NORGES GEOLOGISKE UNDERSØKELSE NR. 197

# MICROPALEONTOLOGY APPLIED TO SOIL MECHANICS IN NORWAY

*Sammendrag:*

## MIKROPALEONTOLOGI ANVENDT PÅ GEOTEKNISKE PROBLEMER I NORGE

AV

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WITH 22 TEXT-FIGURES, 3 PLATES
AND 3 TABLES

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# Contents.

# Abstract.

A brief review of the geological history of the Late Pleistocene marine clay deposits of the Oslofjord area, southeastern part of Norway, has been given, and a stratigraphical division of these sediments, established upon the basis of their included Foraminifera, has been presented. This foraminiferal stratigraphy has been correlated with older divisions of the deposits based on megafossils. The striking observation has been made that a close correlation exists between the stratigraphy of a clay deposit and its geotechnical properties. This is most beautifully demonstrated by one of the properties, viz. the shear strength. It has been attempted to explain this by the relation between original and present salt concentration in the pore water of the clay. Finally, micropaleontology has been applied to the problems of tracing old land slides and recent slip planes, such applications having been illustrated by examples from Trondheim and Oslo.

# Introduction.

The main subjects of soil mechanics in Norway are the properties of Late Pleistocene marine clay deposits, and the present paper is an attempt at introducing the methods of micropaleontology into these practical problems.

The advantages of micropaleontology, compared with the classical invertebrate paleontology, in classifying different layers of a sediment lie in the small size of the fossils with which it deals. By borings through the subsurface megafossils, or fragments thereof, will only accidentally be present in the core even if the sediment is rich in fossils. This is due to the relatively small diameter of the drill hole, or the small entrance diameter of the piston sampler. Stratigraphic work on core material, when based on megafossils alone, would therefore be difficult, if possible at all, whereas microfossils will usually occur abundantly even in drill cores. Instead of single specimens or scattered fragments the microfossils provide whole populations for stratigraphic interpretation. On account of their large number microfossils can be treated statistically, and also by this they constitude a far safer base for paleostratigraphic conclusions than specific determination of a few, occasionally occurring, megafossils. For the same reason microfossils are particularly useful in paleo-ecology, which is concerned with the environmental conditions at the time when the microorganisms lived and died and were deposited—such as temperature, depth and salinity of the water.

The Norwegian Late and Post Glacial marine clays have their greatest extension around Oslofjorden and Trondheimsfjorden, and Foraminifera form the bulk of the microfossils in these sediments. In addition some species of Ostracoda occur in most samples and occasionally a single specimen of Radiolaria or Diatomacea may be observed; microscopic elements of larger animals are represented usually by echinid spines and skeletal remains and intermittently also by sponge spicules.

The Foraminifera are single-celled animals belonging to the Protozoa. By far the greater part of them are marine, only very few live in brackish or even fresh water (Cushman 1940). They develop a test which in a few species is composed of a thin, flexible and transparent layer of chitinous material, in other species it is made up of arenaceous material of foreign origin more or less firmly cemented on a chitinous basal layer, and the largest group have calcareous tests which may be perforate or imperforate and appear hyaline or porcellanous. Siliceous tests also occur, and among larger Foraminifera, such as Fusulinidae, highly elaborate wall structures are developed (Glaessner 1948). Large Foraminifera have, however, not been observed in Norwegian Late Pleistocene deposits.

Foraminiferal tests are surprisingly resistant, and may be preserved in sediments even of Cambrian origin. The size of specimens from Late and Post Glacial clays of Norway generally ranges from 0.1 to 0.5 mm, the majority of them having diameters or lengths between 0.2 and 0.3 mm.

The species of Foraminifera which have been found in these young sediments are all recent, none of them have become extinct in the course of 20,000-10,000 years. Nevertheless, due to their sensibility to changes in environmental conditions, they have proved their usefulness in stratigraphic research even within this comparatively short span of time. The differences in composition of foraminiferal populations from the sequence of Late Pleistocene deposits reflect i.a. the changes in water temperature and salinity which were caused by the variations and oscillations of the climate during this time, and thus, these differences become stratigraphically significant. As the fossil faunas are composed of recent forms, the ecology of some of the species is quite well known.

In 1954 Dr. G. Holmsen of the Trondheim Harbour Committee, recognizing the practical value of micropaleontology, made use of foraminiferal analyses in subsurface investigations of the harbour of Trondheim, and later several micropaleontological investigations have been carried out for the Norwegian Geotechnical Institute (Oslo and Trondheim). This institute has made a considerable number of subsurface explorations and laboratory determinations of the geotechnical properties of soils, mostly connected with engineering projects (Bjerrum 1954 a). The greater part of these soils are Late Glacial and Post Glacial marine clays, and the director of the institute, Dr. L. Bjerrum, has generously placed at my disposal a large number of cores from numerous borings through Norwegian Late Pleistocene deposits. This material, though as yet only partly examined, has greatly contributed to the establishing of a stratigraphy of these sediments based upon microfossils.

In the preparation of this paper my work has been highly stimulated by discussions with Dr. Bjerrum, and I am especially indebted to him for his never-failing interest and for facilitating the work by generously placing samples and geotechnical records at my disposal. I should also like to express my thanks to Dr. G. Holmsen who kindly read the manuscript and offered many useful suggestions, and also to Curator H. Rosendahl and Professor Dr. I. Th. Rosenqvist for their willingness to discuss problems. I am furthermore greatly indebted to the Faculty artist Miss Ingrid Lowzow who prepared the drawings, and to the Faculty photographer Miss Bergliot Mauritz who prepared the photographs. I finally thank Norges Geotekniske Institutt, Norges Varekrigsforsikrings Fond and Norges Almenvitenskapelige Forskningsråd for financial support in the preparation of the paper.

This paper should have been preceded by one dealing with the foraminiferal fauna of the different zones of the new stratigraphical division here presented. This latter paper is, however, not yet ready for publication, but from a geotechnical point of view it has been thought desirable not to delay the publication of the present one.

# Geology.

## Geological history.

During the Pleistocene epoch Scandinavia was at least three times covered by immense ice sheets, the advancing front of which carried away most of the unconsolidated sediments which they met on their way. The unconsolidated sediments of Norway to-day are therefore, in general, those which were deposited at the retreating front of the latest glaciation. The accumulation of snow and ice in Fennoscandia caused a depression of the land mass so that its coasts became deeper submerged into the sea than they were before the glaciation. During the subsequent period of climatic amelioration the weight of the ice masses lessened, and consequently an isostatic elevation of the previously glaciated region took place. A great part of the marine sediments were thus raised above sea level, now forming the building ground in some of the most densely populated areas of Norway, viz. the areas around Oslofjorden and Trondheimsfjorden. Due to the inertia of the earth crust the general elevation of the land mass has continued, at a retarding rate, ever since the ice cover of the latest glaciation decreased and vanished, and is still asserted to-day. At Oslo the highest raised shoreline is now found 221 m above present sea level (see also G. Holmsen 1955).

The retreat of the ice of the latest glaciation was, from one time to another, interrupted by stagnations, oscillations or even readvance of the ice front. The positions of the ice front at these periods are marked by marginal moraines, the most prominent of which is the well known **Ra** which in the Oslofjord area can be traced from Halden over Sarpsborg to Moss, and from Horten to Larvik-Helgeroa. Its stratification, as well as its content of marine fossils, show that this conspicuous moraine is a submarine formation. Of later origin are prominent morainic deposits farther north at Mysen, Ås-Ski, Storsand. These are approx. contemporaneous marking a stagnation or oscillation of the receding ice front which is called the **Ås-Ski stage**. The next distinct stage is found in moraines just north of the city of Oslo—at Linnerud, Grefsen,

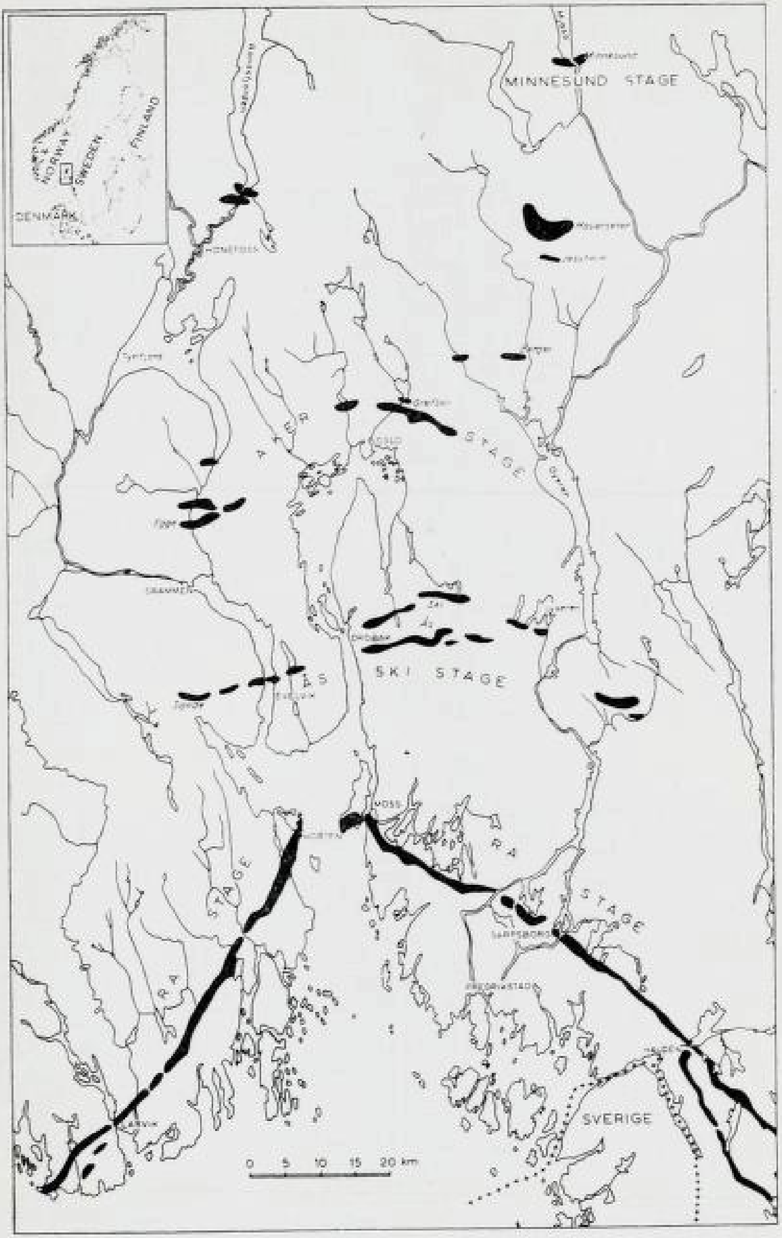

Fig. 1. Schematic illustration of the moraines marking the different stages of the retreating ice cover of the latest (Würm—Wisconsin) glaciation of the Oslo region. (Redrawn from Holtedahl 1953.)

*Morenetrinn avsatt under isens tilbakerykning.*

Sognsvann, Bogstadvann and, farther west, Egge in Lierdalen (Lier valley) north of Drammen. These moraines indicate a glacial readvance, and are referred to as the Aker stage. In the region of Romerike, north and northeast of Oslo, marginal glacial formations are found at Berger, Jessheim and Hauerseter, the latest stagnation of the ice front in this area being the Minnesund stage at the southern end of the lake Mjøsa.

The different morainic stages of the area have been schematically marked in figure 1; for details about the stages the reader is referred to the description of Holtedahl (1953). Marine sediments of Late Pleistocene origin have been found as far north as the southern end of Mjøsa and, along the river Glåma, northwards to Våler (see G. Holmsen 1954 and fig. 2).

