimentary material to draw conclusions regarding the boundaries between the different types of sediment. On the other hand, as the oxidation is different in different types of sediment, their boundaries come to light at least in part, as a consequence of oxidation. In view of this fact, it would be most advantageous to measure the pH from dry, oxidized specimens.

5. SALINITY OF PORE WATER

The salinity of pore water was studied by measuring the conductivity of water filtered from a suspension of a naturally moist sample and distilled water. The results obtained in this way from certain samples with a high salinity were compared with the salinity values of pore water squeezed out of the samples. The results show that the salinity of pore water thus squeezed out is apt in individual cases to be 20···30 per cent higher than in a sample measured from water filtered out of a suspension. On the other hand, the determination of salinity from squeezed-out pore water cannot be considered completely reliable, either [18]. Taking into account the matters mentioned, the salinity values presented in this connection must be regarded as only approximate. The aim was to gain a general idea of the salinity of present pore water contained in fine-grained sediments and of its relative distribution in different types of sediment.

The distribution of the salinity values measured beneath the dry crust is shown in Fig. 19. The highest salinity values appear in Littorina sediments, in which, however, the variation is exceedingly significant (Table 2). In this type of sediment, there occurs both high salinity of the pore water and salt contents indicating the existence of brackish water. By contrast, the sediments of the Ancylus, Yoldia and Baltic Ice Lake stages yield results that predominantly indicate a salinity of less than 1 per mil. In all these sediments, however, there occur individual cases of high salinity values.

In the dry crust, the salinity of the pore water is very slight, owing to the effect of leaching of the surface waters (Table 2). But here, too, the same general distribution is

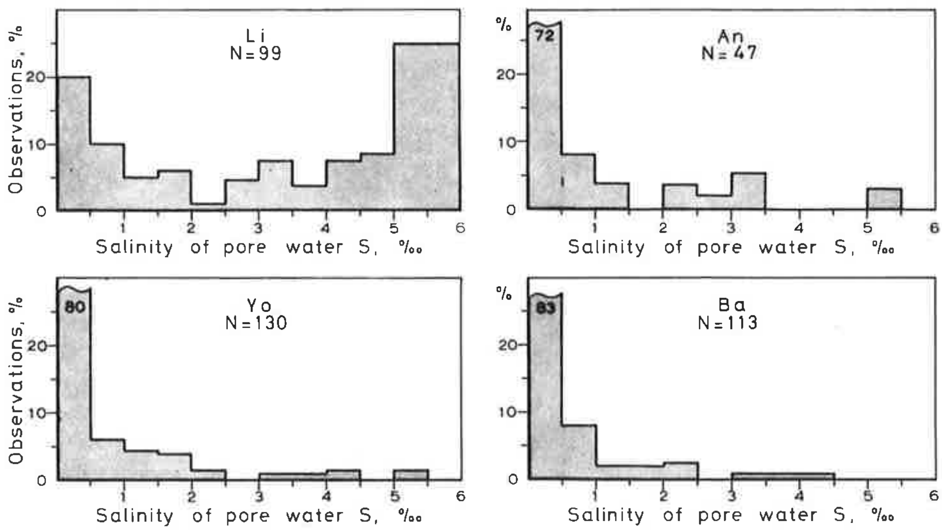

Fig. 19. Distributions of salinity of pore water in different types of sediment beneath dry crust.

Table 2. Pore water salinity means and standard deviations in different sediment types.

Salinity S	Sediment type			
	Li	An	Yo	Ba
S in dry crust, ‰	0,80 ± 1,55 N = 20	0,13 ± 0,10 N = 12	0,13 ± 0,1 N = 16	0,12 ± 0,06 N = 11
S beneath dry crust, ‰	3,32 ± 2,40 N = 99	0,91 ± 1,43 N = 47	0,52 ± 1,0 N = 130	0,42 ± 0,71 N = 113

to be observed as beneath the dry crust; the salinity of the dry crust of the Littorina sediment is markedly higher than in the other types of sediment, in which the mean salinity values are nearly the same.

In the Littorina sediments, the maximum salinity values occur generally in the bottom portion of this sedimentary layer. At the same depth, the humus content is at its highest. The highest salinity values measured in Littorina sediment have been about 8 per mil. These have been registered in the sample series from Salo, in southwestern Finland. Eastward along the coast of the Gulf of Finland, there takes place a diminishing in the maximum values. A corresponding observation is to be made as one moves up the shore of the Gulf of Bothnia northward from the southwest coast. At Inkoo the maximum values measured approximate 5 ‰, at Koivulahti 5···6 ‰, and in the Kemi area 4,5···5,5 ‰ [25]. A corresponding regional decrease in salinity is reported by Jerbo [35]. The occurrence of the highest salinity values in southwestern Finland is a consequence of the passage of saline sea water during the Littorina stage into the basin of the Baltic Sea through the Danish straits. To the north and east from southwestern Finland, the fresh waters flowing from the mainland diluted the salinity of the sea water.

The salinity measured from the pore water has in certain cases been checked by means of diatom analyses. A high pore-water salinity is generally attended by diatoms characteristic of saline and brackish water, as illustrated in, for example, Figs. 20 and 21. The salinity of the pore water measured from the Salo sample series is about 6···8 per mil and, correspondingly, from the Inkoo series about 4···5 ‰. The same correlation appears in the sample series from the rural commune of Kemi, in which the salinity of the pore water increases with depth from a value of approximately 4 ‰ to ca. 5 ‰. The rise in salinity values with depth is reflected most prominently in this case by the diatom contents (Table 3).

In sample series G-806 from Sipoo, the salinity of the pore water in the Littorina sediment was measured to be 1···2 ‰. The diatoms indicate the prevalence of brackish-water, small-lake and halophilous forms (Table 4).

The salinity of the pore water in the Lapua sample series varied between 0,4 and 0,7 per mil. The diatoms, however, indicate a distinctly higher salinity (Table 5). In this instance, it appears as if the salinity of the pore water had lessened markedly owing to diffusion or leaching. The investigation site is located in the flood area of Lapua. One reason for the loss of salinity is apt therefore to be the annual flood of fresh water in this region, with part of the water being soaked up by the ground. This explanation is supported by the low pH-values registered for the upper part of the sample series.

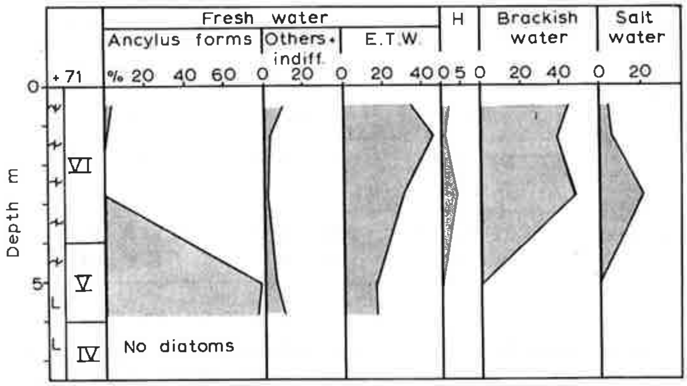

Fig. 20. Diatoms, Inkoo, Degerby.

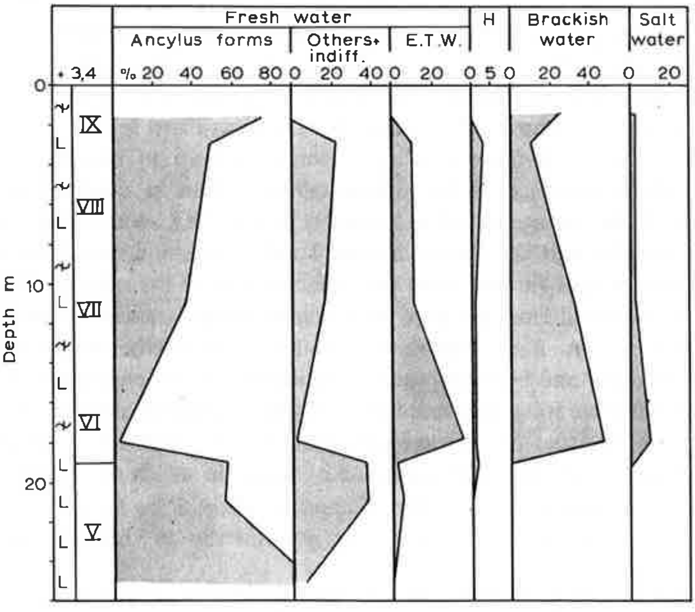

Fig. 21. Diatoms, Salo, Ohikulkutie.

In certain cases, slight pore-water salinities have been measured on the coasts in typical Littorina sediment. Sample series of this kind have borne mainly the labels of Karhula, Lokalahti and Turku [25]. The salinity values measured have been about 0,1···0,5 ‰. The diatom analyses indicate that the sedimentation did not take place in salty water, for brackish-water and fresh-water diatom forms generally prevail (Tables 6···8).

Table 3. Diatoms, rural commune of Kemi.

Depth m	Fresh water, % Ancylus forms	Others + indiff.	E.T.W.	Halo-philous, %	Brackish water, %	Salt water, %
6,9 (Li)	1	6	1	3	62	27
9,9 (Li)	1	2	1	3	43	50
12,7 (Li)	0	1	1	0	36	62

Table 4. Diatoms, Sipoo.

Depth m	Fresh water, % Ancylus forms	Others + indiff.	E.T.W.	Halo-philous, %	Brackish water, %	Salt water, %
3,2 (Li)	5	24	2	10	50	9
4,8 (Li)	2	26	5	15	51	1
7,2 (Li)	1	17	4	11	61	6
10,0 (An)	29	68	1	0	2	0
11,8 (An)	89	8	2	1	0	0

Table 5. Diatoms, Lapua.

Depth m	Fresh water, % Ancylus forms	Others + indiff.	E.T.W.	Halo-philous, %	Brackish water, %	Salt water, %
2,0 (Li)	3	3	1	1	61	31
3,2 (Li)	4	3	1	1	40	51
4,8 (Li)	1	1	0	1	73	24
8,2 (An)	76	22	0	1	1	0

Table 6. Diatoms, Karhula.

Depth m	Fresh water, % Ancylus forms	Others + indiff.	E.T.W.	Halo-philous, %	Brackish water, %	Salt water, %
1,2 (Li)	1	30	2	10	42	15
2,3 (Li)	1	20	6	7	50	16
5,4 (An)	51	38	11	0	0	0
6,9 (An)	84	8	6	2	0	0

Table 7. Diatoms, Lokalahti.

Depth m	Fresh water, %			Halo-philous, %	Brackish water, %	Salt water, %
	Ancylus forms	Others + indiff.	E.T.W.			
0,9 (Li)	1	58	4	4	32	1
1,8 (Li)	1	42	6	6	44	1
3,1 (Li)	0	23	10	7	51	9
6,1 (An)			No diatoms			

Table 8. Diatoms, Turku.

Depth m	Fresh water, %			Halo-philous, %	Brackish water, %	Salt water, %
	Ancylus forms	Others + indiff.	E.T.W.			
2,0 (Li)	55	23	3	2	15	2
3,4 (Li)	3	8	22	5	60	14
4,4 (Li)	3	6	9	2	58	22

The results show that in many sample series the salinity of the pore water of the Littorina sediment amounts to a value of several units per mil, which is also in agreement with the diatom analyses. On the other hand, there occur instances where both methods indicate low salinity. In addition, observations have been made that the salinity of the pore water had significantly decreased after the time of sedimentation.

The maximum salinity values measured correspond approximately to the present salinity of the surface water in the marine area in question. In many cases, the quantity of salt-water diatoms in the bottom part of the Littorina sediment is markedly greater than in the surface part (it has often been observed to be twice as large). This would support the classic view that the salinity of the Littorina Sea might at first have been approximately twice as high as the present salinity of the Baltic Sea. Thus the salinity of the sea water would have been on the order of magnitude of 10···15 ‰ in the area of southern Finland at the beginning of the Littorina stage. According to the research results, a weakening of the salinity of the pore water took place afterward, changing the salinity of the pore water significantly in certain localities (e.g., Lapua).

In the light of findings, the further observation was made that Littorina sediments were deposited in the coastal areas of southwestern and southern Finland also in bodies of slightly brackish water. These areas, like Lokalahti and Karhula, are located at the mouths of sequences of valleys running shoreward from the mainland interior. During the sedimentation stage, a flow of fresh water took place from the interior of the mainland, diluting the salinity of the sea water. Corresponding variation in salinity is revealed by JERBO's investigations [35]. The sampling sites indicating maximum salinity are located in most cases, on the other hand, in flat, open terrain or in depressed areas.

In the boundary zone of the Ancylus and Littorina sediments, the salinity of the pore water varies in certain cases by leaps (Fig. 22). The location of the boundary can in such cases be clearly perceived. In many places, however, the change in salinity is so gradual that the line of demarcation between these sediments cannot be detected in terms of the salt content. This fact is also brought out by ERICSSON's research [18]. Both cases are apt to occur in sample series taken from points situated close to each other in the same area. Thus local factors are apt to have a marked effect on the relative salinities of different types of sediment.

Considerable regional variation is to be noted in the salinity of the pore water of Ancylus sediments. In the southwestern and southern coastal regions, there occur salinities registering valus on the order of several units per mil. By constrast, in the interior of the country, the salt content is generally less than 0,2···0,3 ‰. A primary factor contributing to the occurrence of this conspicuous disparity is the salinity difference prevailing during the time of sedimentation. In deep water in the coastal regions of the present, the salinity dating back to the Ancylus stage has been higher than in the shallow-water areas of the interior. Another significant factor is probably diffusion, as a consequence of which the salinity of the Ancylus sediment of the coastal regions has increased from the overlying Littorina sediment.

The salinity of the Yoldia and Ancylus sediments changes almost without exception by degrees. This indicates an alteration in salinity that has taken place at an even rate, or diffusion. Only in the Inkoo sample series can a marked increase in salinity be perceived in shifting from Ancylus sediment to Yoldia sediment (Fig. 22).

In Yoldia sediment there occurs the same regional variation in salinity as in sediment of the Ancylus type. The highest pore-water salinity values measured occur on the southwest coast, the maximum values having been registered in the Salo area, 2···4 ‰. In the light of the observation material, the salinity decreases in an easterly direction. The maximum values measured have been: at Inkoo 1···3 ‰, Sipoo 1···1,5 ‰ and Kouvola 0,5···1 ‰ [25]. The effect of diffusion and leaching on the values cited is difficult to assess; but there are cases in which the part played by these factors is evident.

The occurrence of the highest salinity on the southwest coast must be regarded as a consequence of the fact that during the Yoldia stage salt water passed through the strait formed in the lowland of central Sweden into the Baltic basin. The maximum values have been registered in the upper part of this type of sediment at, for instance, Raisio and Inkoo. The highest salinity of the close of the Yoldia stage may be regarded as being due to the fact that at that time the continental ice sheet with its fresh meltwaters had receded farther north. In addition, the eustatic rise of the ocean surface broadened and deepened the straits connecting the Baltic Sea with the ocean.