## Stratigraphy.

From a quantitative study of the foraminiferal content of some marine Late Pleistocene samples from the Oslofjord area (Feyling-Hanssen 1954 a and b, 1955) it appears that sediments of Late Glacial age, when an ice cover still existed and the thermal conditions of the sea were arctic, are easily distinguishable from Post Glacial ones, the first being dominated by the foraminiferal species *Elphidium clavatum* together with *Cassidulina crassa*, the latter by *Bulimina marginata* together with *Elphidium incertum*. The number of species are also usually greater in Post Glacial sediments than in Late Glacial.

Later micropaleontological work with core material from a number of borings within the Oslofjord area (Sarpsborg, Fredrikstad, Oslo with suburbs, Drammen, Romerike) and also some from the city of Trondheim has verified the simple distinction between Late Glacial and Post Glacial clays. It has furthermore been possible to subdivide the Late Glacial into 4 zones which are called A, B, C and D, and the Post Glacial into 3 zones, viz. E, F, and G.

These zones are recognized from one core to another; even though local environmental conditions have added different characters to the foraminiferal fauna, the stratigraphic characters appear through the facies differences. In two later papers we will see how our seven zones are defined by the occurence and frequency of certain species of Foraminifera in the deposits, in the Oslofjord

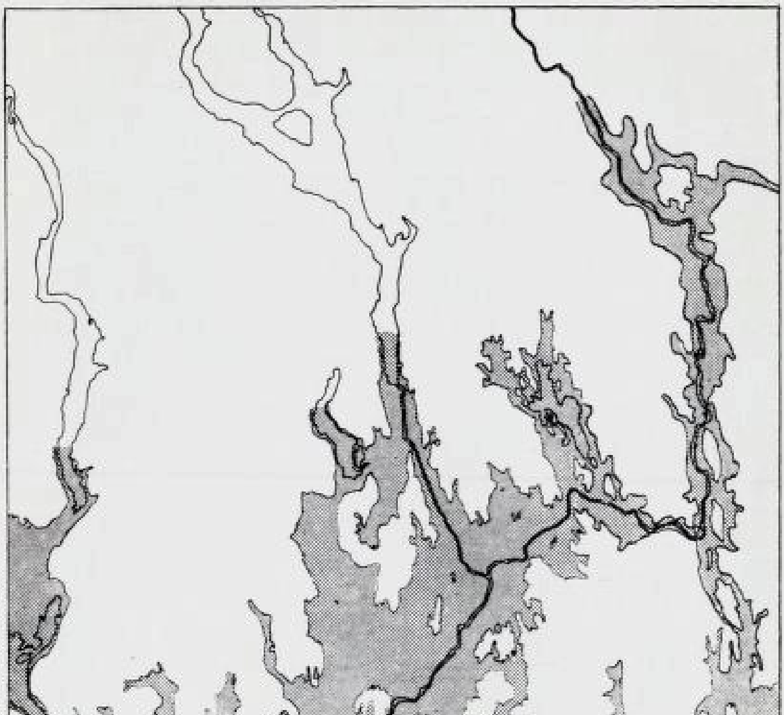

Fig. 2. The maximum extension of the Late Glacial sea. (Holmsen 1954.)

*Den maksimale utbredelse av det senglaciale hav.*

area as well as in the region of Trondheimsfjorden. In current micropaleontological work the zones are in general easily distinguished by a few common species in their foraminiferal content. In the present paper, however, we will just treat our zones as well-defined stratigraphical units, and see how these units may contribute to the solution of practical geotechnical problems.

Zone A comprises the oldest strata of the Norwegian Late Pleistocene, they were deposited under high-arctic climatic conditions when Norway was almost entirely covered by ice. In the Oslofjord area clays of zone A have only been found to the south of, and into, the previously mentioned large marginal moraine called the Ra. For reasons which will be discussed in a later paper, we may assume that the sediments of zone A were deposited in sea-water of rather high salinity. Among the Mollusca *Portlandia arctica* is the index fossil of zone A.

Zone B comprises sediments which were deposited during amelioration of the climate when the ice margin receded northwards from the Ra. Outside (south of) the Ra these deposits occur superposed on sediments of zone A, but north of the Ra they rest on moraine. Clays belonging to zone B are found northwards almost to the city of Oslo. Great masses of ice must have been melted away during this period, and the water of the corresponding Oslofjord must have been much diluted by fresh melt-water. The salinity was therefore probably considerably lower than that of the zone A sea, probably lower than 30 ‰. Among the Mollusca *Bathyarca glacialis* (= *Arca glacialis*) is the index fossil of zone B.

Zone C comprises sediments which seem to have been deposited under marine-ecological conditions which were distinctly better than those of the previous zones. The water temperature must have been comparatively high, at least at the beginning of the period. The highest marine limit in Oslo, 221 m above present sea level, dates from the period of zone C. The corresponding fjord basin was thus considerably wider and better ventilated than the basin of to-day, and the salinity of the water was certainly between 30 and 35 ‰. Clay layers belonging to zone C have been found in borings from Fredrikstad, Oslo, Drammen, Eidanger and Trondheim. In Oslo, when present, they form the oldest part of the clay sequence. Zone C seems to be absent in the area of Romerike northeast of Oslo, in protected localities, however, sediments belonging to this zone would be expected even there. Among megafossils the pelecypod *Yoldiella lenticula* (= *Portlandia lenticula*) is the most frequent one in samples from zone C.

Zone D comprises sediments which contain a poor foraminiferal fauna. These sediments seem to have been deposited in water of low temperature. At the beginning of this period the climatic conditions had once again become arctic or at least subarctic, and the glaciers had readvanced almost to to the site of the city of Oslo forming the marginal moraines of the Aker stage. A considerable decrease in salinity took place when the glaciers receded anew, supplying the fjord with large quantities of fresh melt-water, and during this period of glacial recession great masses of zone D sediments were deposited. The salinity of the corresponding water was probably considerably lower than 30 ‰, probably between 30 and 16 ‰. Sediments belonging to zone D have been found around Oslo and Drammen and northwards over Romerike to the southern end of Mjøsa. The most frequent megafossil of zone D is *Yoldiella lenticula* and in addition *Portlandia arctica* occurs intermittently.

With the deposition of the zone E layers the marine-climatic conditions have changed from arctic or sub-arctic to boreal, and, according to this, we have arrived from Late Glacial into Post Glacial age. A shrinking ice sheet probably still existed in the first part of this period, but, on the whole, the ice cover had vanished from the land. The contemporaneous sea-water must have had high salinity, certainly 30-35 ‰. Sediments belonging to zone E have not been found in the Romerike district but seem to be commonly distributed elsewhere in the Oslofjord area. Among the megafossils of zone E are *Mytilus edulis*, *Cyprina islandica*, *Cardium echinatum* and *Cardium edule*.

Zone F comprises sediments which were deposited during a period of optimum climatic conditions. Both water temperature and salinity seem to have been higher than during any other Late Pleistocene period. Zone F layers occur at Oslo and southwards in the area, but they have hitherto not, at least not in typical development, been met with in the Drammen district. Drammensfjorden is separated from Oslofjorden by the Svelvik moraine through which a narrow sound has been eroded. The moraine is to-day 50 m high in its middle part and rises to approx. 70 m at the eastern fjord side. It dates from the time of zone B and was deposited as a submarine formation. During the subsequent periods the shoreline was lowered, more or less constantly, and at the beginning of the time of zone F its position at Svelvik was approx. 60 m above present sea level (see Holtedahl 1953, p. 735). Consequently the top of the moraine was, about that time, raised above sea level, and the fjord inside the moraine became landlocked with stagnant water in its deeper parts. From this time on the living conditions for a population of benthonic Foraminifera were extremely bad, and, therefore, the foraminiferal fauna characteristic of zone F (and G) probably never existed in Drammensfjorden inside Svelvik, at least not in its deeper parts.[1] Among the mollusks *Isocardia cor* is the index fossil of zone F.

Zone G comprises sediments which contain remarkably less Foraminifera than those of the previous zone. A deterioration of the climate took place during the deposition of the zone G layers, transforming it, little by little, into the present one. Simultaneously the shoreline was lowered from approx. 20 m above sea level, at Oslo, to its present position, in many places changing previously well ventilated parts of the fjord into more or less land-locked bays or inlets with badly ventilated water of low salinity. Accordingly many samples from this zone contain only a few arenaceous forms and, as accessible sediments of zone G were generally deposited in shallow water, they will often contain shallow-water species. Zone G should, therefore, at many places be regarded as a facies unit more than a stratigraphic one. Concerning the inner part of the Oslofjord region, the salinity of the water into which the sediments of zone G were deposited must have been low, probably between 30 and 20 $^0/_{00}$. Among the Mollusca the index fossil of this zone is *Scrobicularia plana*.

The present stratigraphic scheme does not represent a definite, in every detail completed, division. Continued work with Norwe-

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[1] Strøm (1936, p. 68) described a change from laminated to massive clay which occurred in a 0.7 m long core from the bottom of Drammensfjorden inside Svelvik, and explained this as resulting from a change in climate which probably took place at the year 1300 A.D. This change has nothing to do with the conditions discussed above.

gian marine deposits from the Late Pleistocene will most probably involve changes in the diagram as to stratigraphical occurrence of certain foraminiferal species, thus improving its practical value. It has, however, in its present form already proved its usefulness in current micropaleontological work. In the following chapter this scheme, based on Foraminifera, will be correlated with two older stratigraphical divisions of the Late Pleistocene of the Oslofjord area which was based on megafossils.[1]

## Correlation.

Brøgger (1900—1901) established a stratigraphy of the marine sediments deposited at the retreating front of the ice of the latest glaciation on the basis of their content of fossil pelecypods (bivalves). The Late Pleistocene clay sediments of the Oslofjord region were thus divided into 12 zones, and contemporaneous littoral deposits into 6 shell beds as follows:

| Clay deposits | Shell beds |
|---|---|
| *Scrobicularia clay* | *Lower Tapes beds* |
| *Isocardia clay* | *Upper Tapes beds* |
| *Upper Ostrea clay* | *Upper Ostrea beds* |
| *Younger Cardium clay* | |
| *Older Cardium clay* | *Lower Mya beds* |
| *Mytilus & Cyprina clay* | *Upper Mya beds* |
| *Youngest Arca & Portlandia clay* | *Mytilus gravel* |
| *Younger Arca & Portlandia clay* | |
| *Middle Arca & Older Portlandia clay* | |
| *Older Arca clay* | |
| *Younger Yoldia clay* | |
| *Older Yoldia clay* | |

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[1] Our stratigraphical terms, zone A, zone B, etc., have nothing to do with the geotechnical zones A, B, C and D introduced by Bjerrum (1954 c), or with the pollenanalytical zones A-D described by Kari Egede Larssen (1950).

This scheme in general appears to be too detailed for practical purposes because the different zones are not always recognizable in the field. From its shell content a clay deposit can, usually, be identified as a Yoldia clay or an Arca clay or a Post Glacial clay, but if it should be classified as Older or Younger Yoldia clay, or as Older, Younger or Middle Arca clay, or as Upper Ostrea clay or Isocardia clay cannot often be decided. Brøgger's stratigraphy, slightly modified, has been schematically illustrated in figure 3, in which the different clay zones and their relation to morainic stages, shell beds and heights above present sea level are indicated.

To the right in the diagram (fig. 3) another paleontological division, established by Øyen (1915), has been inserted. This is a division of littoral formations based upon and named after characteristic mollusk species and referred to certain intervals in the position of the shoreline. The Littorina stage is thus a period, characterized by the presence of the gastropod (snail) *Littorina littorea* in the littoral deposits, during which the shoreline at Oslo was lowered from 175 to 130 m as referred to present-day sea level. The different stages and the corresponding position above present sea level of their upper shorelines at Oslo and Trondheim are as follows (Øyen 1917):

| Stages | Oslo | Trondheim |
|---|---|---|
| *Mytilus stage* .......... | 221 m | 200 m |
| *Portlandia stage* ........ | 205 ,, | 183 ,, |
| *Littorina stage* ........ | 175 ,, | 164 ,, |
| *Pholas stage* ............ | 142 ,, | 126 ,, |
| *Mactra stage* ........ | ca. 95 ,, | ca. 95 ,, |
| *Tapes stage* ............ | 70 ,, | 69 ,, |
| *Trivia stage* ............ | 47 ,, | 45 ,, |
| *Ostrea stage* ............ | 22 ,, | 22 ,, |
| *Mya stage* ............ | 0 ,, | 0 ,, |

Returning now to Brøgger's stratigraphical zones for the sublittoral deposits (the clays), in their modified form of figure 3, the oldest zone, the Yoldia clay, was deposited under climatic conditions which were high-arctic. Its index fossils is *Portlandia arctica* (= *Yoldia arctica*) which is to-day living in high-arctic

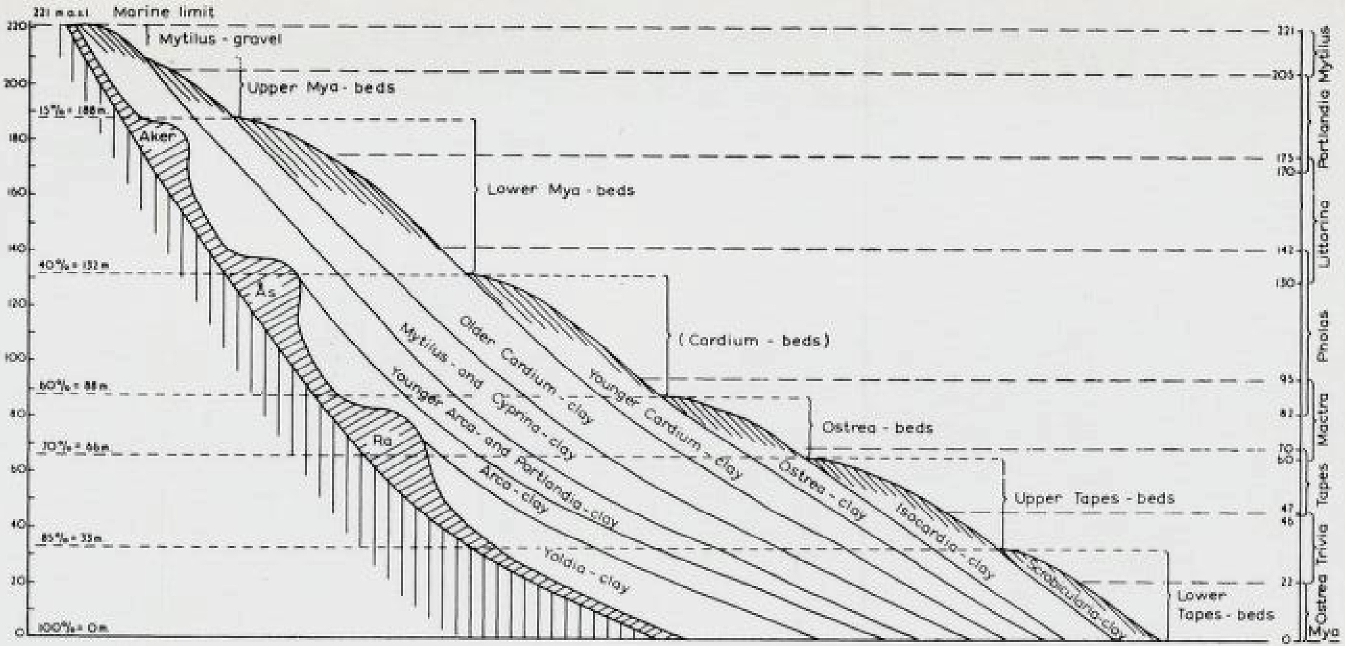

Fig. 3. Schematic illustration of the marine Late Pleistocene deposits of the Oslo region according to Brøgger's stratigraphy (slightly modified). To the right Øyen's shoreline stages. The heights above sea level refer to Oslo, they have also been indicated as percentages of the total elevation of the land. Morainic stages are also indicated. (Constructed in cooperation with O. Holtedahl and H. Rosendahl.)

*Skjematisk fremstilling av de marine senkvartære avsetninger i Osloområdet efter Brøggers stratigrafiske system (modifisert). Til høyre Øyens strandlinjenivåer, høydene referer til Oslo, de er også angitt i prosenter av den hele landstigning. Morenetrinnene er også avmerket.*

waters. The Yoldia clay has only been found outside (south of) the large marginal moraine called the Ra, and is identical with zone A of our micropaleontological division. *Elphidum clavatum* which dominates the fossil foraminiferal fauna of zone A, is also the dominant species of Foraminifera in arctic waters of to-day. Furthermore, *Portlandia arctica* is often found together with the microfossils of zone A.

The Arca clay was deposited during amelioration of the climate when the ice front retreated from the Ra to the Ås-Ski stage, and the Younger Arca & Portlandia clay during further retreat from the moraines of this latter stage. The index fossils are *Bathyarca glacialis* (= *Arca glacialis*) and *Yoldiella lenticula* (= *Portlandia lenticula*). A mild climatic oscillation corresponding to that of our zone C and a subsequent cold one corresponding to zone D are not registered in the sequence of Brøgger's zones. Considering, however, the regional distribution of the sediments and also the content of megafossils within our micropaleontological zones, we may suggest that zone B roughly corresponds to the Arca clay (see also Feyling-Hanssen 1954 a), whereas zone C and zone D fall within the Younger Arca & Portlandia clay.

The Mytilus & Cyprina clay, the Older and Younger Cardium clay and the Ostrea clay were deposited during periods of considerably improved climate. They correspond roughly to zone E, whereas the Isocardia clay, index fossil *Isocardia cor*, should be correlated with zone F, deposited during optimum climatic conditions. The Scrobicularia clay, index fossil *Scrobicularia plana*, (and also the Recent Mya clay) was deposited during climatic deterioration; it usually contains few species, and corresponds to our zone G.

As to the littoral stages of Øyen, the Mytilus stage refers to a period of relatively mild climate, *Mytilus edulis* appearing for the first time in the deposits, whereas the subsequent Portlandia stage involved a severe deterioration of the climate, *Portlandia arctica* reappearing in the deposits. The mild Mytilus stage and the subsequent arctic Portlandia stage must be correlated with the micropaleontological zones C and D respectively which indicate similar climate oscillations. The Tapes and Trivia stages (*Tapes*

| Marine-climatic stages | Micropaleont. Zones (Foraminifera) | Brögger's Zones (Mollusca in clay deposits) | Öyen's Shoreline Stages (Mollusca) | Position of shorelines, Oslo m.a.s.l. | Approximate age years |
|---|---|---|---|---|---|
| POST-GLACIAL | G | MYA ARENARIA | MYA | | |
| | | SCROBICULARIA | OSTREA | 0 | 0 |
| | F | | | | |
| | | | TRIVIA | 22 | |
| | | ISOCARDIA | | | 2000 |
| | | | TAPES | 47 | 4000 |
| | | OSTREA<br>CARDIUM<br>MYTILUS & CYPRINA | | | |
| | E | | MACTRA | 70 | |
| | | | PHOLAS | 95 | 6000 |
| | | | LITTORINA | 142 | |
| LATE-GLACIAL | D | YOUNGER ARCA & PORTLANDIA | PORTLANDIA | 175 | 8000 |
| | C | | MYTILUS | 205 | |
| | B | ARCA | | 221 | ? |
| | A | YOLDIA | | ? | ? |

Fig. 4. Correlation.

*Våre mikropaleontologiske soner sammenholdt med Brøggers og Øyens systemer.*

*decussatus* and *Trivia europea*), indicating optimum conditions, correspond to zone F.

The correlation of the micropaleontological zones with Brøgger's zones and Øyen's shoreline stages has been illustrated in figure 4. In this figure the positions of the shoreline at Oslo have been indicated from the marine limit down to present-day sea level, and to the right in the scheme the approximate age in years B.C., deduced partly from a modified shoreline chronology (Rosendahl 1955) and partly from De Geer's varve chronology.

The Late Pleistocene of the districts around Trondheimsfjorden has had a development parallel to that of the Oslofjord area (Øyen 1915). Investigated Late Glacial strata at Gløshaugen (Høyskoleplatået) in the city of Trondheim show that the zones A, B, C and D are present there with a content of Foraminifera which compares well with that of the corresponding zones of the Oslofjord area, and borings in the bottom sediments of Trondheim harbour have revealed Post Glacial strata with foraminiferal populations similar to the Post Glacial faunas of the Oslofjord area.

In a later paper we will see how our micropaleontological zones are correlated with the stratigraphical result of foraminiferal investigations of borings near Gothenburg in Sweden (Brotzen 1951), and also touch upon a comparison with pollenanalytical zones.

# Application to soil mechanics.

## Stratigraphy and geotechnical properties.

Comparing the stratigraphical result of micropaleontological investigation of a large number of subsurface samples from the Oslofjord area with the geotechnical properties of the same samples, it appears that a transition from one stratigraphical zone to another is, as a rule, accompanied by changes in geotechnical properties, especially in shear strength.

In the diagrams of figures 5-7 stratigraphy and corresponding geotechnical properties have been illustrated for three borings from Oslo, two from the inner harbour at Bjørvika and one from Majorstuen approx. 50 m above sea level. Micropaleontological and geotechnical investigation have been carried out on successive samples from the cores. In boring 4 at Bjørvika the Post Glacial zones G, F and E are represented; in boring 6 of the same locality zone E is lacking, whereas the Late Glacial zone D is present. Boring 5 at Majorstuen contains the Post Glacial zones F and E, and the Late Glacial D and C. Zone G is lacking in this boring because of the high position of the locality (see fig. 4). The upper part of the core from this boring, down to a core level of 7.5 m, consists of comparatively coarse material, clayey silt and silty clay. As, therefore, the grain size distribution of this part is considerably different from that of the rest of the core, the geotechnical properties of the upper part have not been considered in this connection.

Regarding the water content, w, this has, on the whole, its greatest values in the Post Glacial parts of our three borings, reaching a maximum of approx. 50 per cent in the zones G and F. Otherwise the water content seems to decrease with increasing depth in these three cores without any clear relation to the stratigraphy. At any layer of coarser-grained material in a clay deposit the water content will show a pronounced decrease.