Deviating from the rather high salinity of the coastal regions, the salinity of the Yoldia sediments is slight in the interior of the country. In the majority of cases, it is approximately 0,1···0,3 ‰. In the Yoldia sediments with a predominantly silt content, the salinity of the pore water measured has generally been even lower (under 0,1 ‰). The low salinity of the sediments of the interior is affected by, among other things, the fact that they have been deposited close to the edge of the receding continental ice sheet. As a result, the fresh meltwaters have been able to affect the composition of the water of the sedimentation basin significantly. In addition, leaching in, especially,

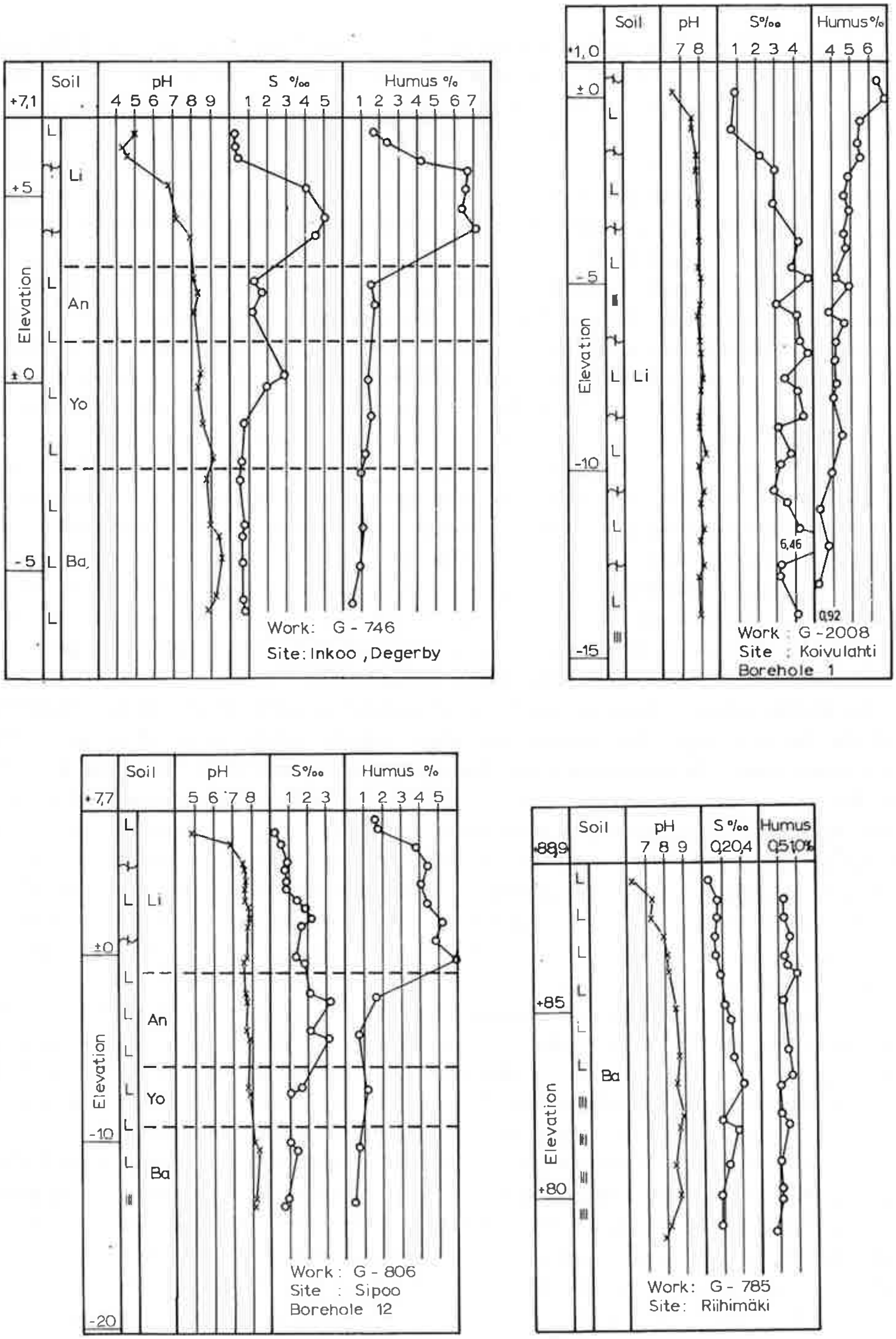

Fig. 22. Results of measurements of acidity, pore-water salinity and humus content in different types of sediment.

the silt-rich sediments has been apt, owing to the greater permeability in comparison with that of clay, to reduce the original salinity.

In the sediments of the Baltic Ice Lake, the salinity of the pore water is continuing to decrease in comparison with the Yoldia sediment. In the majority of cases, the salinity of the pore water in the sediments of the Baltic Ice Lake corresponds to the salinity of the Yoldia sediments of the interior, being approximately 0,1···0,3 ‰. On the southern coast, there occur higher values in this type of sediment, too, than elsewhere (0,5···1 ‰). This is likely to be an effect of the difference in salinity during the period of sedimentation or to diffusion from higher levels. In certain cases, diffusion is an evident phenomenon in places subject to the effect of sea water at present.

The salinity values measured in the pore water cannot be regarded as absolute. According to comparative tests, the salinity of squeezed-out pore water is likely in some instances to exceed the values cited by 20···30 %. In seeking to arrive at an accurate paleo-salinity, one should, according to Ericsson [19], measure the Mg and Ca contents of the pore water. The measurement results clarify, however, the general picture in relative terms as to the salinity of the pore water of different types of sediment as well as the salinity of the different stages in the avolution of the Baltic Sea.

Significant secondary factors affecting the changes in the salinity of the pore water are diffusion and leaching. As a consequence, there takes place a notable decrease in salinity or a shift in salinity to other layers. Furthermore, streams of fresh water flowing from the mainland during the sedimentation period brought about changes in the salinity of the sea water. In addition, mention might be made of contributing factors such as topographic conditions and the permeability of the sedimentary material. All in all, the salinity of the pore water contained in the fine-grained sediments must be regarded as a complicated problem, with many local factors making it difficult to gain even a clear general picture of the situation.

6. DISTRIBUTION OF CLASSIFICATION PROPERTIES

6.1 Classification properties

Classification properties (index properties) mean, according to geotechnical soil classification [46], those properties of soils that represent the composition of the deposits in the main and on the basis of which the soils can be divided with respect to their material constituents and their construction-technical behaviour into fairly uniform classes. On the basis of the classification properties, the geotechnical characteristics of the soils, such as the strength, consolidation and hydraulic properties, can be estimated. The classification properties to be examined in the following are the clay content, humus content, water content, plasticity, unit weight and unit weight of solid particles. Dealt with in this connection will be, in addition, the fineness number and the void ratio, which are not generally included among the classification properties.

The purpose of the part of the study dealing with classification properties was to determine the correlation of these properties with the geological structure of the sediment – in other words, to determine how these classification properties are distributed in the different types of sediment. In addition, it was endeavored to gain a general idea of in regional (geographical) distribution of these properties in Finland.

6.2 Clay content

The distribution of the clay content in different sediment types underneath the dry crust is shown in Fig. 23. The mean clay contents and standard deviations appear in Table 9.

On the basis of Fig. 23, the Littorina sediment can be seen to contain both clay-rich mineral matter and predominantly silty material. Clay-rich material occurs generally in southern and southwestern Finland, as also HEINO's findings [28] in the marine area in the environs of Turku show. The clay content of the Littorina sediments in the coastal region of the Gulf of Bothnia is generally on the order of 15···30 %. In certain sample series, the clay content decreases toward in surface. This may be taken a consequence

Table 9. The clay content (<0,002 mm) means and standard deviations in different types of sediment.

Clay content Sa	Sediment type			
	Li	An	Yo	Ba
Sa in dry crust, %	33 ± 16 N = 23	41 ± 14 N = 14	53 ± 27 N = 17	47 ± 18 N = 22
Sa beneath dry crust, %	40 ± 19 N = 143	42 ± 20 N = 63	64 ± 25 N = 148	34 ± 24 N = 146

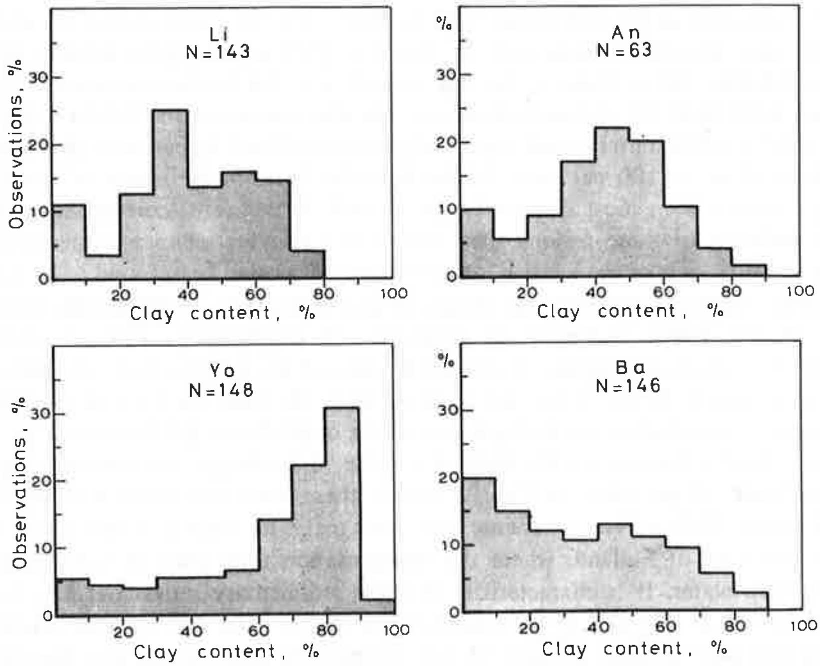

Fig. 23. Distributions of clay content in different types of sediment beneath dry crust.

of the water becoming shallow owing to land uplift. The low clay-content values registered by some of the material may be also due to coagulation that took place during the areometric test in spite of the removal of humus; the coagulation renders accurate determination of the clay content difficult [17].

The mineral matter contained in the Littorina sediment is for the most part derived from older types of sediment. No significant enrichment of the clay material can, however, be noted in the Littorina sediment in comparison with the other types of sediment. This probably explains to a certain extent the salinity of the water in the sedimentation basin as well as the humus content, as a consequence of which the mineral matter, that was deposited into the water, underwent fairly rapid sedimentation.

In Ancylus sediments, both the average clay content and the general distribution correspond closely to the Littorina sediment. In southern and southwestern Finland, the clay content is in many places from 40 to 70 per cent. The Ancylus sediments of the interior, as in, for example, the areas of Jämsä, Jyväskylä and Kuopio, are mostly silts, the clay content generally being from 10 to 30 per cent. The high silt content of these sediments make them very susceptible to disturbance upon their being handled wet. For this reason, from the standpoint of both construction technology and earth construction, such deposits are »difficult». The susceptibility to disturbance of these deposits also contributed to decrease the reliability of the laboratory analyses.

The Yoldia sediment is the type richest in clay. This is indicated by, among other things, the clay-content mean of 64 per cent. In some of the sample series from southern

Finland, an increase in the clay content can be observed in the upper part of the sediment type. The same observation was made by NIEMELÄ [57] in the region between Helsinki and Hämeenlinna. The increase in the clay content was due to the continuous recession of the ice sheet from the sedimentation area. The clay content of the Yoldia sediment of southern and southwestern Finland is generally between 70 and 90 per cent, the maximum values being close to 100 per cent. In the hinterland and in the region of Pohjanmaa, the clay content is in most cases between 10 and 30 per cent, corresponding to the Ancylus sediment of these regions. The Yoldia and Ancylus sediments thus constitute together the silty soils of the Finnish interior which have often been found to be difficult with respect to their construction technical properties. The exceptionally high clay content of the Yoldia sediments of southern and southwestern Finland cannot be explained in unequivocal terms. It cannot be derived exclusively from the previously deposited sediments of the Baltic Ice Lake or from the fine fractions of till deposits. Interglacial clay material comes into question as the original material (Section 2.3).

In the varved sediments of the Baltic Ice Lake, the average clay content is lowest, the mean being 34 per cent. As Fig. 23 shows, these sediments contain in places also clay-rich layers. Rich varved sediments have been met with mainly in the region of the coast of the Gulf of Finland, where the sedimentation took place at many points in relatively deep water. It is characteristic of these sedimentary series that they contain layers of both rich clay and predominantly silty matter. The clay content is generally lowest in the silty bottom portion of the sedimentary type, which was deposited in the near proximity of the glacier. Upward from the bottom portion, the clay content increases as a consequence of the recession of the ice sheet. This comes to light also in comparing the relative clay contents of samples taken from the dry crust and from beneath it (Table 9). Owing to the high silt content of the sediment type, it is in many instances quite as »difficult» with respect to its earth construction properties as the Yoldia and Ancylus silts of the interior of the country. The silts of the Baltic Ice Lake are concentrated, however, primarily in the Salpausselkä zones. Furthermore, they extend in places to the surface of the earth in the coastal region on the southern side of the Salpausselkä ridges, too.

6.3 Humus content

Organic matter occurs in fine-grained sediments mainly in microscopic form. It includes, among other things, plant and animal remains, pollen, micro-organisms, organic molecules and compounds. Macroscopic material is met with only to a minimal extent

Table 10. Mean values and standard deviations of the humus contents in different types of sediment.

Humus content Hu	Sediment type			
	Li	An	Yo	Ba
Hu in dry crust, %	4,0 ± 3,3 N = 23	0,9 ± 0,6 N = 13	0,7 ± 0,3 N = 17	0,7 ± 0,5 N = 21
Hu beneath dry crust, %	3,9 ± 2,0 N = 143	1,0 ± 0,4 N = 63	1,2 ± 0,4 N = 144	0,6 ± 0,2 N = 136

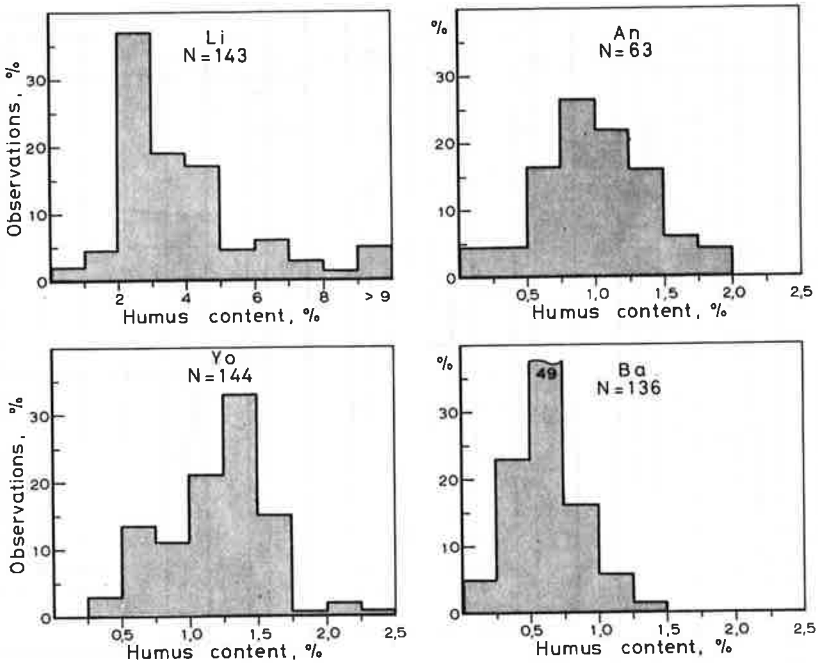

Fig. 24. Distribution of humus content in different types of sediment beneath dry crust.

[62]. The organic matter has a significant effect on both the classification properties and geotechnical properties of the fine-grained sediments [56, 62]. The quantity of organic material (humus content) is determined in Finland in investigations serving engineering technology by, in general, either the colorimetric or the burning method. When the humus contents are high, the results of these methods are apt to deviate significantly from each other [24]. In connection with the present study, the humus contents were determined from all the samples by the colorimetric method, which means that the results are mutually comparable.

The humus contents of the Littorina sediments vary usually from 2,5 to 5 per cent, the mean value for the material being 3,9 per cent (Fig. 24, Table 10). Frequently, humus contents from 6 to 8 per cent are also met with, the maximum values in southern Finland ranging from 10 to 13 per cent. These figures correspond fairly closely with the results arrived at by AARNIO [2] as well as LINDROOS and NIEMELÄ [52]. Aarnio's material cannot, however, be unequivocally divided into sediment types, besides which the study specimens represent mainly the dry crust. According to HEINO [28], the humus content of the sediments dating from the Littorina stage in the marine area around Turku averages 7 per cent. This exceeds the mean of approximately 4 per cent for the material representing the country as a whole. Also in this research material, high humus contents occur in southwestern Finland; hence the disparity in the results may be regarded as being due in part to the regional differences in the material.

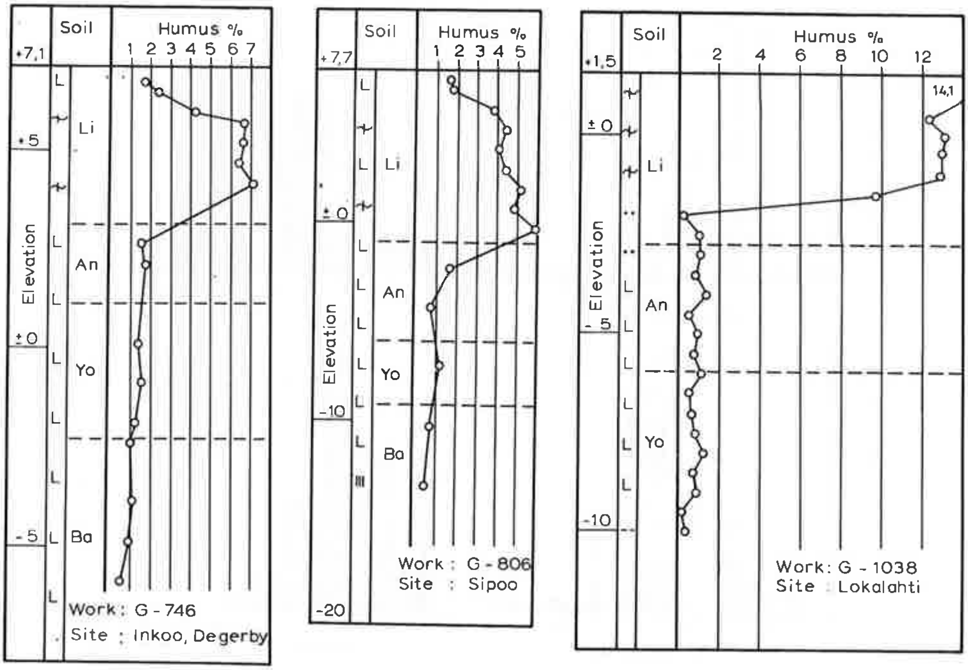

Fig. 25. Stratigraphic distribution of humus content in sample series from Inkoo, Sipoo and Lokalahti.