The liquid limit, $w_L$, which is the water content at which the clay changes from a plastic to a liquid state, has a maximum of

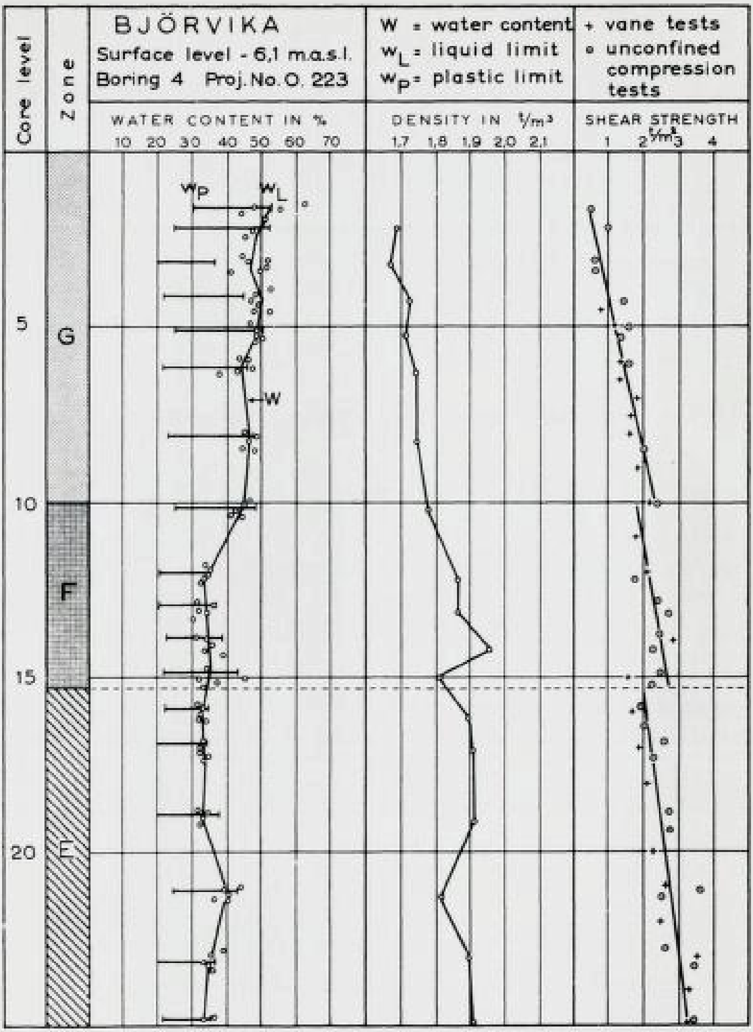

Fig. 5 Stratigraphy and geotechnical properties of clay sediments at the inner harbour of Oslo, as revealed by a 25 m deep boring at Bjørvika.

*Sammenheng mellom stratigrafiske soner (til venstre) og, spesielt, skjærfasthet (til høyre) for en 25 m dyp boring i Bjørvika, Oslo.*

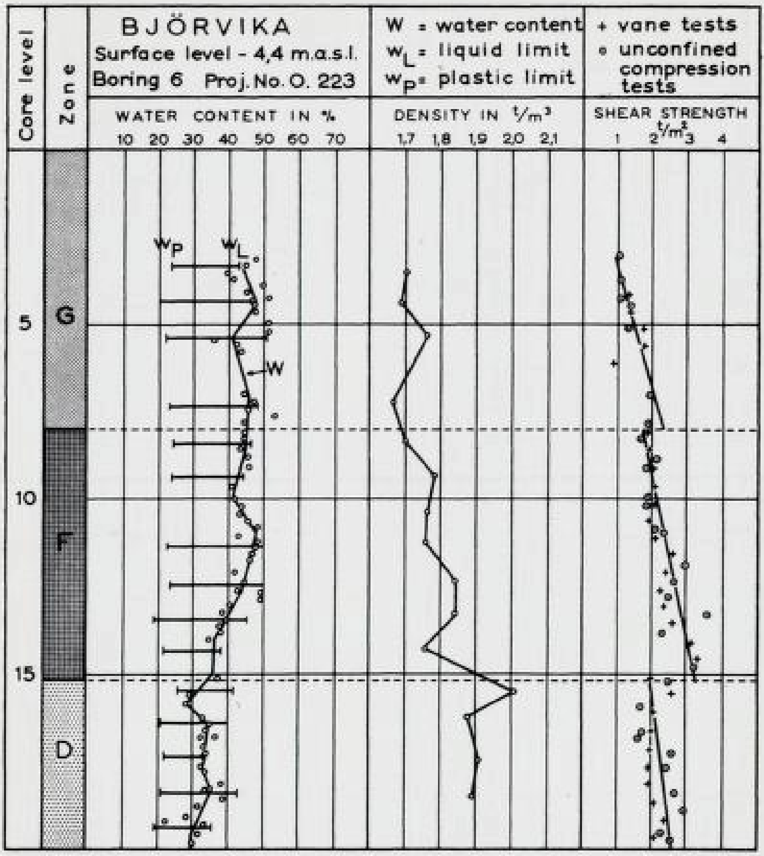

Fig. 6. Stratigraphy and geotechnical properties of a 20 m deep boring at Bjørvika, inner harbour of Oslo.

*Stratigrafi og geotekniske egenskaper, spesielt skjærfasthet, for en 20 m dyp boring i Bjørvika, Oslo.*

approx. 50 per cent within the zones G and F, its smallest values being found within zone D; it increases again in zone C (Majorstuen).

The plastic limit, $w_P$, which is the water content at which a clay sample changes from a plastic to a crumbly state, is quite constant throughout the cores, varying between 17 and 25 per cent.

The plasticity index, $I_P$, which is the difference between liquid limit and plastic limit, has its greatest value within the younger

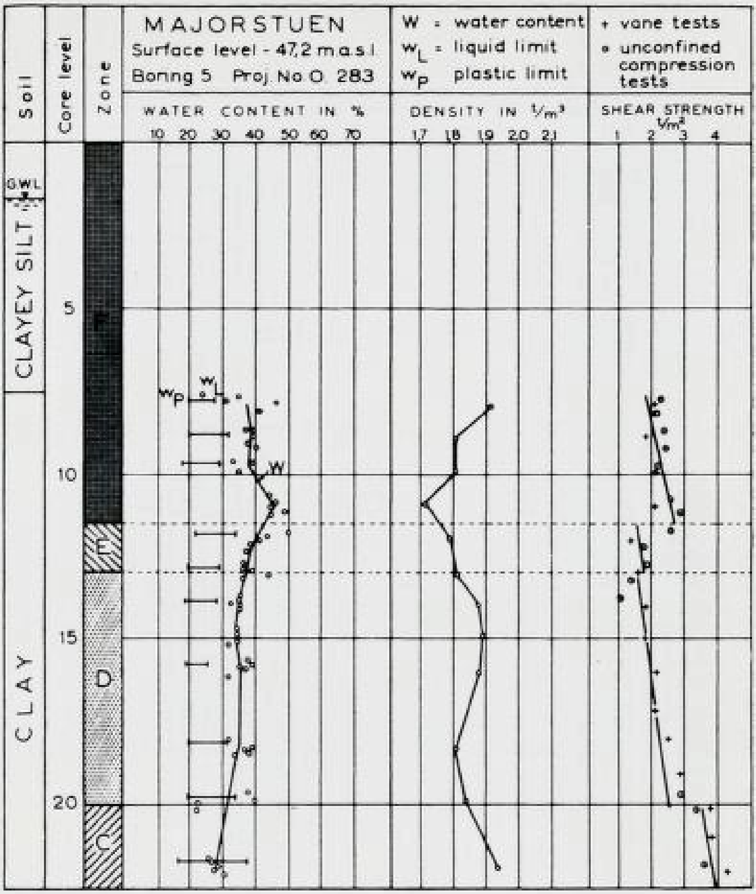

Fig. 7. Stratigraphy and geotechnical properties of clay deposits in a boring at Majorstuen, Oslo, approx. 50 m above sea level.

*Stratigrafi og geotekniske egenskaper i leiravsetninger ved Majorstuen, Oslo, omtrent 50 m over havet.*

stratigraphical zones. It seems to be smallest in zone **D**, and again greater in zone **C**.

The density, in tons per cubic metre, is, on the whole, smaller in Post Glacial parts of the cores than in Late Glacial ones, having its maximum, 1.95 t/m$^3$, within zone **C** of boring 5 at Majorstuen.

The most beautiful demonstration of a relation between stratigraphy and property is, however, given by the shear strength, s, expressed in tons per square metre. The shear strength, determined by vane tests and unconfined compression tests, shows linear increase with depth within every single stratigraphical unit, but at the transition from one zone to another there is a more or less sudden break in this linear increase. At the transition from zone G to F in boring 6 at Bjørvika the shear strength drops from 2.30 to 1.75 $t/m^2$, at the transition from zone F to D (E is lacking) it drops from 3.27 to 2.00 $t/m^2$, and at the transition from D to C in boring 5 at Majorstuen it increases from 2.70 to 3.60 $t/m^3$. This close relation is rather notable because the microfauna, determining the stratigraphical zones, reflects the physical conditions under which the clay was originally deposited, whereas the shear strength, i.a., is a result of that which has later happened to the clay.

In order to eliminate the influence of the depth upon the value of the shear strength and thus facilitate the comparison of the shear strength of different zones at different core levels, the shear strength of a clay is characterized by the ratio between shear strength, s, and effective overburden pressure, $\sigma_c$, i.e., $s/\sigma_c$ (Skempton 1948, Bjerrum 1954 b).[1] This holds good only for clays which are known never to have been subjected to higher pressures than the present overburden, i.e. only for normally consolidated clays (Bjerrum 1954 a). The general linear increase in shear strength with depth does not apply to the upper, so-called drying crust of a clay deposit. This crust is characterized by a shear strength, and a $s/\sigma_c$-value, which is much higher than for other parts of the deposit, and is not considered in the present account.

In the table (p. 26) is brought together the results of micropaleontological as well as geotechnical investigation of clay samples from 10 borings from 5 localities within Oslo. For each boring is given the height above, or below, present sea level of the surface of the deposit, and for each stratigraphical zone within every single boring is calculated the average value of water content, Atterberg

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[1] For the calculation of the effective overburden pressure (= the consolidation pressure) the ground water level is in most cases estimated from observations of the water level in bore holes. If the ground water level is $d$, the density of the clay at the ground water level $\psi_d$, the considered depth $a$, and the density at this depth $\psi_a$, then the effective overburden pressure at $a$ is:

$$\sigma_c = d \cdot \psi_d + (a - d) \cdot (\psi_a - 1)$$

*Stratigraphy and geotechnical data for 10 borings in Oslo.*

| Locality | Project Number | Boring | Height Above Sea Level m | Zone | Water Content w | Atterberg Limits | | | Density t/m³ | Sensitivity | $s/\sigma_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $w_L$ | $w_P$ | $I_P$ | | | |
| Bjørvika | 0.223 | 2 | — 3.5 | G | 46.0 | 45.0 | 23.0 | 22.0 | 1.75 | 5 | 0.33 |
| ,, | ,, | ,, | ,, | F | 46.0 | 50.0 | 22.3 | 27.7 | 1.75 | 4 | 0.24 |
| ,, | ,, | ,, | ,, | E | 42.0 | 46.0 | 26.0 | 20.0 | 1.78 | 3 | 0.18 |
| ,, | ,, | ,, | ,, | D | 35.0 | 37.0 | 21.0 | 16.0 | 1.88 | 3 | 0.14 |
| Bjørvika | 0.223 | 4 | — 6.1 | G | 50.0 | 45.0 | 22.0 | 23.0 | 1.72 | 3 | 0.33 |
| ,, | ,, | ,, | ,, | F | 40.0 | 43.3 | 23.7 | 19.6 | 1.85 | 4 | 0.22 |
| ,, | ,, | ,, | ,, | E | 34.0 | 36.0 | 21.0 | 15.0 | 1.82 | 3 | 0.18 |
| ,, | ,, | ,, | ,, | D | 40.0 | 43.0 | 25.0 | 18.0 | 1.81 | 3 | 0.15 |
| Bjørvika | 0.223 | 5 | — 7.1 | G | 47.5 | 48.0 | 25.0 | 23.0 | 1.74 | 5 | 0.35 |
| ,, | ,, | ,, | ,, | F | 44.0 | 50.0 | 28.0 | 22.0 | 1.74 | 4 | 0.30 |
| ,, | ,, | ,, | ,, | D | | | | | 1.87 | 3 | 0.14 |
| Bjørvika | 0.223 | 6 | — 4.4 | G | 45.0 | 48.0 | 23.0 | 25.0 | 1.67 | 2 | 0.36 |
| ,, | ,, | ,, | ,, | F | 41.7 | 46.0 | 22.5 | 23.5 | 1.79 | 3 | 0.26 |
| ,, | ,, | ,, | ,, | D | 33.0 | 38.0 | 20.0 | 18.0 | 1.90 | 3 | 0.14 |
| Grønland torv | 0.120 | 3 | + 2.5 | G | 38.5 | 48.9 | 23.0 | 25.9 | 1.79 | 5 | 0.33 |
| ,, | ,, | ,, | ,, | F | 37.5 | 50.0 | 23.0 | 27.0 | 1.83 | 3 | 0.25 |
| ,, | ,, | ,, | ,, | E | 33.9 | 43.4 | 21.9 | 21.5 | 1.83 | 3 | 0.17 |
| ,, | ,, | ,, | ,, | D | 35.0 | 47.5 | 20.0 | 27.5 | 1.80 | 5 | 0.10 |
| Majorstuen | 0.283 | 1 | +48.4 | F | 42.2 | 32.2 | 21.0 | 11.2 | 1.80 | 8 | 0.19 |
| ,, | ,, | ,, | ,, | D | 36.8 | 26.3 | 17.8 | 8.5 | 1.85 | 49 | 0.09 |
| Majorstuen | 0.283 | 4 | +48.7 | F | 40.7 | 29.5 | 21.0 | 8.5 | 1.78 | 13 | 0.19 |
| ,, | ,, | ,, | ,, | D | 36.0 | 32.0 | 17.5 | 14.5 | 1.87 | 5 | 0.11 |
| Majorstuen | 0.283 | 5 | +47.2 | F | 36.0 | 29.7 | 19.2 | 10.5 | 1.84 | 9 | 0.24 |
| ,, | ,, | ,, | ,, | E | 42.0 | 34.0 | 22.0 | 12.0 | 1.80 | 9 | 0.14 |
| ,, | ,, | ,, | ,, | D | 36.2 | 28.2 | 19.2 | 9.2 | 1.85 | 6 | 0.13 |
| ,, | ,, | ,, | ,, | C | 27.5 | 37.0 | 16.0 | 21.0 | 1.95 | 5 | 0.18 |
| Bryn | 0.199 | 18 | +81.5 | D | 31.5 | 23.3 | 17.3 | 6.0 | 1.88 | 54 | 0.09 |
| ,, | ,, | ,, | ,, | C | 29.0 | 20.5 | 14.5 | 6.0 | 1.95 | 87 | 0.15 |
| Manglerud | 0.35 | 4 | 118.1 | E | 37.0 | 24.8 | 18.4 | 6.2 | 1.86 | 300 | 0.11 |
| ,, | ,, | ,, | ,, | D | 36.0 | 25.0 | 19.0 | 6.0 | 1.90 | 220 | 0.08 |
| ,, | ,, | ,, | ,, | C | 32.0 | 21.0 | 15.8 | 5.2 | 1.94 | 500 | 0.13 |

limits, density, sensitivity[1] and the ratio between shear strength and effective overburden pressure, $s/\sigma_e$.

It is known (Bjerrum 1954 a) that there is a close correlation between plasticity index and ratio of shear strength to effective overburden pressure. As the value of the plasticity index depends i.a. on the mineral composition and grain size distribution of the clay, the value of $s/\sigma_e$ will also be dependent on these factors. The clay samples from which the geotechnical values in the table are derived originate, however, from a rather narrow area, thus being quite similar as to mineral composition and grain size distribution.

Regarding the ratio shear strength to effective overburden pressure, $s/\sigma_e$, the values of which also in the table show the most convincing relation to the stratigraphy, these values are greatest in samples belonging to zone G, i.e. from the youngest part of the sediments. In the four borings in which this zone is represented its $s/\sigma_e$-value varies between 0.33 and 0.36.[2] Zone F has, for the five borings at approx. sea level, an average $s/\sigma_e$-value of 0.25, whereas the average value for the same zone at Majorstuen, approx. 50 m above sea level, is only 0.20. Zone E has, at sea level, an average value of $s/\sigma_e = 0.18$, and at Majorstuen 0.14. This zone is not represented in boring 18 from Bryn, but at Manglerud, 118.1 m a. s. l., the $s/\sigma_e$-value of this zone is only 0.11. The arctic zone D is in all the borings characterized by the lowest value of the ratio shear strength to effective overburden pressure. In the borings at sea level the average value of this zone is $s/\sigma_e = 0.13$, at Majorstuen it is 0.11, at Bryn 0.09 and at Manglerud 0.08. Zone C is not represented in the low-positioned borings of the table, at Majorstuen its ratio $s/\sigma_e = 0.18$, at Bryn 0.15 and at Manglerud 0.13. Thus, in the borings where zone C is represented, its $s/\sigma_e$-value is greater than that of zone D and also greater than that of zone E.

These conditions are not exceptional and represented only in the borings of the table. They occur in the same way in every boring through homogenic sediments showing discontinuous variation of

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[1] The sensitivity is the ratio between undisturbed and re-moulded shear strength.

[2] Due to possible dredgings, the sediments from the bottom of the bay Bjørvika may previously have been subjected to higher pressures than the present overburden; if so, the calculated values of $s/\sigma_e$ from Bjørvika will be slightly too high.

shear strength with depth. As long as the texture of a clay deposit is approx. the same throughout the section, the breaks in the variation in the shear strength are closely related to the stratigraphical zones. A deposit with another mineral composition and grain size distribution than those of the borings listed in the table on p. 26 will show other geotechnical properties. Zone F of a boring at Fredrikstad, east of the entrance to the Oslofjord, shows a $s/\sigma_c$-value of approx. 0.4, which is considerably higher than of the corresponding zone at Bjørvika in Oslo.

## Reduced salt concentration.

In considering the properties and stratigraphy of clay deposits, the borings from different elevations above sea level have to be kept apart from each other because the geotechnical properties evidently change with the elevation at which the deposits are situated. This change is usually asserted as decreasing magnitude of the properties with increasing height above sea level. The highest water content, table p. 26, is found in samples from Bjørvika these borings being situated close to sea level.

More distinctly such a decrease is demonstrated by the liquid limit, $w_L$, which is 40-50 per cent in the low-positioned deposits, about 30 per cent at Majorstuen (approx 50 m a. s. l.) and about 23 per cent at Bryn (80 m a. s. l.) and Manglerud (approx 120 m a. s. l.). A similar change can also be traced in the values of the plastic limit, $w_P$, but is far more pronounced in the values of the plasticity index, $I_P$, according to the distinct variation of $w_L$. The average changes of $I_P$ in the borings contained in our table have been plotted against height in the diagram of fig. 8 b. Such a correspondence between plasticity index and height above sea level is also found with the borings listed by Bjerrum (1954 a, table 4).

Regarding the shear strength, represented by the ratio $s/\sigma_c$, similar conditions are found. Any one zone has a greater value of $s/\sigma_c$ in deposits close to sea level than the corresponding zone in deposits situated at greater elevation. This dependency of the ratio shear strength to effective overburden pressure on the height above sea level at which the deposits are found, is, for the 10 borings of our table, illustrated in the diagram of figure 8 a. There seems to

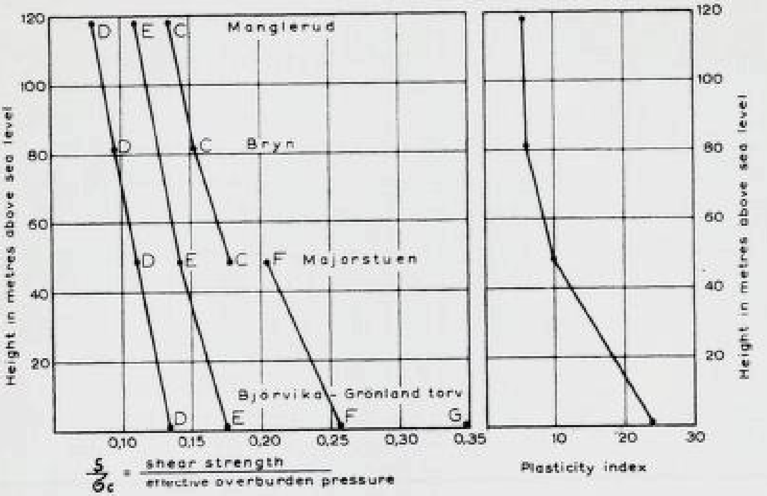

Fig. 8. a) Variation of the ratio shear strength to effective overburden pressure, $s/\sigma_c$, for the different stratigraphic zones of 10 borings from Oslo, with the elevation at which the deposits are found. b) Variation of plasticity index for some clay deposits from Oslo (see table p. 26) with the elevation above sea level at which the deposits are found.

*a) Hvordan forholdet skjærfasthet til effektivt overlagringstrykk, $s/\sigma_c$, varierer med høyden over havet for de forskjellige stratigrafiske soner i 10 boringer fra Oslo (tabellen s. 26). b) Hvordan plastisitetsindeksen for noen leiravsetninger fra Oslo (tabellen s. 26) varierer med avsetningens høyde over havet.*

be also a connection between the sensitivity of a clay and the height above sea level of the deposit, the most sensitive clays of these borings being found at the greatest altitude (table p. 26).

These conditions, in fact, demonstrate the general relation between geotechnical properties and reduced salt concentration in the pore water of the clay.

Systematic investigation of the salt concentration of Norwegian clays has proved that considerable reduction has taken place since the sedimentation (G. Holmsen 1929, Rosenqvist 1946 a and b, Bjerrum 1954 a). It is furthermore known that reduced salt content is accompanied by decreased Atterberg limits (G. Holmsen 1934 and 1938, P. Holmsen 1946, Rosenqvist 1953). In figure 9 are illustrated the changes in properties of a normally consolidated marine clay when subjected to leaching by fresh water (Bjerrum 1954 a).

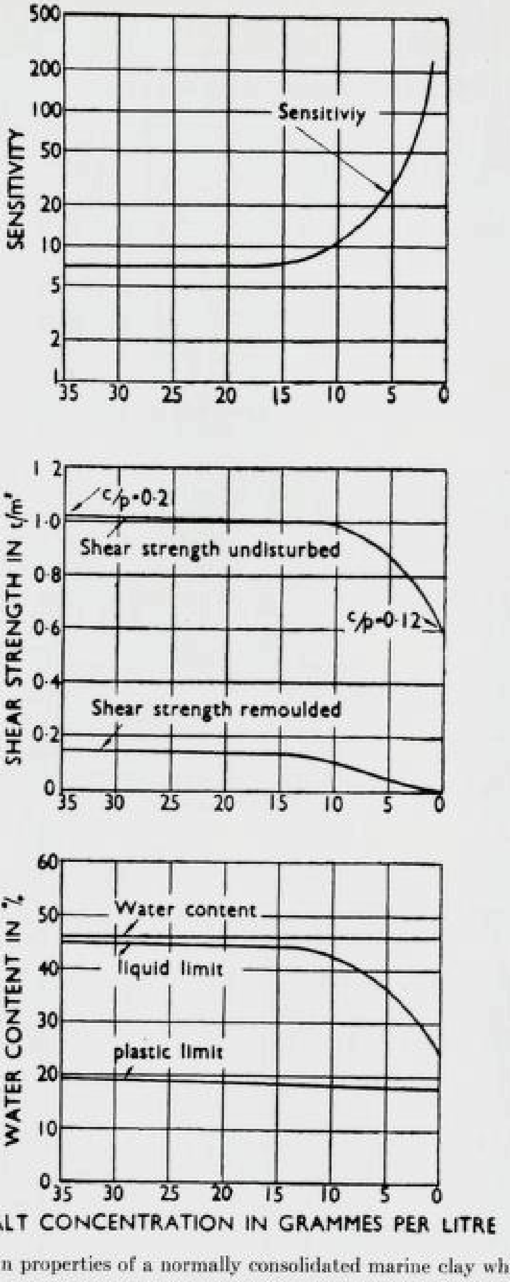

Fig. 9. Changes in properties of a normally consolidated marine clay when subjected to leaching by fresh water (Bjerrum 1954 a; $c/p = s/\sigma_e$).