On the southern and southwestern coasts, the humus content of the Littorina sediment increases usually by leaps in comparison with the Ancylus sediment (Fig. 25). The maximum values occur in many cases in the lower part of the sediment type, thus corresponding in the main to the temperature optimum of the Littorina stage. Toward the surface, the humus content decreases in many instances. The decrease in the humus content thus corresponds to the change in the temperature and salinity of the water in the sedimentation basin. The boundary between the Littorina and Ancylus sediments is not so clear on the whole in the Pohjanmaa region as on the southern coast. The change in the humus content is in many places gradual, though nevertheless clear-cut. Furthermore, the humus content in Pohjanmaa increases in numerous instances toward the surface of the ground. The regional difference in the alteration zone is likely to be partly due to the fact that at the beginning of the Littorina stage the salinity of the water, which affected the content of organic matter, probably increased in the region of the Gulf of Bothnia more slowly than on the southern coast.

The humus content of the Ancylus and Yoldia sediments is nearly the same, varying between 0,5 and 2 per cent, which agrees with the results arrived at by Lindroos and Niemelä [52]. The mean values are 1,0 % (An) and 1,2 % (Yo). These values are lower than Heino's data [28] reported from the environs of Turku. The disparity may be attributed mainly to the aforementioned difference in the conditions represented by the data. In the rich Ancylus and Yoldia clays of southern and southwestern Finland, the humus content is generally higher than in the silty deposits of the interior of the country. The regional variation in humus contents is partly due to the difference in the salinity of the water in the sedimentation basins.

The humus content is smallest in the sediments of the Baltic Ice Lake. The variation is in the main between about 0,4 and 1 per cent, the mean being 0,6 per cent. No clear-cut regional variation can be perceived. The conditions unfavorable to organic matter during the time of sedimentation explain these low humus-content values. In many instances, the humus content increases in this type of sediment in moving upward toward the surface from the bottom portion. This increase in the humus content must be regarded as a consequence of the increasing distance of the ice sheet from the sedimentation site, with a resultant improvement of the conditions favoring organic activity.

In the light of the results, the sediments are seen to fall into three categories on the basis of their humus content. Littorina sediments contain an abundance of humus (generally between 2,5 and 5 per cent). The humus content of Ancylus and Yoldia sediments is generally between 1 and 1,5 per cent. The sediments dating back to the Baltic Ice Lake are exceedingly poor in humus. Humus contents of between about 1,5 and 2,5 per cent occur rather seldom in the material comprising the present study. GRIPENBERG [26] reports the same observation. Littorina sediments can be separated therefore generally into a group apart on the basis of their humus contents. In this sense, the 2 per cent humus limit applied in the soil classifications used in Finland is sensible. The 6 per cent humus limit applied in some classifications, on the other hand, has been criticized by PUSCH [62] as being too high. According to the results of Pusch's investigations, a humus content of even 4 per cent has a highly significant effect on the deformation and strength properties of soils.

6.4 Water content

In the light of the distribution of the results (Fig. 26) and the mean values (Table 11), the water content is found to be distinctly higher in humus-rich Littorina sediments than in other types of sediment. This is due primarily to the great absorption capacity of organic material [56]. Generally, the water content of humus-bearing deposits dating from the Littorina stage varies underneath the dry crust from about 80 to 120 per cent, the mean being 94 per cent. The variation in the water content is, however, striking. This is a consequence primarily of the variations in humus content and grain size. When the humus content is higher on the average (or roughly from 6 to 8 per cent), the water content rises correspondingly to about between 120 and 150 per cent. In the present

Table 11. The means and standard deviations of the water content in different types of sediment.

Water content w	Sediment type			
	Li	An	Yo	Ba
w in dry crust, %	70 ± 39 N = 23	41 ± 16 N = 14	49 ± 21 N = 17	47 ± 14 N = 22
w beneath dry crust, %	94 ± 38 N = 144	71 ± 22 N = 63	76 ± 28 N = 148	51 ± 20 N = 146

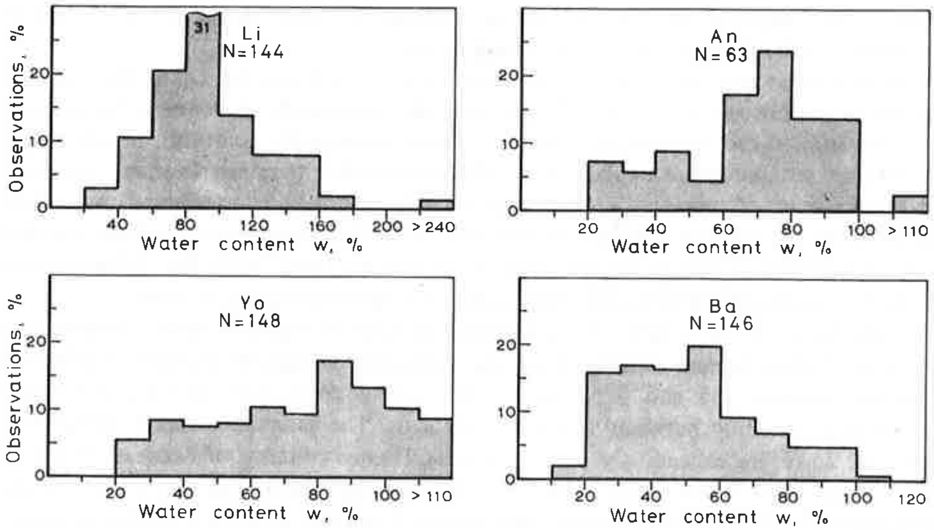

Fig. 26. Distributions of water content in different types of sediment beneath dry crust.

material, the maximum values registered for the water content – approximately 250 per cent – occur at Lokalahti, where humus contents of 12 and 13 per cent were measured. Correspondingly, with the occurrence of low humus values, the water content decreases on the average. The same kind of decrease in water content occurs in Littorina sediments containing a large amount of silt.

The water contents of Ancylus and Yoldia sediments are in many instances the same beneath the dry crust, as is demonstrated by the means registered for the water contents: A = 71 %, Yo = 76 %. The variation in the water contents is large, however, for in the predominantly silty deposits occurring in the hinterland, the water content is markedly lower than that of the Ancylus and Yoldia clays of the coastal regions. The water-content values registered in the interior of the country are in most instances only between 20 and 50 per cent, whereas in the areas along the coast the corresponding values range between 60 and 100 per cent.

In Yoldia sediments, there occurs a distinct maximum area in the distribution of the clay contents, representing values ranging between 70 and 90 per cent (Fig. 23). On this basis, one might assume that a corresponding maximum area exists in the water contents, too. According to Fig. 26, this has not, however, been established, the water content of the Yoldia sediments being distributed notably evenly. A significant factor in this is apparently the arrangement of layers. On the proximal side of the Salpausselkä ridges, the Yoldia clays are in most cases among the oldest sediments, being bounded at the lower end by the coarse-grained base. Although distinct changes do not always occur in the grain size, the water content generally diminishes toward the basal portion. This is due to the greater permeability of the basal layer underlying the clay. A corresponding type of boundary surface, in which the water content decreases gradually even though the grain size might not change occurs underneath the dry crust.

In sediments of the Baltic Ice Lake, the water content is noticeably lower than in other types of sediment, the mean beneath the dry crust being 51 per cent. This is brought about by the high concentration of silt and small amount of humus contained in the material. Rather high water contents (between 60 and 80 per cent) are met with, however, in rich clays included in this category of sediments, which occur in the proximity of the Gulf of Finland. In the lower part of this type of sediment, the water content decreases markedly in general toward the basal portion. At the same time, however, there takes place a distinct decrease in the clay content; hence the decrease in the water content is due not only to the occurrence in many cases of a predominantly sandy basal layer but also to a change taking place in the grain size measured in the sediment itself.

In the dry crust, the water content is smaller than underneath it (Table 11). In certain instances, the values registered for the water content of the dry crust may nevertheless be considered rather high. This is due to the fact that when the lower limit of the dry crust is determined by means of its strength and consolidation properties, there enter the dry crust materials the degree of saturation of which may be close to 100 per cent. In sediments of the Baltic Ice Lake, the decrease in the content of water is relatively less than in other types of sediment. This is probably due to the fact that in the sediments of the Baltic Ice Lake, the clay content generally increases toward the surface. With respect to the dry crust, the data are so scanty, however, that the results are to be considered mainly in an indicative light.

The water contents observed in the sediment types deviate to a slight extent from the findings published by Korhonen and Leskelä [44], which are based mainly on ten series of samples collected in southern Finland. In Heino's material [28], the water content of the Littorina and Ancylus sediments is distinctly higher than that recorded in the present study. Heino's material is different, however, in that his samples were taken from the bottom of the present-day sea. As the sedimentary deposits rise up out of the water because of the land uplift, there begin to take place in them immediately changes in the water content, among other things, as a consequence of the additional loading.

6.5 Plasticity and fineness number

The plasticity of sediments has been studied by means of the so-called Atterberg consistency limits. The consistency limits are the liquid limit (w_L) and plastic limit (w_p), the difference between which is termed the plasticity index (I_p). In the present study, the liquid limit was determined with the so-called Casagrande apparatus and the plastic limit by manual rolling [79]. The liquid limit and the plasticity index are examined in the light of the results.

The liquid limit is appreciably greater in Littorina sediments than in other sediment types (Table 12, Fig. 27). This is influenced most significantly by the humus content [56]. Owing to regional variation in grain size and humus content, the variation, however, is large. The Ancylus and Yoldia sediments approximate each other with respect to their liquid limit. But the marked variation in grain size causes considerable deviation. In each type of sediment, the sediments containing a predominance of silt and with a low liquid

Table 12. Liquid limit means and standard deviations in different types of sediment.

Liquid limit w_L	Sediment type			
	Li	An	Yo	Ba
w_L in dry crust	93 ± 55 N = 23	56 ± 14 N = 14	65 ± 22 N = 17	65 ± 20 N = 22
w_L beneath dry crust	106 ± 42 N = 136	62 ± 22 N = 60	65 ± 25 N = 137	46 ± 20 N = 138

Table 13. Means and standard deviations of the plasticity index (I_p) in different types of sediment.

Plasticity index I_p	Sediment type			
	Li	An	Yo	Ba
I_p in dry crust	50 ± 38 N = 23	31 ± 12 N = 14	38 ± 18 N = 17	33 ± 15 N = 22
I_p beneath dry crust	70 ± 32 N = 136	36 ± 19 N = 60	38 ± 23 N = 137	22 ± 17 N = 137

limit (ca. 20 to 50 per cent) fall into a separate category (Fig. 27). In the silty sediments of the Baltic Ice Lake, the liquid limit is distinctly lower than in other types of sediment. High liquid-limit values are met with, however, in the rich varved clays of the coastal zone. Also with respect to the plastic limit (w_p), the sediments are divided into three groups, for the means registered for the plastic limit in different types of sediment beneath the dry crust are as follows: Li = 36 %, An = 26 %, Yo = 27 % and Ba = 24 %.

The plasticity index falls into a division corresponding to that of the liquid limit (Table 13, Fig. 28). Taken almost in their entirety, the Littorina sediments are highly plastic ($I_p > 25$), the mean being 70. The highest individual values range from about 100 to 150. In the rich, highly plastic Ancylus and Yoldia sediments of southern and southwestern Finland, the plasticity index varies in general between about 30 and 60. The silty sediments of the interior of the country, on the other hand, register low values ($I_p < 10$) or are moderately plastic (I_p 10···25). The sediments dating from the Baltic Ice Lake, owing to the preponderance of silt in their composition, are mainly also slightly or moderately plastic – although highly plastic deposits do occur in this category, too, to a small extent.

Irrespective of the type of sediment, the water content generally exceeds the liquid limit in clays, organic clays and ooze. In silt deposits, the liquid limit and the water content in most cases correspond to each other. For this reason, fine-grained Finnish sediments – excepting the dry crust – are sensitive to disturbances, as in connection with digging operations and transportation.

In the dry crust and underneath it, no appreciable differences appear in the plasticity of Ancylus and Yoldia sediments (Table 12 and 13). With respect to the dry crust, the data are limited, however, as far as drawing conclusions is concerned. In the dry crust

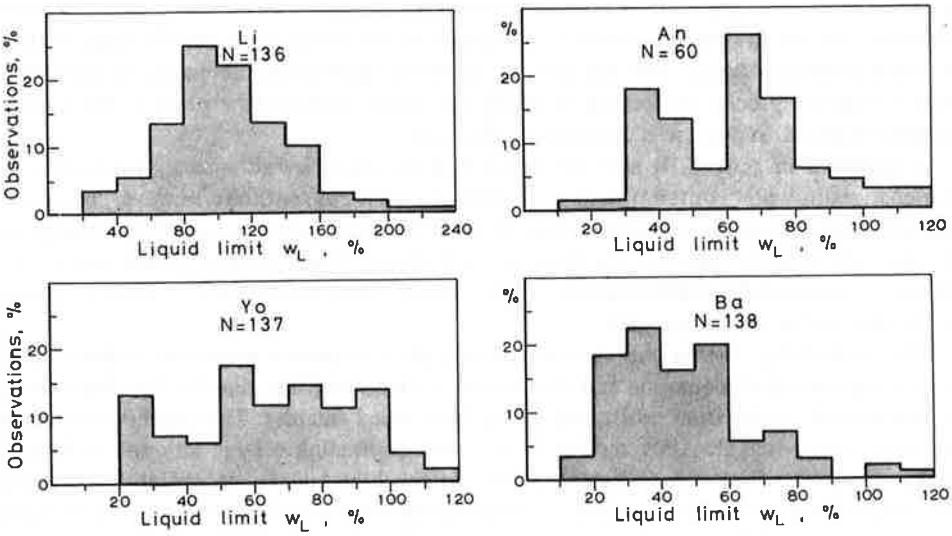

Fig. 27. Distributions of liquid limit in different sediment types beneath dry crust.

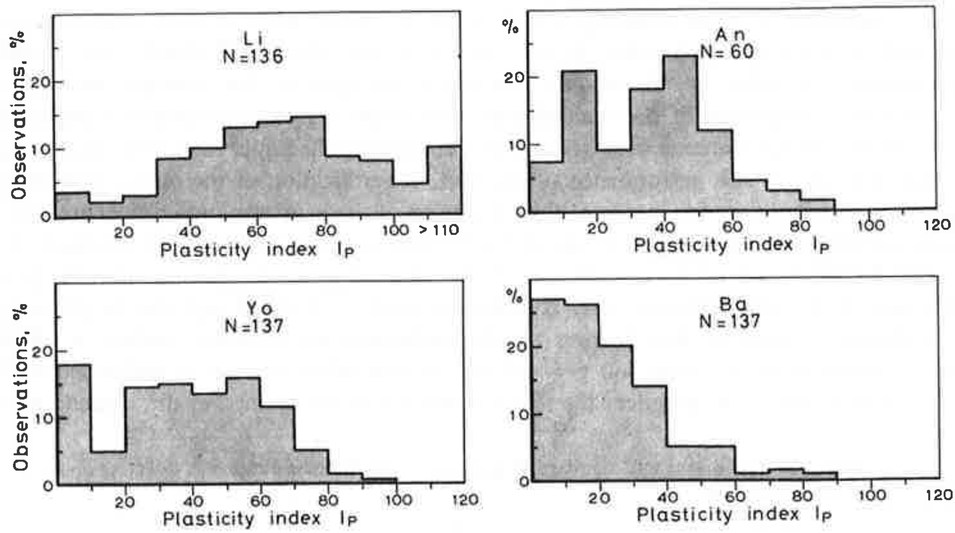

Fig. 28. Distributions of plasticity index in different types of sediment beneath dry crust.

of the Littorina sediment, the plasticity is slighter, on the other hand, and in that of the sediments of the Baltic Ice Lake greater than in underlying strata. Contributing to this difference are the previously mentioned changes in humus content and clay content in these sediment types. In Littorina sediments, the humus content is often seen to decrease toward the surface, while in sediments of the Baltic Ice Lake the clay content increase correspondingly. On the part of Littorina sediments, moreover, it is possible that during the process of formation of the dry crust, changes take place in the humus-bearing material that cause a decrease in plasticity.

Considered in general, it may be stated that the plasticity adheres approximately to the changes in water content (grain size and humus content) without, however, becoming altered drastically in the boundary zones of the different types of sediment. An exception to this rule is made only by the Littorina sediments, which contain a large amount of humus. Consequently, differentiating the sediment types solely on the basis of plastic properties is not always possible.