*Forandring i normalt konsoliderte marine leirers egenskaper under en saltutvasking.*

It is shown that the liquid limit decreases considerably with reduced salt concentration whereas the plastic limit is practically unaffected. This means decrease in plasticity index with reduced salt content. It is furthermore found that a leaching out of the original salt content is accompanied by reduction in shear strength of the undisturbed clay. Small values of the ratio of shear strength to effective overburden pressure occur in relatively salt-free clays with low plasticity index, whereas the high $s/\sigma_c$-values are found in clays which have, more or less, kept their original salt concentration. As the re-moulded shear strength is reduced to a very low value by a reduction in the salt content, such a reduction consequently results in increased sensitivity. The reduction in geotechnical properties does not take place in linear proportion to the reduction in salt concentration. Even a considerable decrease in salt concentration will result only in negligible reduction in properties as long as the salt content is kept above 10 gram per litre, but further leaching, resulting in salt concentration beyond this value, will cause considerable change in geotechnical properties (Bjerrum 1954 a).

The degree of leaching, resulting in reduced salt concentration, is dependent on the ground water flow in the deposit, and the ground water flow is again dependent on the hydraulic gradient of the locality (Bjerrum 1954 a). The hydraulic gradient will be larger in places where the sediments have been raised above the erosion base than in places where they have remained below or close to this level. Very often, but not always, the hydraulic gradient increases with increasing height above sea level, and consequently a marine sediment situated high above sea level has, very often, been subjected to a higher degree of leaching than a sediment, of corresponding age, situated close to sea level. The salt concentration in the pore water of our samples from Majorstuen (approx. 50 m a. s. l.) varied between 0.19 and 0.91 gram per litre whereas at Manglerud (approx. 120 m a. s. l.) it was 0.06-0.18 gram per litre.

This is, of course, no general rule. A clay sediment deposited in a closed rock basin will have a hydraulic gradient which is in most cases approx. zero whatever altitude this place may be raised to. At many localities, however, the degree of leaching, and consequent reduction in salt concentration, is evidently higher in deposits situated close to the former marine limit than in such which are found close to present-day sea level—as demonstrated by the geotechnical properties of the borings of the table on p. 26.

## Salt concentration and stratigraphy.

As we have seen, the relation between the original and the present salt concentration in the pore water of a clay is essential to its geotechnical properties. The degree of reduction in salt content depends upon the hydraulic gradient of the deposit and, as a matter of fact, also upon the span of time during which the deposit has been subjected to leaching. A young clay sediment will therefore possess high plasticity index and high value of the ratio of shear strength to effective overburden pressure for two reasons, firstly because it is young and has not had time enough for any considerable degree of leaching, secondly because it has not been subjected to any considerable degree of isostatic elevation since its deposition. An increase of the hydraulic gradient, augmenting the velocity of the ground water flow, has therefore generally not taken place.

Provided undisturbed original stratification and constant conditions as to mineral composition and grain size distribution, an approximately constant decrease in salt content with increasing depth would be expected in a marine deposit. The deeper layers are older than the upper, and in consequence they have been subjected to longer periods of leaching. Disregarding the effect of chemical weathering, which is especially high in the upper 5-6 metres of a deposit (Moum and Rosenqvist 1955), this decrease in salt content would be expected to be accompanied by similarly constant decrease in geotechnical properties, especially in $I_p$ and $s/\sigma_c$, with increasing depth in the deposit. Where a succession of stratigraphical zones, G, F, E, D, C, occurs in a boring through a homogenic clay deposit, the value of $s/\sigma_c$ should thus be smaller in zone F than in zone G, and smaller in E than in F, a continuous decrease would be expected from the younger to the older layers of the deposit. As we have seen, however, the variations in plasticity index and $s/\sigma_c$-value do not appear in this way. Certainly the $s/\sigma_c$-value is smaller in zone **F** than in zone G, smaller in E than in **F** and even smaller in D than in E, but in zone **C** it is again greater, according to our table (p. 26) and other borings. Furthermore there is in these borings more or less sudden breaks in the variation of $s/\sigma_c$ at the transitions from one zone to another. In any particular boring any one stratigraphical zone can be related to a certain value of $s/\sigma_c$.

In order to explain this relation between geotechnical properties and geological history of a clay deposit it is natural to bring into focus the salinity of the water into which the clay was originally deposited supposing that the original total salt concentration in the pore water of a clay was the same at the total salinity of this sea-water (for details about the salinity, see G. Holmsen 1930 and Rosenqvist 1955). As we know from the description of the different micropaleontological zones, the sediments of these zones were deposited during periods of different climatic conditions which were accompanied by changes in the salinity of the contemporaneous sea. Indications of brachyhaline sea-water, with salinity between 16 and $30\,^0/_{00}$, were found in zone **D** and zone G, whereas the microfauna of zone C and zone **E** indicates sea-water of rather high salinity, between 30 and $35\,^0/_{00}$. Zone **F** was formed in sea-water of high salinity, approx. $35\,^0/_{00}$. Sediments of zone A and especially those of zone **B**, were deposited in water of salinity lower than that of zone C.

It is thus evident that these marine Late and Post Glacial sediments were deposited in a sea which never had a salinity lower than approx. $15\,^0/_{00}$, probably even not lower than $20\,^0/_{00}$. The original salt concentration in the pore water of these clays has thus for all stratigraphical zones been well above the critical value of 10 gram per litre, and there would seem to be little hope of finding an explanation of the different geotechnical properties only in the original salt concentration of the clays from the different zones. On the contrary, a sequence of stratigraphical zones in a homogenic clay deposit would be expected to provide samples with approximately constant value of the ratio shear strength to effective overburden pressure throughout the sequence. This is also the case—as long as the salt concentration of the clays has not been considerably reduced by leaching.

Regarding therefore the leaching out of salt in a clay deposit, this process takes place at different rates from one place to another, as previously mentioned, and varies considerably with the permeability of the sediment. At any particular locality, however, it is a function of time. What kind of a function cannot be told, because many details of the leaching process are still insufficiently investigated. The adsorption of ions to clay minerals (Rosenqvist 1955), to mention one complicating factor only, has a retarding effect upon the leaching process, whereas silty laminae in the deposit accellerate it (oral communication with L. Bjerrum and I. Th. Rosenqvist). However, for the purpose of explaining the relation between geotechnical properties and stratigraphical zones as a principle, and in order to simplify the account, we may assume that the leaching process takes place in linear proportion to time. This has been illustrated in the diagram of figure 10, the abscissa of which has been divided into hypothetical time units of 1000 years. We thus assume that a certain clay, which was once deposited in sea-water with total salinity of 35 ‰ and later subjected to constant leaching, will after 10,000 years have the salt concentration of its pore water reduced to 15 ‰. Another clay with an original salt concentration of 30 ‰ will, according to the same hypothetical diagram, have its salt content reduced to 10 ‰ in the course of 10,000 years.

From geotechnical investigations (i.a. Rosenqvist 1946 a, b, 1955; Bjerrum 1954 a, b) we know, as previously mentioned, that the leaching out of salt in the pore water of naturally consolidated marine clays is accompanied by changes in their geotechnical properties. As we have also seen, these changes are negligible as long as the reduction in salt content has not reached a value of approx. 10 gram per litre, but they become considerable and extremely important when this critical value is surpassed.

Turning now to the hypothetical diagram of the process of leaching, we will regard two clay deposits during the process. One was deposited in sea-water giving to the pore water of the sediment an original salt concentration of 35 gram per litre, the other in brachyhaline water giving this sediment an original salt concentration of only 25 gram per litre. If the mineral composition, grain size distribution and other conditions are the same for the

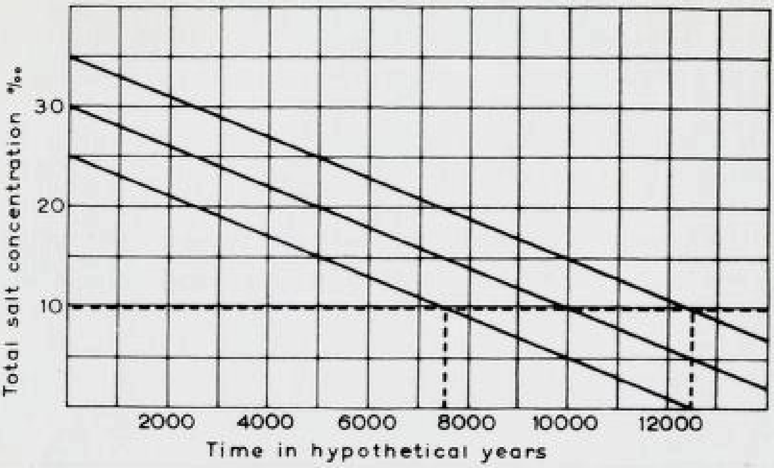

Fig. 10. Hypothetical reduction in salt concentration with time.

*Hypotetisk reduksjon av saltkonsentrasjonen med tiden.*

two deposits, they will, before leaching, probably also show the same geotechnical properties even though there is a difference in salt content of 10 gram per litre in their pore water. However, if they were deposited contemporaneously, and later subjected to a process of leaching according to the diagram of figure 10, the decreasing salt concentration of the brachyhaline clay, 25 gram salt per litre, will surpass the critical value of 10 gram per litre 5000 years before the sea-water clay. When the sea-water clay has reached a salt content of 15 gram per litre, and is consequently still a normal clay of low sensitivity, the brachyhaline clay has had its salt content reduced to 5 gram per litre, and has most probably changed into a highly sensitive quick clay.

From the borings of the table (p. 26) it appears that the value of $s/\sigma_c$ is greater in zone G than in zone F even though the original salt concentration of zone F is considerably higher than that of zone G. However, the G-clays are the youngest in the stratigraphical sequence and have thus had little time for leaching, whereas the F-clays may have been subjected to leaching during a period of 5000 years, on an average. The great difference in $s/\sigma_c$ between zone F and zone D, $s/\sigma_{cF}$ in any particular boring being approximately twice as great as $s/\sigma_{eD}$, is explained both by the fact that zone **D** is almost 4000 years older than **F** and also by the much higher original salinity of zone **F**. The reason why $s/\sigma_{eC}$ is greater than $s/\sigma_{eD}$, even though zone **C** is probably 1000 years older than **D**, is found in the higher original salt concentration in the pore water of the C-clays, this factor overshadowing the effect of the relatively small difference in age.

As previously stated, we do not know the details about the leaching process, we know that it is an extremely complicated process and that it certainly differs much in rate from one locality to another. It is probable, however, that this leaching process, together with the value of the original salt concentration in the pore water of a clay, explains the close relation between the geotechnical properties of a clay and the stratigraphical zone to which it belongs.