The probability is that the variation taking place in plastic properties is due in part to the experimental technique and the manner of handling the samples. The liquid limit is determined partly from moist and partly from dried samples. This has been observed to cause somewhat deviating results. In deposits containing a large amount of humus, an appreciable variation may have occurred in the liquid limit, necessitating repeating or rejecting the tests. The method of determining the liquid limit is slow and to some extent subjective. The trouble with the Casagrande apparatus is that it does not take into account the susceptibility of different soils to disturbances [13].

To avoid the difficulties referred to, FLAATE [20], among others, has tried determining the liquid limit with a cone penetrometer. SHERWOOD and RYLEY [69] have observed that practically the same plasticity values can be registered with the cone penetrometer as with Casagrande's apparatus. In the conditions prevailing in Finland, too, plastic properties may often be observed to cast additional light on, for example, the earth-construction properties of fine-grained soils. One might therefore recommend switching over to the use of the cone penetrometer in determining the liquid limit. With increasing speed and ease in the performance of the test, the utilization of the plastic properties could be boadened in, for instance, the estimation of earth-construction properties, such as heapbility and transportability, as well as to serve as a possible basis of classification.

In the definition of the consistency of fine-grained soils, the fineness number (F), determined by the fall-cone test, is generally used in Finland and the neighboring Scandinavian countries. The fineness number is defined as that water content in which the penetration of the cone (60 g – 60°) is 10 mm when the test is performed with a disturbed sample. In practice, the fineness number is determined in the fallcone test,

Table 14. The means and standard deviations of the fineness number in different types of sediment.

Sediment type			
Li	An	Yo	Ba
106 ± 45 N = 140	63 ± 18 N = 60	70 ± 24 N = 132	52 ± 19 N = 123

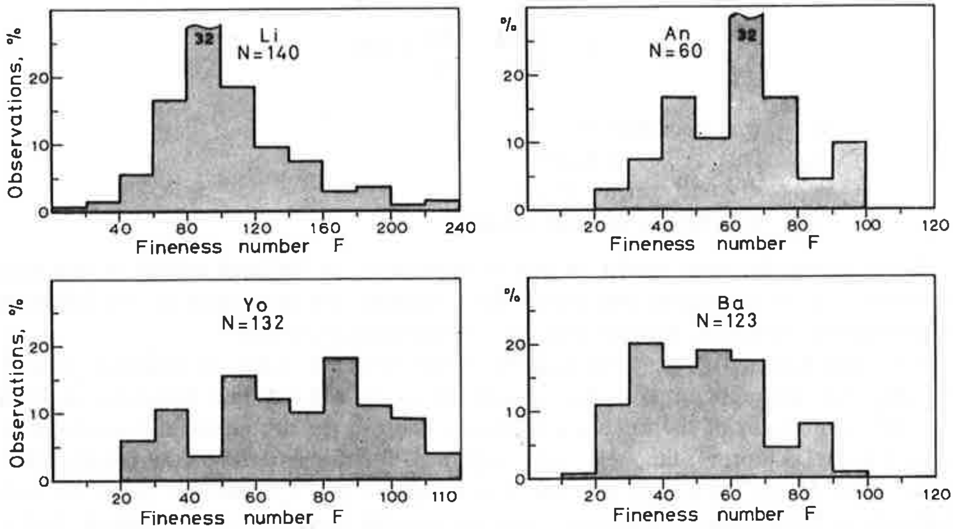

Fig. 29. Distributions of fineness number in different types of sediment beneath dry crust.

however, from a disturbed sample with a water content corresponding to its natural state by multiplying its water content with an experimental coefficient [37]. The fineness number cannot in general for this reason be determined from the material of the dry crust by this method.

The fineness number has generally been observed to be close to the liquid limit. In comparative tests carried out by KARLSSON [37], the fineness number has been somewhat lower than the liquid limit in the case of high liquid-limit values. In silt deposits with low liquid-limit values, the fineness number, on the other hand, has been higher than the liquid limit. In studies dealing with Finnish sediments carried out by AIRAKSINEN and KORHONEN [3], the fineness number has generally been higher than the liquid limit.

In the present study, the distributions of the fineness number in different types of sediment were found to correspond closely to the distribution of the liquid limit (Fig. 29). In addition, the mean values of the fineness number and the liquid limit are quite close to each other (Tables 12 and 14). In the light of the research material, it would appear that the liquid limit, which is difficult to determine, could in many cases be substituted by the fineness number.

6.6 Unit weight of soil

Changes in the unit weight of soil follow closely the changes in the water content of sediments, for in a state of saturation with water, the unit weight and the water content have a mathematical correlation as expressed by the equation (1).

$$w = \left(\frac{\gamma_w}{\gamma_d} - \frac{\gamma_w}{\gamma_s} \right) 100 \qquad (1)$$

w water content, %
γ_w unit weight of water
γ_d dry unit weight of soil
γ_s unit weight of solid particles

In addition, the unit weight of soil is dependent on the unit weight of the solid particles. The unit weights that have been measured are dealt with in the following independently, however, because they are of practical significance.

The distributions of the unit weights in the different types of sediment beneath the dry crust are represented in Fig. 30 and the means and standard deviations in Table 15. The unit weight of the Littorina sediments beneath the dry crust varies in the main from 1,4 to 1,6 Mp/m^3, the mean value registered for the material of the present study being 1,50 Mp/m^3. Exceedingly low unit weights (1,1···1,3 Mp/m^3) occur in ooze deposits with high humus and water contents, notably in southwestern Finland. Rather high unit weight values are met with in silt-bearing Littorina sediments in, for instance, the Kemi region. In other respects, no distinct regional distribution can be observed in sediments dating from the Littorina stage.

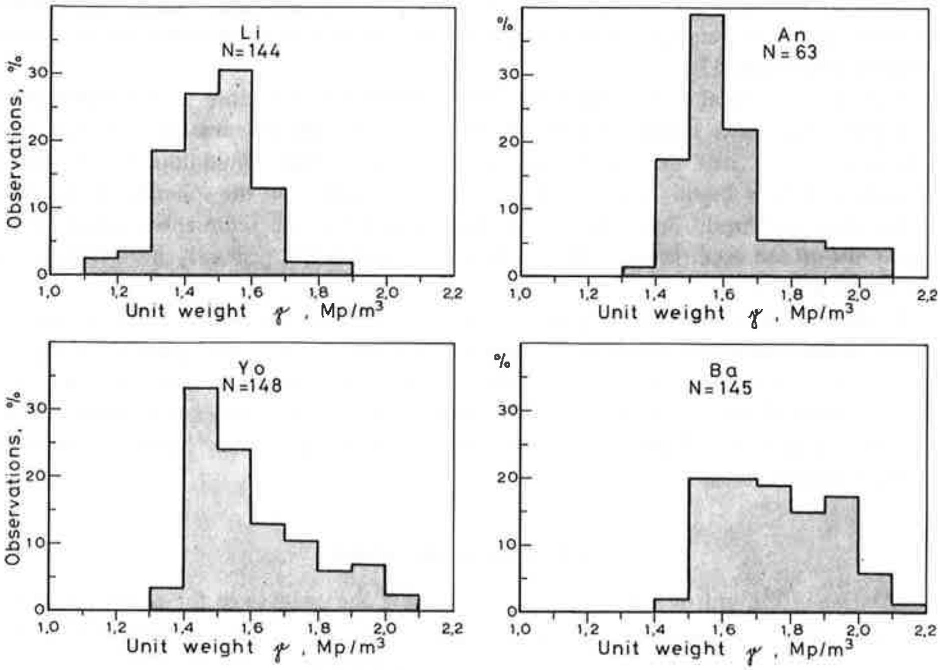

Fig. 30. Distributions of unit weight in different types of sediment beneath dry crust.

Table 15. Means and standard deviations of the unit weight in different types of sediment.

Unit weight γ	Sediment type			
	Li	An	Yo	Ba
γ in dry crust Mp/m^3	1,55 ± 0,22 N = 23	1,80 ± 0,14 N = 14	1,74 ± 0,16 N = 17	1,77 ± 0,11 N = 22
γ beneath dry crust Mp/m^3	1,50 ± 0,14 N = 144	1,61 ± 0,15 N = 63	1,60 ± 0,20 N = 148	1,77 ± 0,17 N = 145

In Ancylus and Yoldia sediments, the unit weight varies in the main from ca. 1,4 to 1,7 Mp/m^3, thus corresponding closely to the Littorina sediments. The unit weight values represent in the main the rich Ancylus and Yoldia clays with a high content of water that occur in southern and southwestern Finland. In the sediments found in the interior of the country with a preponderantly silt content, the unit weight is, on the other hand, more generally roughly 1,7···2,0 Mp/m^3.

In the sediments of the Baltic Ice Lake, the average unit weight is distinctly above that of the other types of sediments (mean 1,77 Mp/m^3). Differences in grain size and water content, however, cause considerable variation in this respect. In the coastal zone, therefore, the unit weight of the varved clays is less than that of the predominantly silty material occurring in the vicinity of the Salpausselkä zone.

In the dry crust, the sedimentary material is only to some extent saturated with water. The mean values for the unit weights of the clay in the dry crust of the Littorina, Ancylus and Yoldia sediments exceed, owing to a decrease in the water content, those registered beneath the dry crust by some 3···12 per cent. On the other hand, in the sediments of the Baltic Ice Lake, the mean unit weights registered for the dry crust and the underlying material are the same. This is due to the high clay content of the dry crust of the sediments dating from the Baltic Ice Lake stage.

6.7 Unit weight of solid particles

The distribution of the values representing the unit weight of the solid particles in the different types of sediment is shown in Fig. 31 and the mean values and standard deviations in Table 16. In the sediments of the Ancylus, Yoldia and Baltic Ice Lake stages,

Table 16. Mean unit weights of solid particles and their standard deviations in different types of sediment.

Unit weight of solid particles γ_s	Sediment type			
	Li	An	Yo	Ba
γ_s in dry crust Mp/m^3	2,54 ± 0,12 N = 23	2,65 ± 0,09 N = 14	2,63 ± 0,06 N = 17	2,67 ± 0,07 N = 22
γ_s beneath dry crust Mp/m^3	2,58 ± 0,08 N = 144	2,67 ± 0,05 N = 63	2,69 ± 0,05 N = 148	2,69 ± 0,05 N = 146

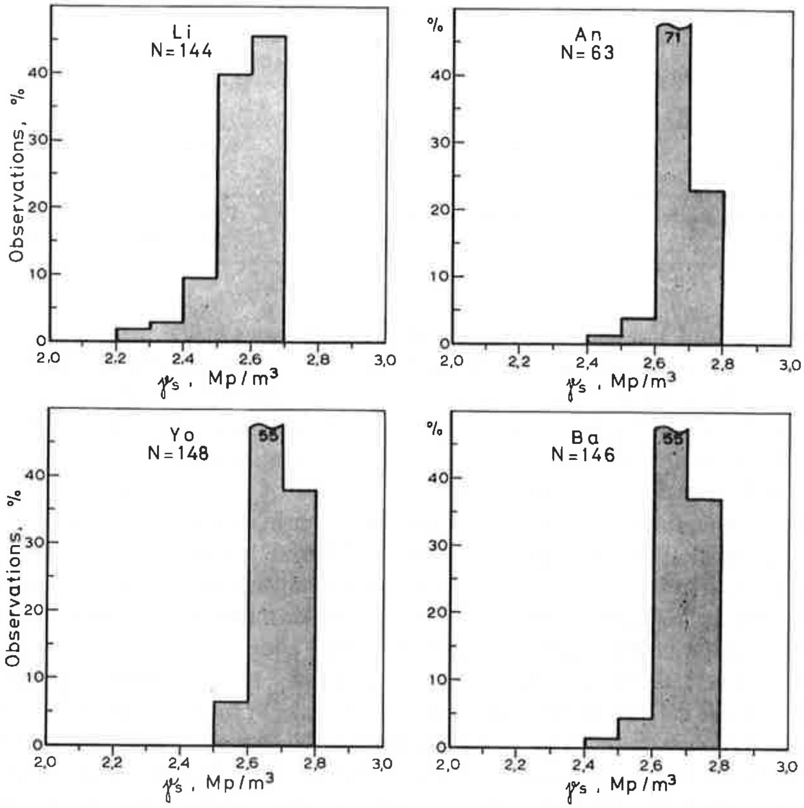

Fig. 31. Distributions of unit weight of solid particles in different types of sediment beneath dry crust.

the unit weight of the solid particles is practically the same, provided consideration is not given to the correlation between grain size and unit weight of solid particles. In humus-bearing Littorina sediments, the unit weight of the solid particles, on the other hand, is clearly less than in the other types of sediment.

In the light of the observation material, the unit weight of the solid particles contained in Finnish sediments depends to the most significant degree on the nearly constant mineral composition and the content of organic matter. The marked effect of the humus content begins to appear in the Littorina sediments – that is, when the humus content rises above about two per cent. In other types of sediment, the humus content is so low that its effect on the unit weight of the solid particles is slight. In these types, on the other hand, the monotonous mineral composition produces roughly the same values. Heinonen [29] has in his studies arrived at a mean of 2,74 Mp/m³ for the unit weight of the solid particles of soils without any humus content. This figure is slightly higher than that registered for corresponding soils in the present study. Heinonen's material consists, however, of cultivated mineral soils, besides which his method of determining the unit weight of solid particles was different.

The unit weight of the solid particles in the dry crust is generally slightly less than it is in underlying strata. This may be due to, among other things, a difference in mineral composition, for the dry crust contains a larger amount of mixed-layer minerals, produced by weathering (Ch. 3). The scantiness of samples of dry-crust clay, however, is insufficient for drawing clear-cut conclusions.

6.8 Void ratio

The void ratio expresses the quotient of the combined volume of the gas and liquid in soil and the volume of solid soil (Equation 2).

$$e = \frac{V_v}{V_s} \tag{2}$$

e void ratio
V_v volume of voids
V_s volume of solids

The void ratio of soil saturated with water can be computed by applying Equation (3).

$$e = \gamma_s \frac{w}{100} \tag{3}$$

e void ratio
γ_s unit weight of solid particles
w water content, %

The void ratio is used generally to represent a certain structural property of soil. Its values vary in fine-grained Finnish soils, according to KORHONEN [41], between about 0,5 and 4. The highest values occur generally in young sediments with a high humus content.

The void ratio (e_0) of sedimentary material in a natural state was determined in the present study in conjunction with the oedometer test. Although the determination was carried out from so-called undisturbed samples, the susceptibility to disturbance of, in particular, silt-bearing samples and the non-homogeneous structure of the sediments caused variations in the results.

According to the results arrived at, the void ratio is higher in the Littorina sediments than in the other types of sediment (Table 17). In the main, the void ratio values range

Table 17. Mean values and standard deviations of the void ratio in different types of sediment.

Void ratio e_0	Sediment type			
	Li	An	Yo	Ba
e_0 in dry crust	1,91 ± 1,08 N = 23	1,11 ± 0,40 N = 14	1,29 ± 0,54 N = 17	1,26 ± 0,32 N = 22
e_0 beneath dry crust	2,46 ± 0,91 N = 144	2,00 ± 0,70 N = 63	2,13 ± 0,78 N = 148	1,42 ± 0,56 N = 146

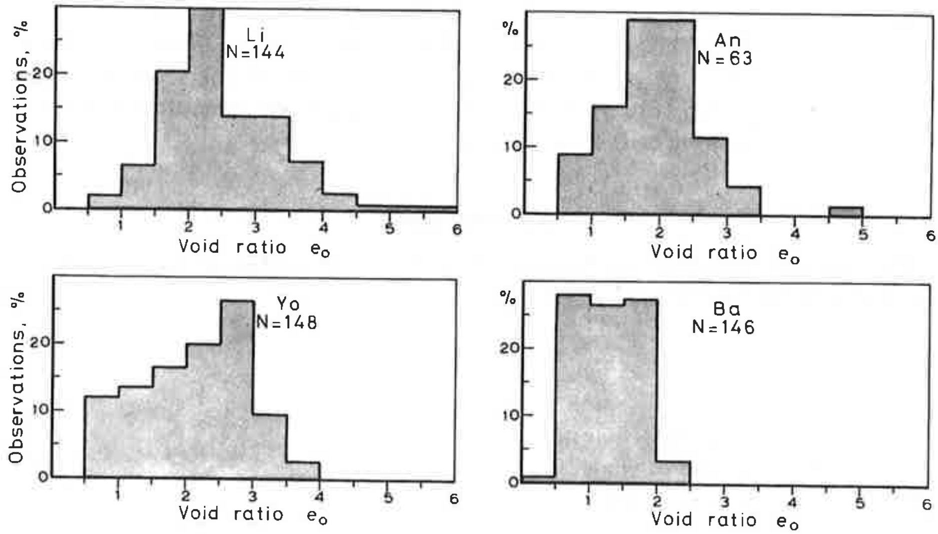

Fig. 32. Distributions of void ratio in different types of sediment beneath dry crust.

from about 1,5 to 4 (Fig. 32). High void ratio values occur in ooze with a high humus (water) content, the maximum values being approximately 6.

In Ancylus and Yoldia sediments, the values representing the void ratio vary in the main between 1 and 3, the means registered in the present material being An = 2,0 and Yo = 2,13. Since the humus content of these types of sediment is low, the void ratio is primarily dependent on the amount of clay material. On corresponding grounds, the void ratios of the sediments originating in the Baltic Ice Lake are lower than in the other types of sediment (Table 17). The differences between the void ratios of Littorina sediments and Ancylus-Yoldia sediments are generally rather slight. In Littorina sediments, the void ratio is significantly dependent on the humus content. In Ancylus-Yoldia sediments, the humus content is low. Its effect is compensated for to a notable extent, however, by the high clay content (water content) of, in particular, the sediments of the coastal regions.

The void ratios of the dry crust are in close agreement in the sediments dating from the Ancylus, Yoldia and Baltic Ice Lake stages (means ca. 1···1,3). This must be regarded as being due primarily to a grain composition of the same type. The void ratio in the dry crust of Littorina sediment is somewhat greater, owing to the humus content, than in that of other types of sediment.

As the void ratio is significantly dependent on the humus content of the sediment and the amount of the clay component, the regional variation likewise accords with these factors. The highest void ratios have been met with in the humus-rich Littorina sediments of southwestern and southern Finland as well as in the rich Ancylus and Yoldia clays of the same regions. The lowest void ratios (in many instances, 0,6···1,3) occur in the predominantly silty materials of the last-mentioned sediment types as well as in the varved clays of southern and southeastern Finland.

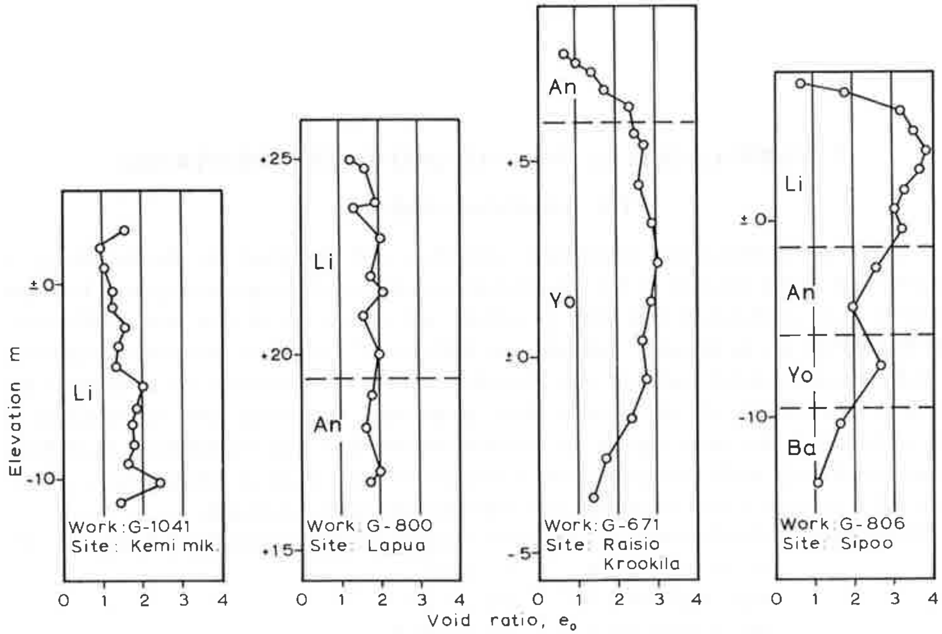

Fig. 33. Examples of variations in void ratio in different types of sediment.

In homogeneous sediment, the void ratio diminishes with depth, owing to an increase in the loading. In the series of sample studied, the void ratio nevertheless varies even in the same type of sediment – in many instances, quite considerably toward deeper levels (Fig. 33). This is due in most cases to alteration of properties independent of the compactness of soil. Such properties are primarily the clay content, humus content and plastic characteristics. A layer in which the properties referred to are nearly constant has been described by PYLKKÄNEN [63] as a geotechnically homogeneous layer, insofar as certain parameters of the deformation function (power function) dealt with by him are constant. In certain normally consolidated samples, Pylkkänen has observed that, although the properties mentioned remain nearly unchanged, the void ratio does not decrease with increasing depth (loading) but tends rather to remain nearly constant. In carrying out the division of layers, Pylkkänen held the parameters in question as the primary criterion. In connection with the present study, it was noted that the changes in the void ratio almost without exception accompany changes in the aforementioned properties that are independent of the compactness of soil. Variables independent of the compactness are, in addition to those mentioned in the foregoing, the salinity of the pore water, the pH, and the sulphur content of the sediments of the coastal regions, etc. It is obvious that, in the geotechnically »homogeneous» soil layer described by Pylkkänen, so many factors are at work that the »behavior» of the void ratio cannot be unambiguously explained in detail.

7. CORRELATION BETWEEN CLASSIFICATION PROPERTIES

7.1 Correlations dealt with

Among the classification properties, attention will be given in the following to the physical characteristics of the sedimentary material underlying the dry crust between which a clear correlation has been perceived and which are of practical significance. The examination will be made primarily on the basis of correlation matrices and thereby it will be endeavored, without any detailed statistical processing, to determine the physical correlations of the classification properties. To clarify the distribution of the correlations, the most significant correlations in each type of sediment have been drawn graphically with a computer; but, owing to the large quantity of pictorial material, they will not be presented in conjunction with the following discussion.

The following classification of correlation coefficients has been used in Tables 18···22.

═══	strong correlation,	$r > 0{,}85$
───	distinct correlation,	r 0,70···0,85
-----	moderate correlation,	r 0,50···0,70
.....	weak correlation,	r 0,30···0,50
	no correlation,	r 0,00···0,30

The significance of correlation coefficient r was measured by the t-test by calculating the test quantity t according to Formula (4). The test quantity was compared with the table of the $t\ (N-2)$ distribution.

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \qquad (4)$$

t test quantity
r correlation coefficient
N number of observation pairs

The following symbols were used in Tables 18···22 to represent the degree of significance:

+++	highly significant, probability	> 99,9 %
++	significant, probability	99,0···99,9 %
+	slightly significant, probability	95,0···98,9 %
-	not significant, probability	< 95,0 %

7.2 Clay content

Between clay content (< 0,002 mm) and humus content, there is a highly significant positive correlation in Yoldia sediments and Baltic Ice Lake sediments with a low humus content (Table 18). This may be explained by means of the conditions prevailing during

Table 18. Correlation coefficients with respect to clay content.

Soil property	Sediment type			
	Li	An	Yo	Ba
Humus content	−0,35^{+++}	0,28^{+}	0,71^{+++}	0,53^{+++}
Water content	0,01^{-}	0,71^{+++}	0,80^{+++}	0,89^{+++}
Unit weight	−0,14^{-}	−0,71^{+++}	−0,81^{+++}	−0,85^{+++}
Liquid limit	0,19^{-}	0,48^{+++}	0,75^{+++}	0,83^{+++}
Plasticity index	0,27^{+}	0,49^{+++}	0,73^{+++}	0,83^{+++}

the time of sedimentation (Chapters 6.2 and 6.3). As the distance between the melting ice sheet and the site of sedimentation increased, both the clay and the humus contents increased, too. In Ancylus sediment, the correlation between the clay material and the humus content is only slightly significant. In Littorina sediment, the correlation is highly significant. It is noteworthy, however, that in Littorina sediment the correlation between clay and humus contents is negative – in other words, as the content of organic matter increases, the clay content decreases. This is due to, among other things, the fact that the sediments containing large amounts of humus were in many instances deposited in saline water. Both the salinity of the water and the organic matter itself cause a rapid coagulation of the fine-grained material. The negative correlation is apt, in addition, to be affected by the difficulty of making a reliable determination of the clay content in deposits containing large amounts of humus. Notwithstanding the burning of humus in the aerometric test, it is possible that the humus caused the coagulation – which means that the measured clay content might, in certain cases, be too small as far as humus-rich sediments are concerned.

Between clay content and water content, there is a highly significant correlation in Ancylus, Yoldia and Baltic Ice Lake sediments. In Littorina sediments, the water content, on the other hand, is independent of the clay content, being correlated primarily with the humus content. The humus content of the three first-mentioned types of sediment is less than 1,5···2 %, whereas in Littorina sediments the humus content is mostly over 2 %. Thus also the correlation between clay content and water content indicates that the 2 % humus limit used in soil classification in Finland is a sensible one, especially in the geotechnical sense, for it separates the Littorina sediments into a group apart.

Between the clay content and the unit weight of soil, there occurs a (negative) correlation corresponding to that between the clay content and the water content. This is due primarily to the fact that between the water content and the unit weight there is a mathematical correlation. Between the clay content and liquid limit, there is a highly significant correlation in the Ancylus, Yoldia and Baltic Ice Lake sediments. In the Littorina sediment, the liquid limit is not dependent on the clay content but on the humus content. Since the plasticity index and the liquid limit are correlated mathematically (empirically), the correlations correspond to each other.

In the sediments dating from the Ancylus, Yoldia and Baltic Ice Lake stages, the properties considered are dependent on the clay content. The Ancylus sediment constitutes a kind of inhomogeneous intermediary class. The properties investigated in the Littorina sediments are not, viewed in the light of the present material, dependent on the clay content.

7.3 Water content

Between the water content and the humus content, there is a highly significant correlation in all the sediment types (Table 19). Any increase in the water content of sedimentary material along with an increase in the humus content is due primarily to the capacity of humus to adsorb water. With an increase in the humus content of more than 2 per cent, this effect in Littorina sediments becomes quite clearly evident. As far as Yoldia and Baltic Ice Lake sediments are concerned, the correlation between the water content and the amount of humus is also positively affected by the significant correlation between the water content and the clay content. As the humus content increases, the clay content of these sediment types likewise increases (Table 18). In the light of the foregoing discussion, the water content of the sediments is dependent – in the material underlying the dry crust – on the humus content and the clay content. Furthermore, it is affected by, among other things, the loading state and the drainage conditions. The high coefficients of correlation of the water content and the unit weight are due to the mathematical correlation.

The correlation between water content and liquid limit is highly significant in all the types of sediment. The liquid limit is thus dependent in the Littorina sediments mainly on the humus content and in the other types of sediment on the clay content.

Table 19. Correlation coefficients with respect to water content.

Soil property	Sediment type			
	Li	An	Yo	Ba
Humus content	0,74^{+++}	0,41^{+++}	0,59^{+++}	0,50^{+++}
Unit weight	−0,89^{+++}	−0,93^{+++}	−0,69^{+++}	−0,88^{+++}
Liquid limit	0,89^{+++}	0,57^{+++}	0,77^{+++}	0,83^{+++}
Plasticity index	0,85^{+++}	0,56^{+++}	0,76^{+++}	0,82^{+++}

7.4 Unit weight of solid particles

According to Table 20, it may be stated that the unit weight of the solid particles in the various types of sediment, excepting the Littorina sediment, is nearly constant as far as clay content is concerned. This is due mainly to the one-sided mineral composition. In Littorina sediments, there prevails a highly significant correlation between clay content and the unit weight of the solid particles – but a contributing factor is the humus, too. As the clay content increases, the humus content diminishes (Table 18), as a result of which the unit weight of the solid particles is augmented.

Table 20. Correlation coefficients with respect to unit weight of solid particles.

Soil property	Sediment type			
	Li	An	Yo	Ba
Clay content	0,34^{+++}	−0,08^{-}	−0,19^{+}	−0,11^{-}
Humus content	−0,86^{+++}	−0,35^{+++}	−0,18^{+}	0,04^{-}
Void ratio	−0,63^{+++}	−0,18^{-}	−0,15^{+}	0,02^{-}

Since the density of humus is appreciably less than that of mineral matter, the unit weight of the solid particles in Littorina sediments is highly correlated to the amount of humus present. The same degree of significance occurs in Ancylus sediment, although the coefficient of correlation is noticeably smaller than in Littorina sediment.

In the light of the present research material, it is evident that if the humus content of fine-grained sedimentary material (in Finland) is less than 2 per cent, the unit weight of its solid particles may be assumed, under rought examination, to be 2,7 Mp/m^3 (Section 6.7). When the humus content exceeds 2 per cent, the unit weight of the solid particles must be separately determined. For approximate estimation, Fig. 34 represents the correlation between humus content and the unit weight of the solid particles in Littorina sediments, as revealed by the present material.

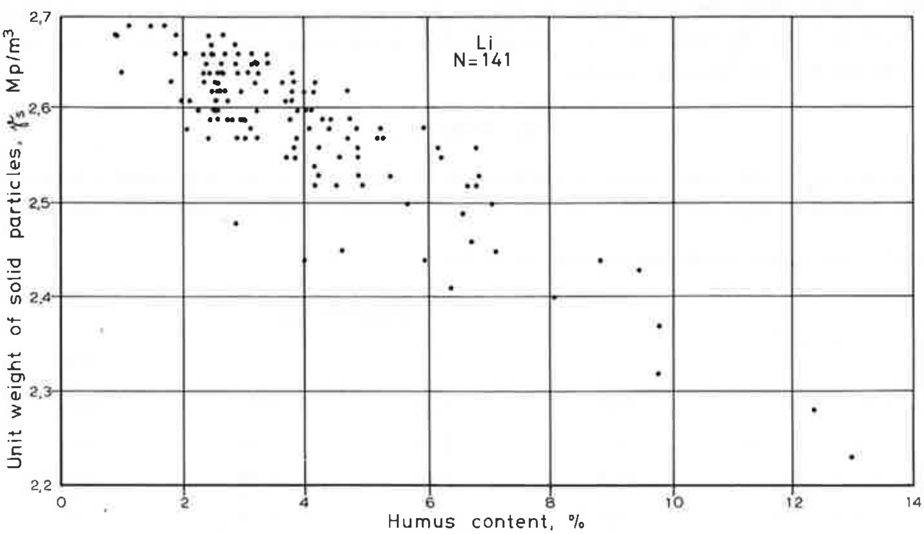

Fig. 34. Unit weight of solid particles in ratio to humus content in Littorina sediments.

Table 21. Correlation coefficients with the fineness number.

Soil property	Sediment type			
	Li	An	Yo	Ba
Clay content	−0,17+	0,38+++	0,72+++	0,68+++
Humus content	0,78+++	0,43+++	0,55+++	0,47+++
Water content	0,86+++	0,61+++	0,79+++	0,76+++
Liquid limit	0,78+++	0,83+++	0,86+++	0,74+++
Plasticity index	0,74+++	0,83+++	0,85+++	0,71+++

7.5 Fineness number

Inasmuch as the fineness number is in many instances nearly as high as the liquid limit, the correlation of the fineness number with clay content, humus content and water content correspond to that with the liquid limit (Table 21). The fineness number determined with the fall-cone test is accordingly dependent on the humus content (Li) and the clay content (An, Yo, Ba). For the same reason, there is a highly significant correlation between the fineness number and the water content.

Fig. 35 presents the material collected from the different types of sediment underneath the dry crust in the light of the fineness number and the liquid limit. On the basis of the figure, it may be noted that in Littorina sediments the fineness number is generally slightly smaller than the liquid limit when the values registered for the liquid limit are approximately 80···150. In Ancylus and Yoldia sediments, the fineness number is very nearly the same as the liquid limit. On the other hand, in the predominanrly silty sediments of the Baltic Ice Lake with a low liquid limit, the fineness number is generally slightly higher than the liquid limit. These observations agree with KARLSSON's [37] reported findings. In view of the foregoing, the liquid limit can be replaced in rough estimations by the fineness number.

7.6 Void ratio

Inasmuch as the void ratio is mathematically dependent on the water content in water-saturated deposits, there prevails between them a highly significant correlation

Table 22. Correlation coefficients with the void ratio.