There will also be a tendency towards greater shear strength, or $s/\sigma_e$-value, in younger sediments than in older, because the particles of younger sediments may be assumed to have been repeatedly redeposited thus probably having been weathered to a higher degree than particles in older sediments which have remained in situ unaccessible to the oxygen of the air (oral communication with I. Th. Rosenqvist).

Homogenic clay deposits which have not been subjected to any considerable degree of leaching will show little or no discontinuity in geotechnical properties from one stratigraphical zone to another. Such clays have to a large extent kept their original salt content, and even though this is different for the different zones, this does not affect the geotechnical properties to any considerable degree as long as the salt concentration is higher than 10 gram per litre. Thus borings through undisturbed clay deposits at Drammen show shear strengths which increase continuously with depth, giving a constant ratio of shear strength to effective overburden pressure throughout the profile (see Bjerrum 1954 a, fig. 8, reproduced in the present paper as fig. 11). The salt concentration in the pore water of these clays varied between 26.7 and 13.4 gram per litre. Such clays are usually found close to present-day sea level, or in other places where the ground water flow has been small. On the other hand, deposits at Vaterland and Bjørvika in the city of Oslo

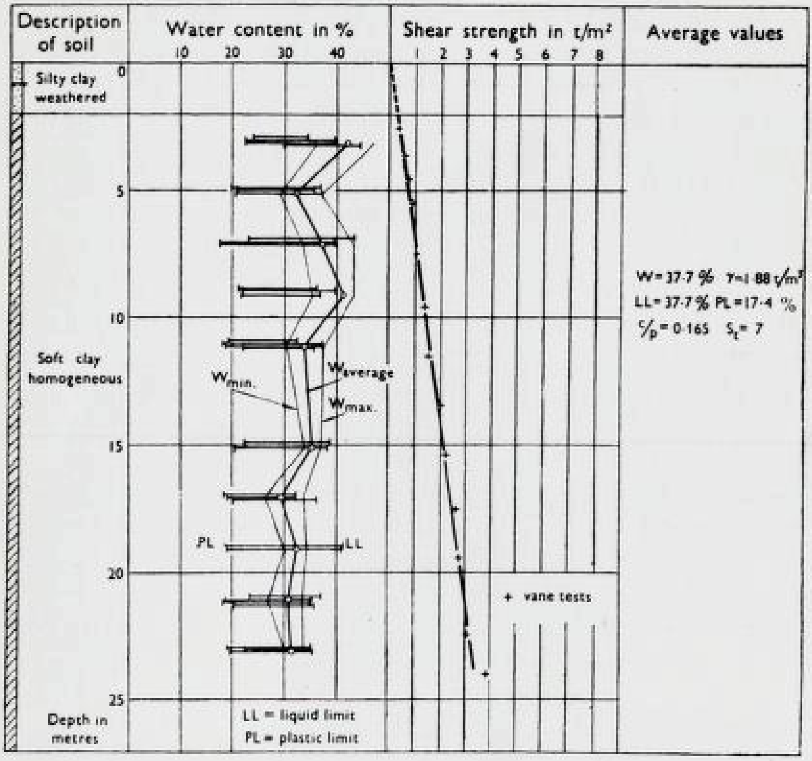

Fig. 11. Results of a boring in Drammen (Bjerrum 1954 a).

*Resultat av en boring i Drammen.*

show that also clays situated close to, and even below, present-day sea level may have been subjected to leaching resulting in discontinuous changes in geotechnical properties at the transitions between different stratigraphical zones.

The borings from the city of Oslo, which we have treated here (table p. 26), show that in any one boring, samples from the stratigraphical zone D have the lowest value of $s/\sigma_c$, and this condition will certainly be found in most borings from the Oslofjord area. This, however, does not mean that quick clays should necessarily belong to zone D. As we have seen, quick clays are formed when marine clay deposits which originally have a high salt concentration in their pore water are subjected to a considerable degree of leaching, and such a leaching out of the original salt content may take place within any one stratigraphical zone. In accordance with this P. Holmsen (1949) states that the quick clays of Norway are not associated especially with Post Glacial clays, some of the largest quick clay slides have occurred in old Late Glacial deposits (see also G. Holmsen and P. Holmsen 1946).

## Tracing of old land slides.

Clay deposits which have been involved in land slips, have attained geotechnical properties highly different from those of the undisturbed sediment. Carrying out subsurface investigations for the purpose of engineering projects it therefore interests the geotechnician to know whether the sediment in question has remained undisturbed, or if the deposit, or parts of it, has been subjected to previous slides, i.e. whether the stratification of the sediment is the original one, or if any secondary disturbance has taken place. The existence of old slides are in must cases revealed by the tracing of unconformities of the strata or even by inversion of the stratigraphical sequence. For this purpose already the micropaleontological demonstration of strata which can be recognized from one borehole to another within the area of a certain exploration, may lead to useful conclusions even if these strata are not correlated with any regional stratigraphy. If the borings are numerous enough and propitiously spaced, the normal sequence of the local stratigraphy will soon appear and anomalies readily detected.

To illustrate this kind of application of micropaleontology to soil mechanics, an investigation of marine clay deposits at Høyskoleplatået in the city of Trondheim is recorded in the following.

Høyskoleplatået, or Gløshaugen, is formed by a plateau, or terrace, with an area of approx. 170 x 100 m, and its surface situated 55 m above sea level. This plain is terminated to the south by a cliff descending to a much smaller terrace surface at 46 m a. s. l. Another cliff slopes from the lower terrace down to approx. 37 m a. s. l. (figs. 12 and 13). This complex is made up of clay, except for a quite thick layer of sand in its western part. The total thickness of the deposit, from the upper terrace surface to bedrock, is about 20-25 m.

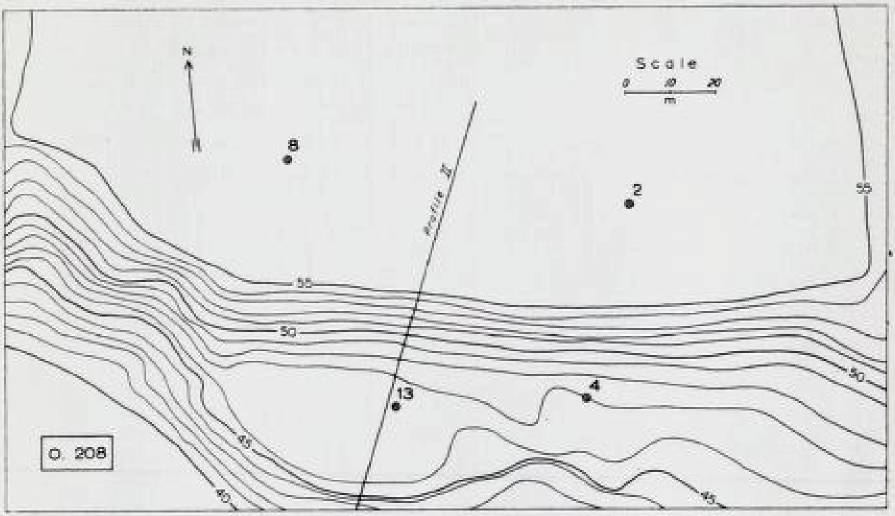

Fig. 12. Sketch map of Høyskoleplatået (Gløshaugen) in the city of Trondheim with positions of borings and direction of the profile of fig. 13. Equidist. 1 m.

*Kartskisse over Høyskoleplatået i Trondheim med angivelse av boringer og retningen av profilet i fig. 13.*

Samples from four borings (cf. figs. 12 and 13) were micropaleontologically investigated; samples from the sand layer were not examined. The fossil microfauna was composed of rather few species, and the number of specimens was also low in most samples. In order to give an impression of the foraminiferal fauna and its variations, analyses of four representative samples are recorded on page 40.

The scarcity of species together with the relative high frequency of *Elphidium clavatum* and *Cassidulina crassa* suggest Late Glacial age for the sediments (see Feyling-Hanssen 1954 a, b), this view being supported by the presence of *Cassidulina teretis*. The occurrence of some valves of the pelecypod *Yoldiella lenticula* is also in accordance with Late Glacial age. No part of the deposits is Post Glacial. The age is of minor interest in connection with this particular task; it is, however, worth mentioning because it shows that, altough the whole section represents exclusively Late Glacial sediments, a stratigraphical subdivision is still possible. This has been

| Species | Zone A Boring 4 Depth 9.7 m | Zone B Boring 4 Depth 6.6 m | Zone C Boring 4 Depth 3.3 m | Zone D Boring 2 Depth 2.1 m |
|---|---|---|---|---|
| *Elphidium clavatum* ...... | 111 | 146 | 346 | 24 |
| *Cassidulina crassa* ........ | 23 | 175 | 284 | 790 |
| *Pyrgo williamsoni* ........ | 1 | 16 | | |
| *Virgulina loeblichi* ........ | – | 4 | 207 | |
| *Elphidium subarcticum* .... | – | 1 | 6 | |
| *Astrononion gallowayi* .... | – | 1 | 1 | |
| *Virgulina* sp. ............. | – | 4 | – | 12 |
| *Cassidulina teretis* ........ | – | – | 104 | 2 |
| *Nonion labradoricum* ...... | – | – | 13 | |
| *Bulimina marginata* ...... | – | – | 7 | |
| *Elphidium incertum* ...... | – | – | 5 | |
| *Lenticulina* sp. .......... | – | – | 3 | 1 |
| *Pullenia osloensis* ........ | – | – | 3 | |
| *Cassidulina leavigata* ...... | – | – | 2 | |
| *Lenticulina d'orbignyi* .... | – | – | 1 | |
| *Quinqueloculina stalkeri* .. | – | – | – | 16 |
| *Quinqueloculina subrotunda* | – | – | – | 2 |
| *Virgulina fusiformis* ...... | – | – | – | 2 |
| | 135 | 347 | 982 | 849 |
| Ostracoda ................ | 1 | 28 | 86 | 8 |

carried out in the three vertical distribution charts (figs. 14-16), the cores having been divided into four zones, A, B, C and D, according to the composition of the foraminiferal faunas. The most rare species have been excluded from the charts.

Zone A, the lowest part of the section, was characterized by an exceptional poor fauna, most samples from this zone containing only a few specimens of *Elphidium clavatum* and *Cassidulina crassa*. The maximum number of species in one sample was 10, and ostracods were absent in most samples. *Elphidium clavatum* was the dominant species except for two samples from the lower part of the zone in boring 2 and 8 which contained more *Cassidulina crassa*. Zone A was represented in all the borings, and had a thickness of approx. 10 m in boring 8.

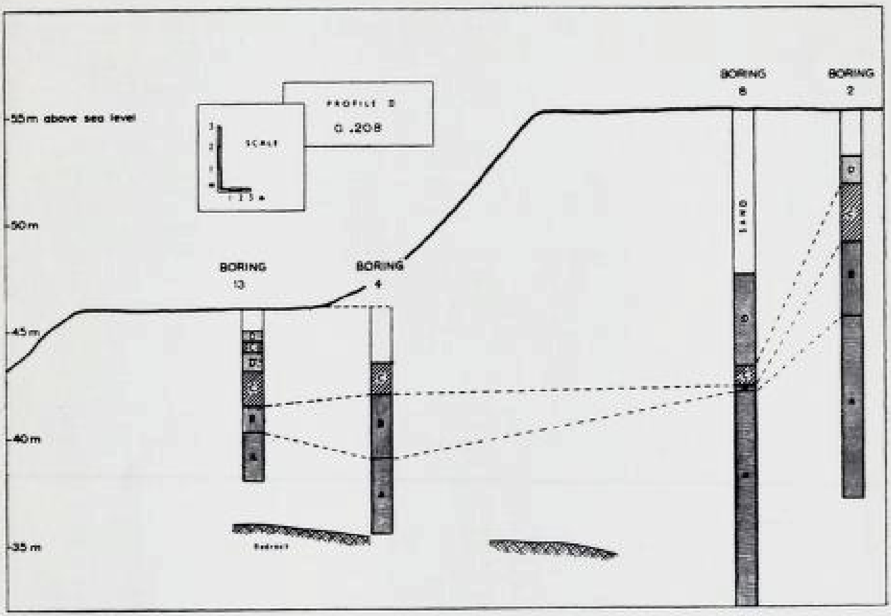

Fig. 13. Profile II. Høyskoleplatået (see fig. 12) with the borings projected into the same profile. The white parts of the cores have not been micropaleontologically investigated, they consist of coarse sand.