Soil property	Sediment type			
	Li	An	Yo	Ba
Clay content	0,07-	0,71+++	0,82+++	0,84+++
Humus content	0,72+++	0,29+	0,60+++	0,50+++
Water content	0,96+++	0,92+++	0,88+++	0,91+++
Liquid limit	0,87+++	0,47+++	0,76+++	0,77+++
Plasticity index	0,85+++	0,46+++	0,73+++	0,74+++
Fineness number	0,82+++	0,47+++	0,70+++	0,67+++

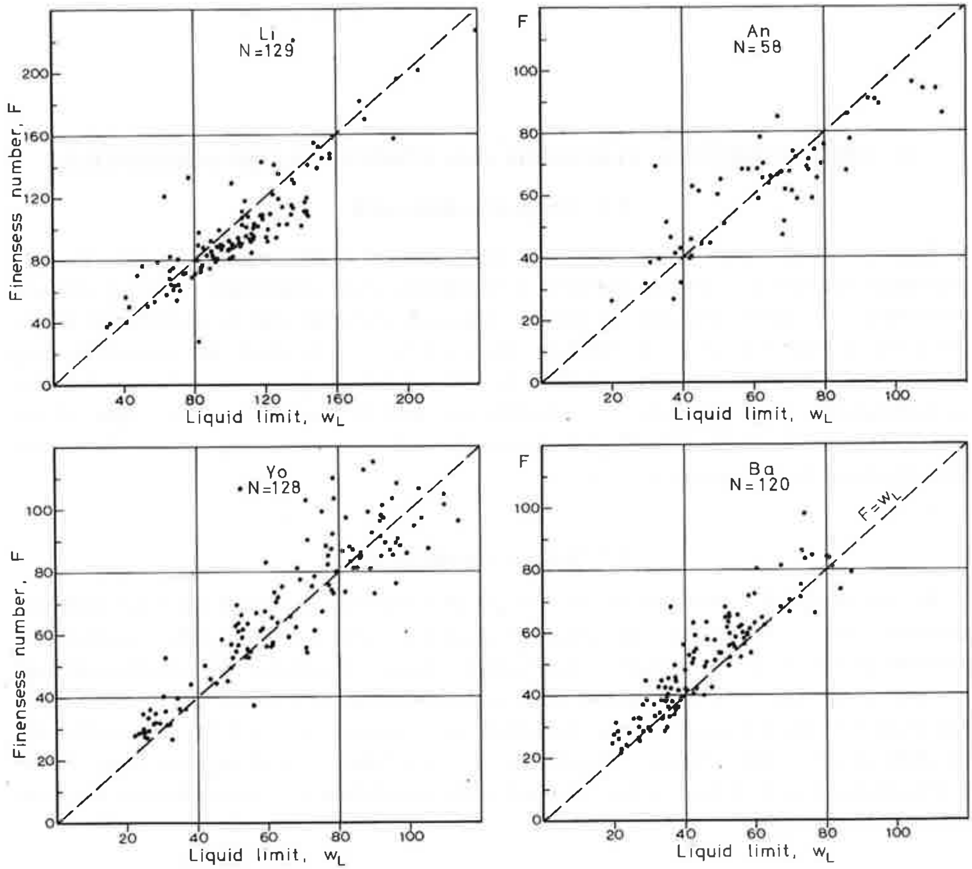

Fig. 35. Fineness number in ratio to liquid limit in different types of sediment.

(Table 22). Correspondingly, the void ratio depends on those properties that most significantly influence the water content. The clay content therefore influences the void ratio highly significantly in the sediments originating during the Ancylus, Yoldia and Baltic Ice Lake stages. In Littorina sediment, the clay content is not significant. Here, on the other hand, the humus content is the most decisive in relation to the void ratio. There is also a highly significant correlation between humus content and void ratio in Yoldia and Baltic Ice Lake sediments. However, here, as in the matter of the water content, a contributing factor is the positive correlation between the humus content and the clay content. As far as the Littorina sediments are concerned, moreover, it should be noted that the void ratio is highly significantly influenced by the unit weight of the solid particles (Table 20). In other types of sediment, this has only a slight significance, owing to the small amount of humus present.

8. DISTRIBUTION OF STRENGTH AND CONSOLIDATION PROPERTIES

8.1 Properties dealt with

The aim of this part of the study was to determine along general lines the effect of geological factors on certain strength and consolidation properties. Among strength properties, the shear strength of various types of sediment will be considered in the following as determined in the field by the vane test, along with the factors affecting the strength. Correspondingly, among the consolidation properties, the modulus of compressibility and the state of consolidation will be discussed in the light of the oedometer test performed in the laboratory. In addition, sensitivity will be dealt with as determined by the vane test.

8.2 State of consolidation

By the state of consolidation of fine-grained deposits is meant the ratio between the consolidation pressure and the effective overburden pressure (p_c/p_0). By consolidation pressure (p_c) is meant the effective overburden pressure exerted at some geological stage on any given layer of soil or the corresponding state into which a layer has been compacted or strengthened through the influence of various factors. Effective overburden pressure denotes the effective weight of the soil layers overlying the layer under investigation. The following terms are used in the geotechnical soil classification of states of consolidation [46]:

	p_c/p_0
– underconsolidated	$<$ 0,8
– normally consolidated or slightly overconsolidated	0,8···1,5
– overconsolidated	1,5···10
– highly overconsolidated	$>$ 10

In the present study, it has been endeavored to estimate the state of consolidation by the methods developed by Kotzias [48] and Ohde [59], used in conjunction with the oedometer test. The material includes many cases, however, where these methods do not lead to any reliable value to represent the consolidation pressure (p_c). Moreover, it should be noted that consolidation pressure is dependent, in part, also on the method of testing, primarily the pressure time [14]. Effective overburden pressure (p_0) was calculated in connection with field investigations on the basis of the observed water level. The p_c/p_0 ratios of silt samples taken from different depths of the same investigation site varied in many instances without any consistency. This phenomenon is attributed mainly to disturbance of the samples. It was not therefore possible to determine the state of consolidation of silts reliably.

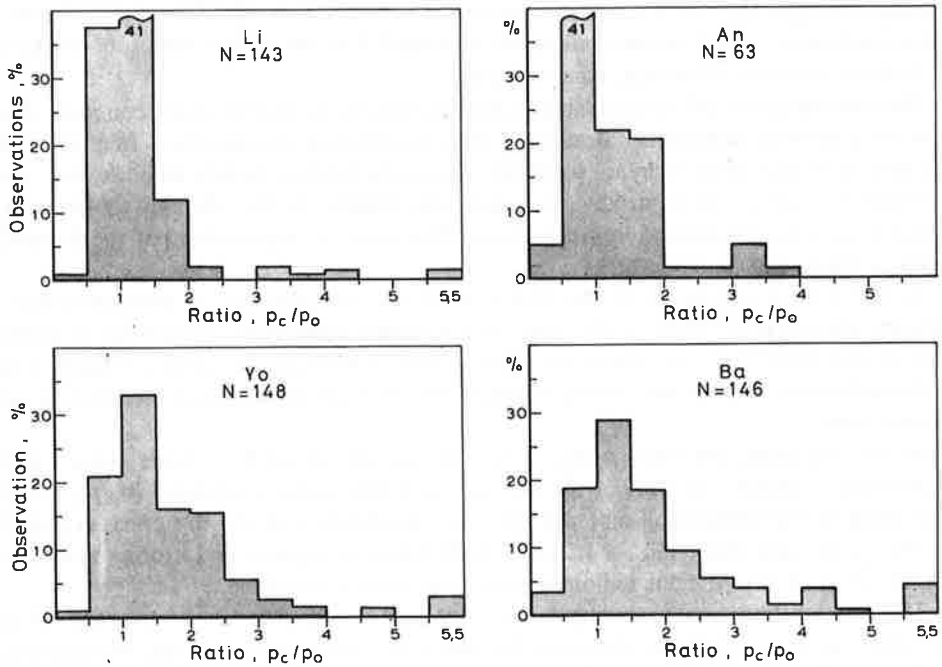

Fig. 36. Distribution of p_c/p_0 ratio in different types of sediment beneath dry crust.

For the estimation of state of consolidation, methods based on approximation have also been developed; in the application of these methods, a state of consolidation is estimated on the basis of plastic properties (I_p, w_L) and shear strength [inter alia, 71, 27]. KORHONEN and LESKELÄ [45] noted that by these methods it was not possible to estimate to a sufficiently high degree of accuracy the state of consolidation of sediments in southern Finland. According to LESKELÄ [50], a state of consolidation can, however, be approximately determined on the basis of shear strength, consolidation pressure, plasticity index and clay content arrived at by the vane test.

In the light of the material dealt with, Finnish fine-grained deposits underlying the dry crust are in the main normally consolidated or slightly overconsolidated (Fig. 36). Underconsolidation was found to occur in certain silt-bearing samples representing the basal portions of deposits. This phenomenon is regarded as being due mainly to disturbance of the samples. Overconsolidation was observed in all the types of sediment, the ratio p_c/p_0 being generally about 2···4.

Overconsolidation of Littorina sediment occurs mainly in the coastal region of southern Finland. Overconsolidation is often to be observed in such Littorina deposits which deviate markedly from underlying deposits by reason of their high humus content. Many exceptions, however, have been met with. In the Lokalahti area, where the humus content at its highest is about 13 per cent, the Littorina sediment is normally consolidated.

Correspondingly, the thick Littorina deposits investigated in the Salo region are not overconsolidated. The Littorina sediments investigated in the coastal region of the Gulf of Bothnia have been normally consolidated.

Overconsolidation of Ancylus and Yoldia sediments is slightly more common than that of Littorina sediments. Moreover, overconsolidation occurs more frequently in samples of Yoldia than Ancylus sediment. Overconsolidation occurs in both clay- and silt-bearing material. It is striking that soft and watery Yoldia clays in southwestern Finland are overconsolidated in many places. This is most characteristic of the Somero, Loimaa, Viiala and Tampere areas.

In the varved sediments of the Baltic Ice Lake, the number of overconsolidated samples approximates that in the case of the Yoldia sediments, amounting to nearly half of the total material. Overconsolidation occurs without any clear consistency in both predominantly silty and clayey material. No clear-cut geographical distribution can be discerned.

In the dry crust, the ratio p_c/p_0 is on the average about 5···7 times greater than underneath it (Table 23). Part of the dry crust is highly overconsolidated ($p_c/p_0 > 10$). According to the observation material, the overconsolidation of the dry crust, as judged by the mean value registered for its overconsolidation, is greatest in Littorina sediment, the dry crust of the Ancylus sediment being least overconsolidated.

The overconsolidation appearing in soft fine-grained deposits has been explained as the effect of several factors. Overconsolidation may have been caused by, for example, mechanical pressure exerted on the soil layer under consideration by another layer of drift, the advance of a glacier over the area, or chemical cementation. One factor estimated, in addition, by KANKARE [36] to have produced the slight overconsolidation of the clay at Kimola, in southeastern Finland was the action of capillary forces, along with the extra pressure caused by a change in the ground-water table. According to BJERRUM [6], no unmistakable cementation could be discerned in Norwegian clays, whereas in the clays occurring in the Göta valley, in Sweden, a certain kind of cementation is likely to be taking place. KENNEY's investigations have shown that iron compounds are responsible for the cementation taking place in Canadian clays [6]. According to CRAWFORD [14], seepage stresses of pore water are apt to produce some of the overconsolidation.

In the light of the present research material, it would appear as if the overconsolidation occurring in humus-rich Finnish Littorina clays were connected with the humus content, which in certain cases could act as a cementing agent [62]. On the basis of the examination

Table 23. Means of the p_c/p_0 ratio in different types of sediment.

Ratio p_c/p_0	Sediment type			
	Li	An	Yo	Ba
p_c/p_0 in dry crust	10,9 N = 22	7,1 N = 13	9,4 N = 17	8,3 N = 22
p_c/p_0 beneath dry crust	1,4 N = 143	1,3 N = 63	1,8 N = 148	1,9 N = 146

of the correlations, the observation was made that it is only in Littorina sediments that a highly significant correlation prevails between the p_c/p_0 and the humus content. The humus does not, however, alone explain possible sedimentation, for in many cases no overconsolidation occurs in humus-rich sediment. It is evident that, besides the humus content, also its quality and the chemical composition of the pore water are contributing factors in cementation.

It has been observed that overconsolidation in varved Baltic Ice Lake sediments occurs especially in cases where a deposit is situated topographically in such a way that a flow of the pore water to, for instance, lower levels is possible. Considering the varved structure of the type of sediment, it is probable that the capillary forces or seepage stresses influence the state of consolidation.

If the material composing the rich clays of southwestern Finland are to be viewed as being at least in part of interglacial origin, this might also explain the overconsolidation occurring in them. Accordingly, the overconsolidation caused by the weight of the continental ice sheet might to a slight degree have been preserved in the clayey material after its resedimentation.

In certain instances, it is conceivable that the overconsolidation was due to, for example, pressure exerted mechanically by earlier layers of soil, which have been removed by erosion. Chemical cementation is not a probability under the geological conditions that have prevailed in Finland. All in all, it may be noted that quite a few different factors are likely to have contributed to the overconsolidation occurring in fine-grained Finnish sediments. Consolidation pressure depends, however, apparently on both internal factors in the material and the geological evolution of the deposits.

8.3 Shear strength

Shear strength was determined in the field by the vane test and in the laboratory by the unconfined compression test and the fall-cone test. Triaxial tests were made, moreover, with some of the samples. Toward determining the relative strength of the various types of sediment, the shear strengths measured in situ by the vane test will be discussed in the following.

The strength measured by the vane test in impermeable homogeneous clays represents the so-called undrained shear strength ($\phi = 0$). This observation applies to clay-rich Littorina, Ancylus and Yoldia sediments. The vane test is not suitable for the determination of the strength of deposits containing large amounts of coarse silt. In silt and varved Baltic Ice Lake sediments, the soil layer investigated is apt to become consolidated during the vane test to such an extent that the strength measured may nearly present the so-called drained shear strength. In deposits of this kind, furthermore, the varved structure caused significant anisotrophy, which is reflected in the shear strength measured by the vane test, too [75, 45, 70].

When the undrained shear strength values measured by the different methods were compared, the observation was made that the unconfined compression test yielded markedly lower strength values than did the vane test. In many cases, the reason proved to be disturbance of the samples put through the unconfined compression test. The strength measured by the fall-cone test was most frequently on the same order of magnitude as the strength arrived at by the vane test – or, then, slightly greater. According to KORHONEN and LESKELÄ [45], the strength measured by the vane test corresponds quite closely to the strength values obtained with the triaxial test. The strength obtained with the vane test depends, moreover, on the shape of the vane. According to HANSEN and GIBSON [39], undrained shear strength is not a property of soil but a mode of its »behavior», which depends on the method of testing used. In the conditions prevailing in Finland, the vane test and the fall-cone test seem to be best suited to determining undrained shear strength. In important cases, shear strength ought to be measured by both of these methods.

In the present research material, the undrained shear strength of the Littorina sediments underneath the dry crust as measured by the vane test varies in general between about 1 and 3 Mp/m^2. In predominantly silty and humus-rich sediment in the Kemi region, shear strengths have been measured of between 3 and 6 Mp/m^2. Correspondingly, in the region of the coast of the Gulf of Finland, strengths have been met with of 0,5···1 Mp/m^2, and at the bottom of the sea immediately off shore of about 0,2···0,5 Mp/m^2.

The strengths of the Ancylus and Yoldia clays have been found to vary between about 1 and 3 Mp/m^2. The vane test has not proved to be suitable in measuring the shear strengths of Central Finnish silty sediments dating back to the Ancylus and Yoldia stages. The material is disturbed in connection with the thrusting of the vane into the ground in the case of these deposits to the extent that the shear strength measured is too small, in relation to the values obtained by the other methods applied in the present study – and it was often found to be nearly constant irrespective of depth (Fig. 37). Since the taking of undisturbed samples is difficult, the reliable determination of the shear strength of these silty sediments occurring in Central Finland, in particular, is in many cases exceedingly difficult.

The shear strength of the varved sediments dating from the stage of the Baltic Ice Lake varies considerably, depending primarily on grain size and water content. In the rich varved clays occurring along the south coast, the shear strength has frequently been measured between only one and two Mp/m^2. In the silty deposits of the hinterland, on the other hand, the strength varies usually from 2 to 6 Mp/m^2.

The shear strength of the dry crust varies according to its thickness. The values measured in thin crusts (ca. 1 m) have been at the minimum approximately 3 Mp/m^2. Those measured in thick crusts (2···4 m) have been 10···20 Mp/m^2. Owing to the cracked structure of the dry crust, the strength values registered have, however, been only indicative rather than definitive. Norwegian investigations [7] would show that the high strength of the dry crust is significantly due to the oxidation of iron: trivalent iron and, possibly, also aluminum are reported to act as cementing agents.

The strength values measured are dependent on depth (pressure) and the state of consolidation of the sediment. The relative distribution of the shear strength in different types of sediment has therefore been studied also by means of the ratio between the strength measured by the vane test and the consolidation pressure (s_v/p_c). On the basis of Fig. 38 and Table 24, it will be noted that the relative strength values measured in the sediments of the Ancylus and Yoldia stages and the Baltic Ice Lake by this method do not essentially deviate from each other. The relative strength of the Littorina

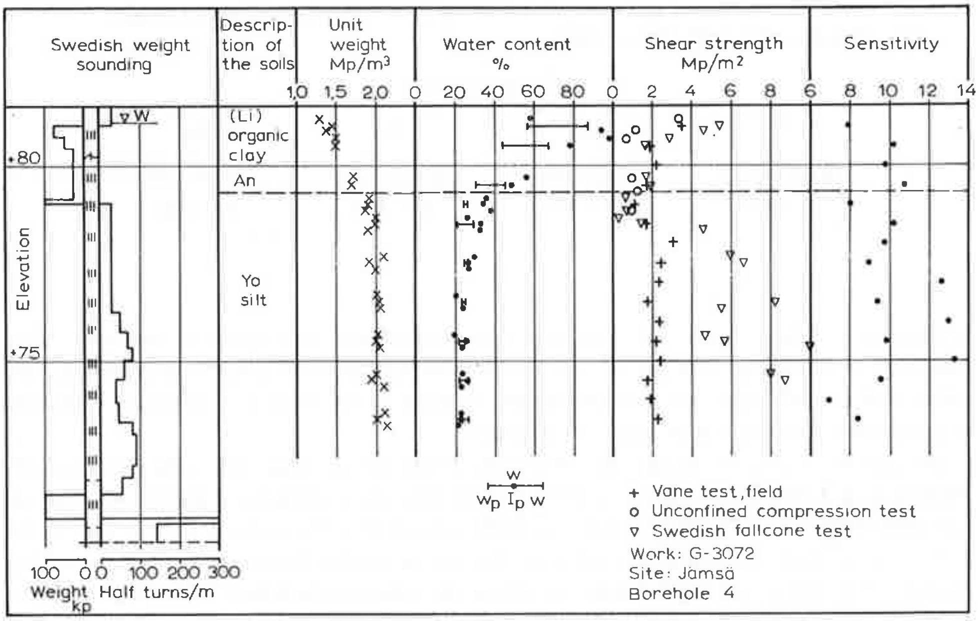

Fig. 37. Classification and strength properties, Jämsä.

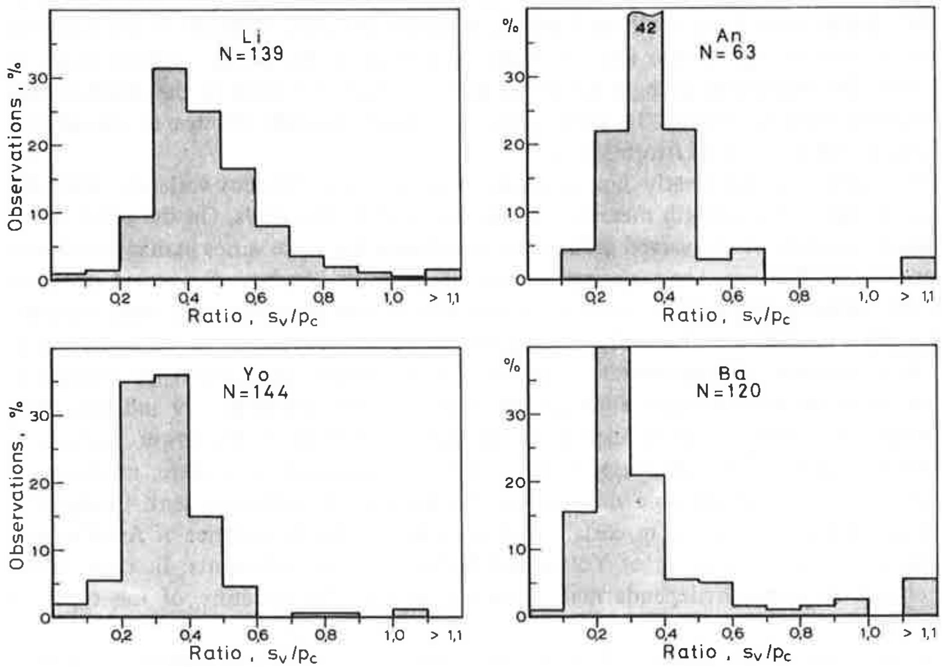

Fig. 38. Distributions of s_v/p_c ratio in different types of sediment beneath dry crust.

Table 24. The means and standard deviations of the ratio s_v/p_c in different types of sediment beneath the dry crust.

Sediment type			
Li	An	Yo	Ba
0,45 ± 0,17 N = 139	0,36 ± 0,10 N = 63	0,33 ± 0,13 N = 144	0,38 ± 0,30 N = 120

sediments, on the other hand, is greater than that of the other types of sediment. This disparity is probably due partly to the humus content of Littorina sediment. An additional contributing factor is the smaller effective unit weight of Littorina sediment as compared with the other types of sediment.

In certain cases, it should be observed, furthermore, that the vane-test strength measured in Littorina sediment is greater than that in underlying deposits and that in the same Littorina deposit the shear strength measured with a vane test increases along with any increase in the humus content. According to the investigations conducted by NASSIF [56], the presence of humus increases the cohesion between soil particles; hence as the humus content increases, also the strength (cohesion) measured by the vane test also increases in many cases. According to PUSCH [62], a humus content produces, especially in a saline sedimentation environment, a microstructure that can be largely deformed without rupture. The effect of humus on shear strength appears in numerous of the sample series from southern Finland, in which the shear strength of the Littorina sediment and the s_v/p_c ratio increase with an increase in the humus content (Figs. 39 and 40). The maximum strength has often been perceived to occur at the depth having the highest humus content. In these cases, the shear strength adheres to the general geological changes of the Littorina stage.

On account of the nearly homogeneous structure, no clear-cut variation generally occurs in the shear strength measured in Ancylus and Yoldia clays. On the other hand, the shear strength of the varved sediments of the Baltic Ice Lake varies in many instances in quite minor features. The variations in strength are caused by both the varved structure and the irregular alteration of predominantly clayey and predominantly silty deposits.

Locally, in southern Finland, changes occurring in »leaps» are to be observed in the shear strength of sedimentary deposits. These changes in strength are located in certain cases in the boundary zones of the types of sediment (Figs. 39 and 40). Such a change in strength is most clearly to be seen in general in the lower portion of Littorina sediment. The decrease in shear strength appearing, as it were, in »leaps» is attributable to an appreciable decrease in the amount of humus present. Changes of a corresponding type occur in certain instances also at the boundaries of Ancylus and Yoldia sediments as well as of Yoldia and Baltic Ice Lake sediments. In these cases, the change in strength depends mainly on changes in the structure of the types of sediment.

Of the shear strength measured by the vane test, it may be stated on the whole that it does not generally, with the exception of the afore-mentioned instances, vary with

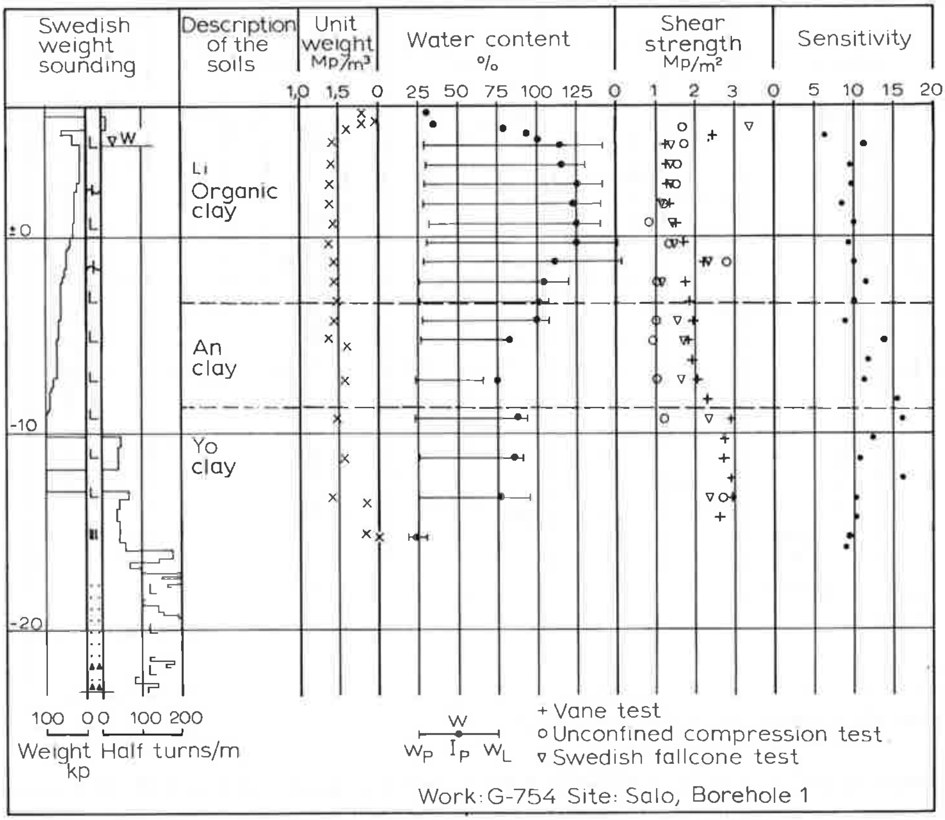

Fig. 39. Classification and strength properties, Salo.

the type of sediment. PUSCH [61] has observed, moreover, that no simple correlation exists between undrained shear strength and the microstructure of clay. The shear strength of fine-grained Finnish sediments beneath the dry crust is thus dependent mainly on the humus content (in this case, the type of sediment), the clay content and the consequent water content. Shear strength is further influenced by the state of consolidation of sediments. In addition, the varved structure of sediments dating from the stage of the Baltic Ice Lake causes conspicuous anisotropy.

8.4 Sensitivity

By sensitivity is meant the ratio between the undrained shear strength of a soil in its natural state and the shear strength of the soil when its structure has been totally disturbed. Sensitivity is usually determined by the vane test or the fall-cone test. KORHONEN and LESKELÄ [45] have observed that no clear correlation exists between sensitivity values measured by the vane test and those measured by the fall-cone test.

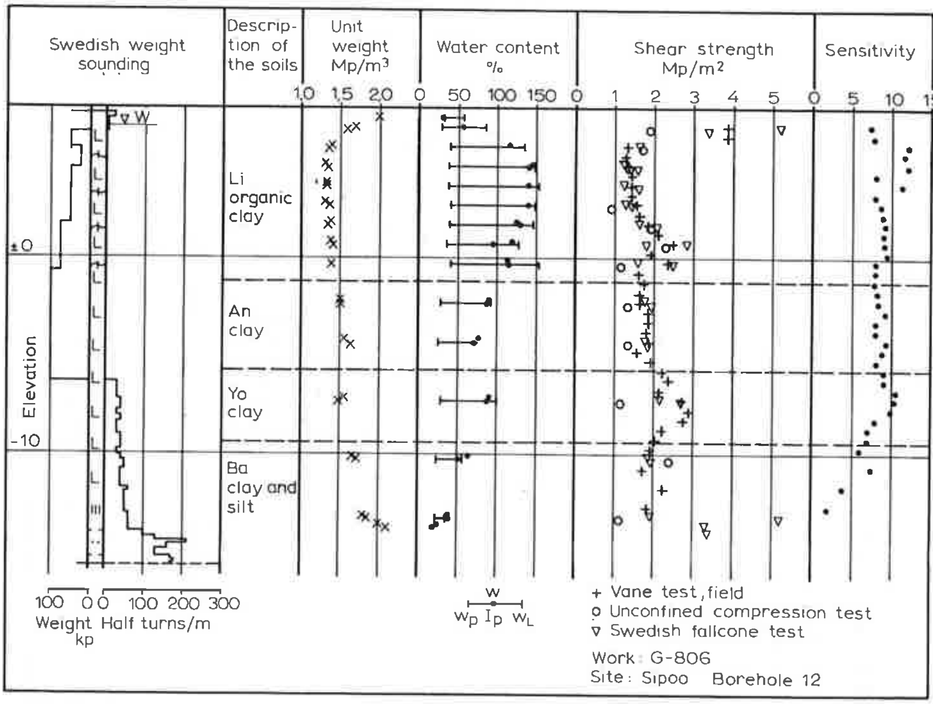

Fig. 40. Classification and strength properties, Sipoo.

Many slides on a noteworthy scale have occurred in quick clays, and for this reason the causes of sensitivity have been investigated widely. According to the most recently expressed views, it appears as if the quick clays occurring in Norway and Sweden can develop from normal clay through leaching by changes taking place in the relation between Na and Ca-Mg [77]. According to Pusch [61], however, »extreme sensitivity is not solely dependent on the microstructural constitution although an open particle network may be a necessary prerequisite.» Investigating the sensitivity of Finnish sediments, Keinonen [38] reached the conclusion that the fundamental prerequisite of sensitivity is the existence of a soil grain structure that is capable of resisting a far greater load with no noteworthy change of volume than the same soil can if the arrangement of its grains or the bonds between the grains have been disturbed.

In the course of the present study, exceptionally sensitive soils ($S_t > 32$) were met with in different parts of Finland. Highly sensitive soils occur on the whole as intercalations in a sedimentary deposit. The sensitivity measured by the vane test in these soils varied between about 30 and 80. As far as silts are concerned, however, it should be noted that the »undisturbed» shear strength measured with a vane test is in some instances clearly too small (Section 8.3). The sensitivity value thereby arrived at is correspondingly too low. This observation applies primarily to the silty deposits occurring in Central Finland. On the basis of the distribution of the sensitivity values determined by the vane test (Fig. 41), it can be stated that only in Ancylus and Yoldia sediments represented in the material of the present study do exceptionally sensitive soils occur.

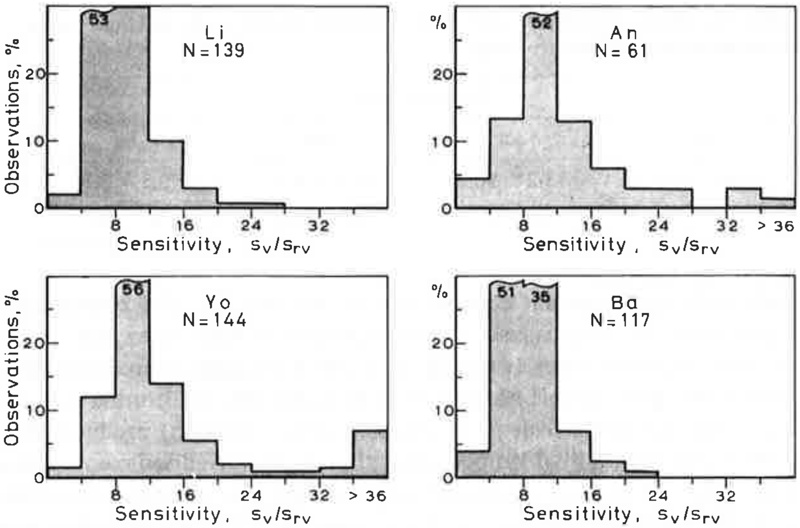

Fig. 41. Distributions of sensitivity determined by vane test in different types of sediment beneath dry crust.

In Ancylus sediments, the occurrence of these soils amounts to approximately five per cent and in Yoldia sediments to about nine per cent. Also KEINONEN's [38] studies reveal the occurrence of highly sensitive soils primarily in Ancylus and Yoldia sediments. In Sweden, TALME, PAJUSTE and WENNER [77] have run across exceptionally sensitive soils in Ancylus sediment. The Littorina and Baltic Ice Lake sediments correspond to each in this respect, their sensitivity ranging in the main between 4 and 12. Corresponding low sensitivities have been reported by SIMON [70] as accorring in varved clays of different countries. The variation in the sensitivity values measured in Ancylus and Yoldia sediments, however, is wide (Table 25). No clear geographical distribution can be detected in sediments containing highly sensitive soils.

The classification properties of the exceptionally sensitive soils investigated vary within a broad range. High sensitivity occurs in both silts and very rich clays. The clay content varies for this reason from about 10 to 80 per cent. The humus content, on the other hand, was found to be approximately 0,5···1,5 per cent. Mainly depending on the clay content, the water content was found to vary between about 25 and 120 per cent. The salinity of the pore water was measured at between 0,02 and 3 per mil, the principal range being, however, 0,1···0,3 ‰. The mineral composition cannot be regarded as having any influence on high sensitivity (Section 3).

On the basis of the geological evolution of the sedimentation basins, it was observed that highly sensitive soils had been deposited as sediment in both saline water along the southwestern coast and fresh water in the interior of the country. Leaching cannot therefore alone explain the development of sensitive soils occurring in Finland. In the light of the foregoing and according to KEINONEN's studies [38], sensitivity is not dependent on the classification properties of soils, either. Thus it is evident that the basic prerequisite of the sensitive soils occurring in Finland is an open particle network, which

Table 25. Mean sensitivities and their standard deviations in different types of sediment beneath the dry crust.

Sediment type			
Li	An	Yo	Ba
8,6 ± 3,7	13,2 ± 10,3	13,5 ± 9,7	8,5 ± 3,1
N = 139	N = 61	N = 144	N = 117

exists in soils with a predominant content of both silt and clay. The occurrence of high sensitivity primarily in Ancylus and Yoldia sediment is hard to explain. A common feature of these sediment types is usually a nearly homogeneous material with a low humus content. An open particle network is to be found also in Littorina sediments, but it is possible that the enhancement of cohesion (shear strength) produced by a high humus content is reflected by disturbed strength, too. In varved sediments dating from the Baltic Ice Lake, which were deposited in fresh water, the network of particles is not so open as in the sediments deposited in saline water [61]. It is apparent that, in general, exceptionally sensitive soils can develop through the work of many factors dependent on local geological conditions.

8.5 Consolidation properties

The consolidation properties of the soils investigated were determined with the type of oedometer normally used in Finland. The height of the samples used was 14 mm and the diameter 43,8 mm. The height of the dry-crust samples was 20 mm and the diameter 99,6 mm.

The samples were loaded in three stages, called: first loading stage, reversion stage and reloading stage. In the first stage, the sample was usually loaded by steps by doubling the pressure between 0,06 and 15,36 kp/cm². In the reversion stage, the pressures used were 0,96 and 0,12 kp/cm². The reloading stage involved 0,12, 0,48 and 1,96 kp/cm².

The correlation between the pressure and the consolidation of the sample is approximated in Formula (5) [cf., 58].

$$\epsilon = a \cdot \left(\frac{p}{p_1}\right)^k + c \tag{5}$$

$$\epsilon = \frac{\Delta h}{h_0}$$

Δh consolidation of sample under pressure p
h_0 initial sample height
a settlement number
p pressure, kp/cm²
p_1 1 kp/cm²
k settlement exponent
c constant

The tangent modulus and its coefficients were computed by means of the group of Equations (6) below [42].

$$E'_t = \frac{dp}{d\epsilon} \tag{6}$$

$$E'_t = \nu \cdot p_1 \cdot \left(\frac{p}{p_1}\right)^{\omega}$$

$$\nu = \frac{1}{a \cdot k} \; (k \neq 1)$$

$$\omega = 1 - k$$

E'_t tangent modulus (modulus of compressibility)
ν modulus number
ω modulus exponent

The coefficients a, k, ν and ω were computed on the basis of the observation results yielded by the oedometer tests by a computer.

The difference between the consolidation properties of different types of sediment is considered in the following by means of a modulus of compressibility corresponding to the consolidation pressure (p_c), which was worked out by applying Formula (7). This modulus represents the minimum value of the modulus of compressibility; hence it cannot be used as such in calculations of consolidation.

$$E'_{tc} = \nu \cdot p_c^{\omega} \tag{7}$$

Figure 42 makes it evident that the Littorina, Ancylus and Yoldia sediments correspond on the basis of the distribution of the modulus of compressibility quite closely to each other. The varved and predominantly silty Baltic Ice Lake sediments, on the other hand, constitute a separate category, in which the modulus of compressibility is distinctly higher than in the case of the other types of sediment. In all the types of sediment, however, there exists a wide range of variation.

In Littorina, Ancylus and Yoldia sediments, the modulus of compressibility varies underneath the dry crust largely between 1 and 4 kp/cm^2. These values represent the organic clays contained in Littorina sediments as well as the clay-rich soils of Ancylus and Yoldia sediments. In all three types of sediment, furthermore, there occur high values, which amount to several tens of kp/cm^2. The maximum values registered have been 100···200 kp/cm^2. They account, however, for only about from 5 to 15 per cent of the number of observations. The high values for the modulus of compressibility beneath the dry crust are met with in shallow-water silt sediments. For this reason, the predominantly silty Littorina sediments found in the coastal region at the far end of the Gulf of Bothnia are less compressible than the organic clays occurring in the coastal areas of southern and southwestern Finland. Correspondingly, the Ancylus and

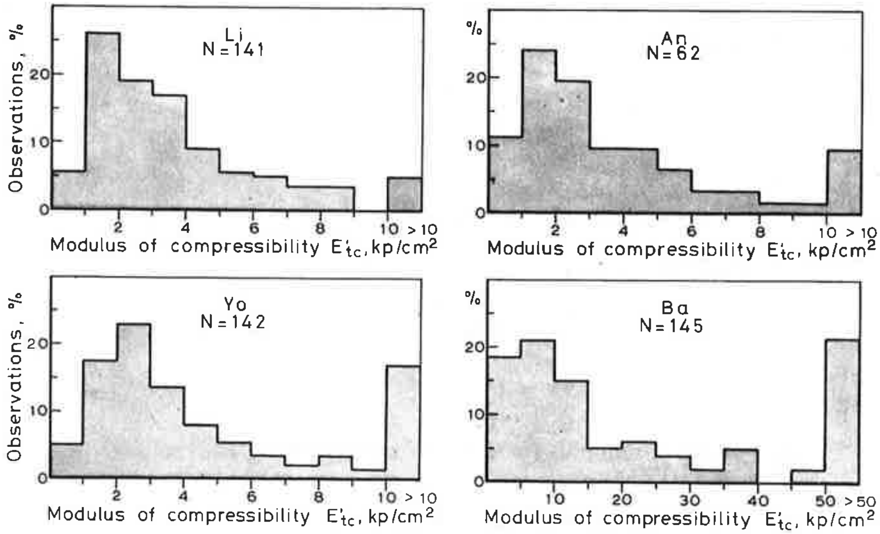

Fig. 42. Distributions of modulus of compressibility in different types of sediment beneath dry crust.

Yoldia silts of Central Finland are notably less compressible than the Ancylus and Yoldia clays of southern and southwestern Finland.

The modulus of compressibility of the varved sediments beneath the dry crust dating from the Baltic Ice Lake stage varies in the main between about 2 and 15 kp/cm^2. Higher values, however, occur in many places, the maximum values measured ranging from 100 to 200 kp/cm^2. Also in this type of sediment, the lowest values occur in clay-rich material and the highest in silty soils. Consequently, the clay-rich varved deposits found in the coastal region of the Gulf of Finland are compressible to a considerably greater extent than are the varved silt deposits occurring in the hinterland.

The modulus of compressibility in the dry crust amounts to several tens of kp/cm^2, the maximum values varying between 100 and 200 kp/cm^2. Compressibility is not dependent on the type of sediment but varies largerly according to the clay content and the thickness of the dry crust.

The compressibility of fine-grained soils is not clearly dependent in Littorina, Ancylus and Yoldia sediments on the type of sediment. Compressibility is thus not unambiguously dependent on the variation in the structure of the soil met with in these sediments. Investigating the microstructure of Swedish clays, Pusch [61] reached the conclusion that their compressibility was on the same order of magnitude irrespective of their microstructure. Pusch's findings thus support the results of the present study as far as the Littorina, Ancylus and Yoldia clays are concerned. In Pusch's view, among the factors most significantly affecting compressibility are the humus content and grain size of fine-grained soils. On the basis of the present research material, the observation can be made that the modulus of compressibility in Littorina sediment correlates most significantly of the physical properties with water content and humus content. The compressibility of Ancylus and Yoldia sediments is significantly dependent on the clay and water contents.

In sediments originating during the stage of the Baltic Ice Lake, the modulus of compressibility is highly significantly correlated with the clay and water contents – as well as with the unit weight. The lesser compressibility of these sediments in comparison with the other sediments is at least partly dependent on their varved structure. A clearly developed varved structure is not so easily compressible as the open structure occurring in other types of sediment. It is to be noted, moreover, that varved sediments consolidate, owing to their higher permeability, more rapidly under pressure from overlying deposits than do other types of sediment. The compressibility of fine-grained Finnish soils would thus be primarily dependent on their clay, humus and water contents as well as their state of consolidation. A varved structure has the effect of reducing compressibility.

9. CONCLUSIONS

The soft, fine-grained sediments occurring in Finnish geological conditions were deposited during the final stage of the last Ice Age or after it. They are less than 10 000···12 000 years old. In accordance with the evolutionary stages of the Baltic Sea, these sediments can be divided into four types, which are as follows, from the youngest to the oldest: Littorina, Ancylus, Yoldia and Baltic Ice Lake sediments. The former two types of sediment are nearly homogeneous in structure. Yoldia sediment is homogeneous in structure or is characterized by symmyctic varving. The sediments dating from the Baltic Ice Lake are in general distinctly varved, diatactic. Consequently, this type of sediment is distinctly anisotropic in its properties.

In line with geological evolution, fine-grained sediments occur primarily in southern and southwestern Finland as well as, in general, in coastal areas. In Central, eastern and northern Finland, fine-grained sediments are rarely met with. Sedimentary deposits generally include all the stratigraphic series of layers that might be assumed to exist on the basis of the geological development of each area. Locally, however, hiatuses occur owing to the absence of certain types of sediment, notably those dating from the Ancylus and Littorina stages. The reason for the lack of such deposits appears to be random sedimentation, a water stage of short duration and erosion by bottom currents and waves. Considerable sedimentation might have taken place even after the local area of water connected with the basin of the Baltic Sea had contracted and formed a separate lake basin.

The average thickness of the sedimentary deposits in southern and western Finland is on the order of magnitude of about 10 meters. The thickness of the predominantly silty deposits met with in the interior of the country varies generally between about five and ten meters. Thick sedimentary deposits are met with in the valley formations of southern and southwestern Finland, where clay deposits between 30 and 50 meters thick are likely to occur. Even in valleys, the thickness of a sedimentary deposit is apt to vary considerably: a ridge of bedrock or a moraine is apt to rise to the surface in the middle of a valley.

In the older view, the Finnish fine-grained sediments originated when meltwaters from the receding continental ice sheet washed off the fine particles from till deposits. Considering, however, the quantity of sedimentary material, such an explanation alone is insufficient. The probability is that a substantial portion of the material composing the fine-grained sedimentary deposits derives from interglacial (Eem) or interstadial sediments. This view is supported by, for example, the microfossils contained in the Somero district of southwestern Finland and local submorainic clay layers.

In mineral composition, the sedimentary material is monotonous. The granular minerals are predominantly quartz and feldspar, with minerals of the amphibole group occurring in small amounts. The main group of micaceous minerals consists of mica and/or illite minerals as well as, in many instances, chlorite. The regional variation is slight. The shallow-water sediments of Central and eastern Finland contain in places small amounts of vermiculite. The general occurrence of mixed-layer minerals and vermiculite is largerly associated with the dry crust. Apparently, in the cool climatic conditions prevailing in the northern countries, the mineralogical development of the sediments leads at a fairly early stage to illite clays, beyond which no significant changes take place. The slight variations in the mineralogical composition of the sediments have no bearing on, inter alia, the geotechnical properties of the soils.

The mean pH values of fresh sedimentary material vary between 7,3 and 8,3. The most basic material occurs in the sediments of the Baltic Ice Lake. When reliable pH values are sought, the acidity should be measured in the field in conjunction with the taking of the samples, for oxidation begins immediately after a sample has been taken. Oxidation is the most intense in highly saline layers. It is not possible to differentiate types of sediment on the pH values of fresh material. On the other hand, it is possible in certain cases on the basis of the pH determined from the material of dry samples.

Appreciable variation occurs in the salinity of the pore water of sedimentary material. The highest salinity values (ca. 8 ‰) have been measured in Littorina sediments in southwestern Finland. Salinity decreases toward the north and the east from the southwest, owing to the passage of salt water from the southwest into the basin of the Baltic Sea. The maximum salinities of Littorina sediments at present appear to represent approximately one-half of the original salinity. The salinity has therefore, as a result of, among other things, diffusion and leaching, diminished significantly. In the basin of the saline Littorina Sea, there also occurred sedimentation under conditions of brackish or nearly fresh water. Areas of this kind are to be found in certain parts of valleys, through which during the Littorina stage fresh water flowed from the mainland.

In other types of sediment, the average salinity of the pore water is considerably below the level met with in Littorina sediments. The variation in the results is large, however, for in the sediments of coastal areas salinities of many units per mil occur, whereas the salinity of the pore water contained in the sediments of the hinterland is very slight. The difference is due, as in Littorina sediments, too, to the direction from which the salt water from the ocean came as well as to the meltwaters streaming from the continental ice sheet. Local factors, such as topography, the flow of ground water, etc., are apt to change salinity significantly. It is to be noted, in addition, that saline pore water worked down, as a result of, for example, diffusion, to lower, fresh-water levels.

The classification properties of fine-grained deposits vary in general according to the type of sediment. The classification properties of Ancylus and Yoldia sediments are frequently found to be on the same order of magnitude. Accordingly, three classes of sediment differing from each other in their classification properties can be distinguished: Littorina sediments, Ancylus-Yoldia sediments and sediments of the Baltic Ice Lake stage.

Yoldia sediments contain clayey material in the largest amounts. The varved sediments of the Baltic Ice Lake have the highest silt content. The humus content is highest in Littorina sediments, the mean being about 4 per cent. The average humus content of Ancylus and Yoldia sediments is 1···1,2 per cent and that of Baltic Ice Lake sediments 0,6 per cent. The other classification properties, with the exception of the unit weight of solid particles, follow primarily the changes in clay and humus content.

In Littorina sediments, the unit weight of the solid particles depends on the humus content. In other types of sediment, the average unit weight of the solid particles is nearly constant, owing to the low humus content and the one-sided mineralogical composition. With respect to the unit weight of the solid particles, the sediments are thus divided into two groups.

The dependence of the classification properties primarily on the clay and humus content strengthen, moreover, the correlations between these properties. It should be noted, however, that the correlation between the different types of sediment varies. A highly significant correlation between the classification properties and the humus content is found primarily in Littorina sediments. In the other types of sediment, the classification properties are most significantly correlated with the clay content.

In Finland, fine-grained deposits are normally consolidated for the most part. Overconsolidation occurs, however, in many places beneath the dry crust, the ratio p_c/p_0 being in quite a few instances in the overconsolidated portions on the order of 2···4. Overconsolidation is met with in all the types of sediment as well as in material composed predominantly of clay and of silt. Evidently, in humus-bearing Littorina sediments, the humus is apt in certain cases to act as a cementing agent. As far as varved sediments dating from the stage of the Baltic Ice Lake are concerned, observations indicate that capillary forces or seepage stresses had contributed to the state of consolidation. The pressure of overlying deposits removed by erosion as well as, possibly, overconsolidation partly preserved in old clay material would account for, among other things, the overconsolidation existing in Ancylus and Yoldia sediments. Chemical cementation, properly speaking, is not a likelihood under the conditions that have prevailed in Finland. The slight overconsolidation met with in Finnish sediments was apparently brought about by a number of factors operating within the material itself as well as by the local geological evolution.

The undrained shear strength measured by the vane test is apt to vary in the fine-grained Finnish sediment beneath the dry crust inside the range of about 0,2···6 Mp/m^2. In certain instances, changes by leaps are to be observed in the shear strength of sedimentary deposits in southern Finland. These changes in strength are often met with in the boundary zones of the different types of sediment. The most distinct change in shear strength occurs generally in the lower portion of Littorina sediment, where under the maximum value of the humus the shear strength decreases clearly in many instances. Corresponding changes in strength are occasionally observed in the boundary zones of other types of sediment, too; in such cases, the change in shear strength is due mainly to changes in the classification properties of the sediment.

When the shear strength is measured by the vane test in the light of the ratio between strength and consolidation pressure (s_v/p_c), the observation is made that these relative strengths in the Ancylus, Yoldia and Baltic Ice Lake sediments deviate slightly from each other. The relative strength of Littorina sediment, on the other hand, exceeds slightly that of the other types of sediment. This is influenced by both the humus content of Littorina sediment and its rather small effective unit weight. In the conditions prevailing in Finland, the shear strength of fine-grained sediments is thus dependent mainly on the humus content (Li), the clay content (An, Yo, Ba) and the water content.

In addition, varving causes appreaciable anisotropy in, notably, the sediments dating from the Baltic Ice Lake.

The present study revealed that exceptionally sensitive clayey and silty soils ($S_t > 32$) are contained primarily in Ancylus and Yoldia sediments. The sensitivity does not depend on the classification properties, in addition to which the salinity of the pore water varies within wide limits. The basic prerequisite of exceptionally sensitive soils in Finland appears to be an open particle network, which resists a far heavier load with no noteworthy change of volume than does the same soil if the arrangement of the grains has been disturbed [38].

The modulus of compressibility corresponding to the consolidation pressure of fine-grained sediments varies beneath the dry crust in humus- and clay-rich Littorina, Ancylus, and Yoldia sediments most commonly from 1 to 4 kp/cm^2. The modulus values of the silty soils of the hinterland are apt to be several scores of kp/cm^2. The modulus of compressibility of the varved sediments of the Baltic Ice Lake varies in clay-rich material between about 2 and 15 kp/cm^2, the compressibility of the silt soils being on the same order of magnitude as in the case of the other types of sediment. The average compressibility is not distinctly dependent on the variation in structure that occurs in Littorina, Ancylus and Yoldia sediments. Only the sediments of the Baltic Ice Lake can be set apart in this respect. Compressibility is thus dependent in the first place on the clay, humus and water contents. A varved structure has the effect of diminishing compressibility. In settlement calculations, the state of consolidation of the deposits should further be taken into account.

The classification properties of fine-grained Finnish sediments as well as their strength and consolidation properties are influenced most significantly, according to the present study, by – among the properties of the sedimentary material itself – the contents of clay and humus and the water content dependent on them. When these properties vary clearly in the different types of sediment and do not cancel out each other's influence, the sediments dating from different stages in the evolution of the Baltic Sea can be separated into different classes on the basis of their engineering-geological properties.

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