*Boringene i Høyskoleplatået (fig. 12) projisert inn i profil II. De hvite deler av borkjernene er ikke undersøkt, de består av grov sand.*

In zone B the samples contained more species and more specimens. *Elphidium clavatum* was the dominant species in most samples, but *Cassidulina crassa* dominated some of them. *Pyrgo williamsoni*, which occurred only in two samples from zone A, was quite common in zone B. *Virgulina loeblichi* occurred in most of the samples and *Elphidium subarcticum* in some of them; they were not found in zone A. The maximum number of species in one sample was 11, and ostracods were quite common.

Zone C was characterized by almost equal abundancy of *E. clavatum* and *C. crassa*, and by a high frequency of *Virgulina loeblichi. Cassidulina teretis* was common and so was *Nonion labradoricum. Bulimina marginata* occurred in one of the investigated samples from zone C, indicating amelioration of the water temperature at the corresponding period. The maximum number

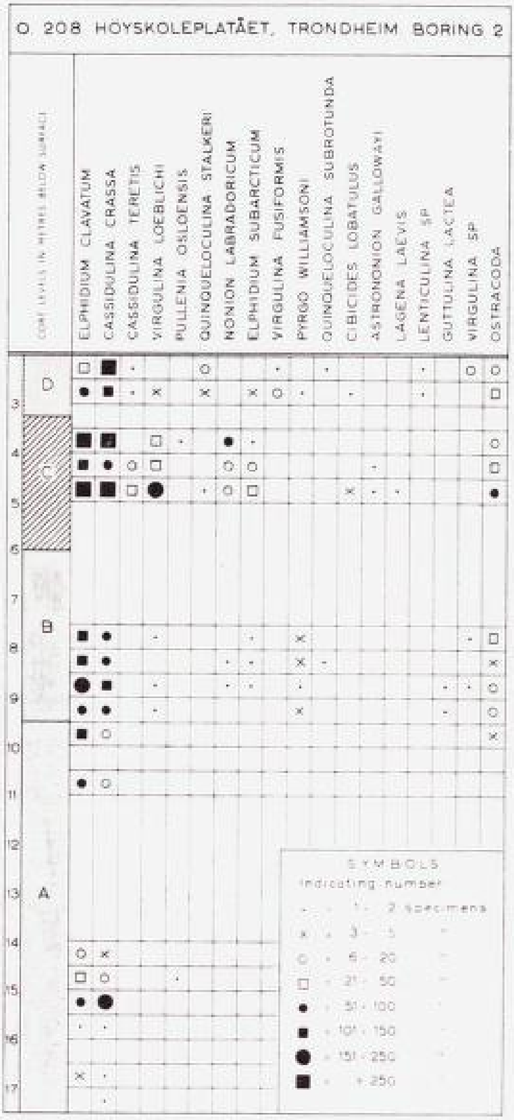

Fig. 14. Vertical distribution chart of boring 2, Høyskoleplatået (Gløshaugen), Trondheim. As samples are lacking between core level 5 and 7 m, the position of the border between zone B and C is only estimated.

*Vertikalfordelingsdiagram for de vanlig forekommende foraminiferer i boring 2, Høyskoleplatået, Trondheim.*

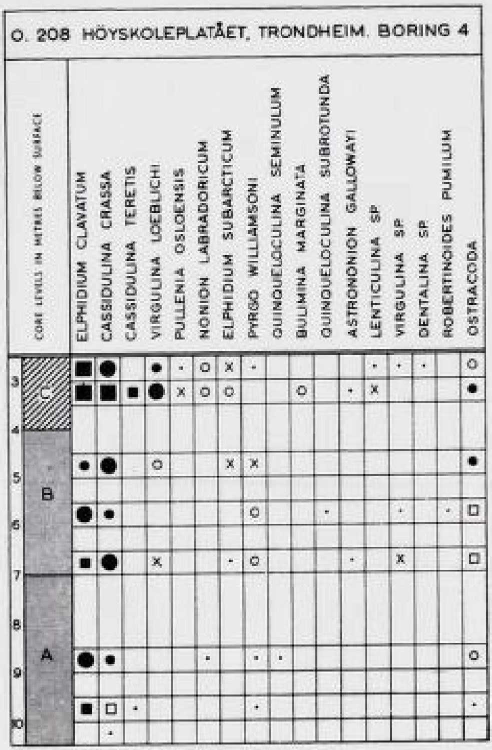

Fig. 15. Vertical distribution chart of boring 4. Høyskoleplatået (Gløshaugen), Trondheim; for explanation of symbols see fig. 14.

*Vertikalfordelingsdiagram for boring 4, Høyskoleplatået, Trondheim (symbolforklaring i fig. 14).*

of species in one sample was 17, and ostracods were frequent. This zone was also represented in all the borings.

Zone D was characterized by pronounced dominance of *C. crassa* together with the appearance of *Quinqueloculina stalkeri*. *V. loeblichi*, *N. labradoricum* and *P. williamsoni* were absent in most samples, and *C. teretis* and *E. subarcticum* were rare. *E. clavatum* was less frequent than in the previous zone, and so were the ostracods. The maximum number of species in one sample was 20. This zone was not represented in boring 4.

The cores from the four borings, stratigraphically divided in accordance with the scheme, have been introduced into figure 13,

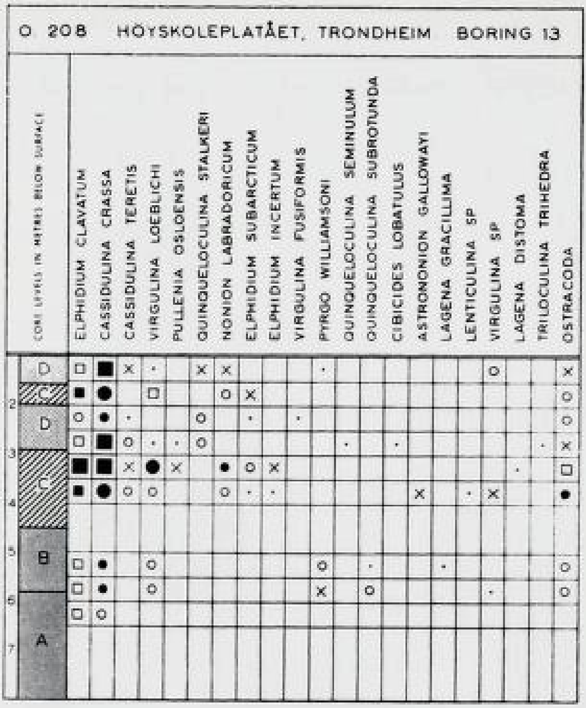

Fig. 16. Vertical distribution chart of boring 13, Høyskoleplatået, Trondheim.

*Vertikalfordelingsdiagram for boring 13, Høyskoleplatået, Trondheim.*

in which the borings have all been projected into one and the same profile. From this illustration it appears that the succession of the zones is the same in all borings, zone A obviously being the oldest one and D the youngest. This would suggest primary and undisturbed stratification of the deposits, if not the thickness of corresponding strata were highly different from one boring to another. This is clearly demonstrated in boring 8, where the thickness of zone C, and particularly that of zone B, is very small compared with the corresponding zones in the other borings, suggesting movements and deformations to have taken place, at least within the strata above zone A. The upper part of the core of boring 13 evidently represents material which has slid down from the cliff of the higher plateau, the younger part of the stratigraphical sequence being repeated at the top of the boring.

Comparing the result of the micropaleontological examination with those provided by geotechnical investigations of Gløshaugen, the geotechnicians arrived at the conclusion that large-scale slides must have taken place at times when the deposits were not yet raised above the sea. By these slides the layers above zone A slid upon the gently sloping surface of this zone in such a way that inversion of strata generally did not occur.

Old landslides of this type may sometimes be difficult, or impossible, to detect by paleontological methods. Younger parts of the sediments have been moved from one place to another, but micropaleontological investigations of borings through the deposits reaveals no break in the stratigraphical sequence, because younger layers still rest conformably upon older ones after the slide. In most cases, however, landslides have been more tumultuous, deformed strata and inverted stratigraphical sequence proving their existence.

## Tracing the slip plane.

A large group of landslides occur at slopes or cliffs where the equilibrium of the clay deposits is unstable. The immediate cause of such slides is nowadays very often provided by man, e.g. by removal of counter-pressure in dredging for quays and channels or by construction of road or rail embankments on clayed soil (Wenner 1951). This kind of a slide takes place along a more or less spherically curved slip plane.

For the checking of stability computations, wich is generally carried out by using imaginary slip planes in circular arcs, it would be very important to find in the clay deposits the position and form of the real slip plane. Some indications may be drawn from the occurrence of dry crust in the core samples, in most cases, however, it is hardly possible to trace the slip plane by geotechnical methods alone. Wenner (1951), investigating a large number of landslides, could only in four cases determine the probable position of the slip plane in the cores. In the solution of this problem micropaleontology may, in some cases, prove to provide a useful additional method.

Figure 17 illustrates a schematical profile of clay deposits in unstable equilibrium, I before, and II after the slide. The slip plane is indicated by the dotted curve of figure 17 I. Soon after the primary slide has taken place, additional slumping will, in most cases, obscure the rear part of the slide scar, as schematically indicated by the dotted curve (between boring 5 and 7) of figure 17 II. Provided no previous slide has disturbed the stratification of the deposits and that, e.g., four zones, D, E, F and G are micropaleontologically recognizable, the stratigraphical conditions before and after the slide will be approx. as illustrated in figure 17.

For geotechnical as well as micropaleontological investigation, core samples should be secured from borings carried out both within the actual slide area and in the adjacent part of the deposits, which has remained undisturbed after the slide. Micropaleontological examination of samples from the undisturbed part of the deposits, e.g. boring 6 and 7 of figure 17, reveals the local stratigraphy which, in this case, is a succession of four nearly horizontal zones mentioned above, D being the oldest one and G the youngest. When this stratigraphy has been thoroughly established for the undisturbed deposits, the zones have to be recognized within those parts of the sediments which have been involved in the slide.

In boring 1 the Foraminifera will demonstrate the presence of zones F, E and D in the same succession as in the undisturbed deposits. The lack of the youngest zone, G, indicates that this part of the clays represents the lower part of the original cliff (fig. 17 I), but there are no micropaleontological indications of the slip plane. In boring 2 the whole sequence from G to D will be present, but also there is no indication of the position of the slip plane; zone E of the slid material rests upon zone D, which is the normal succession in the undisturbed sediments. The borings 3, 4 and 5, on the other hand, provide excellent demonstration of the position of the slip plane; in boring 3 and 4 the succession will be G, F, D, zone E being absent in both borings, and the slip plane situated at the transition between F and D. In boring 5 zone F is lacking, and the slip plane situated at the transition between G and E.

In this idealized landslide the rear part, or the rear half, of the slip plane could be traced by micropaleontological examination of core samples, and such is the case with most landslides of this type.

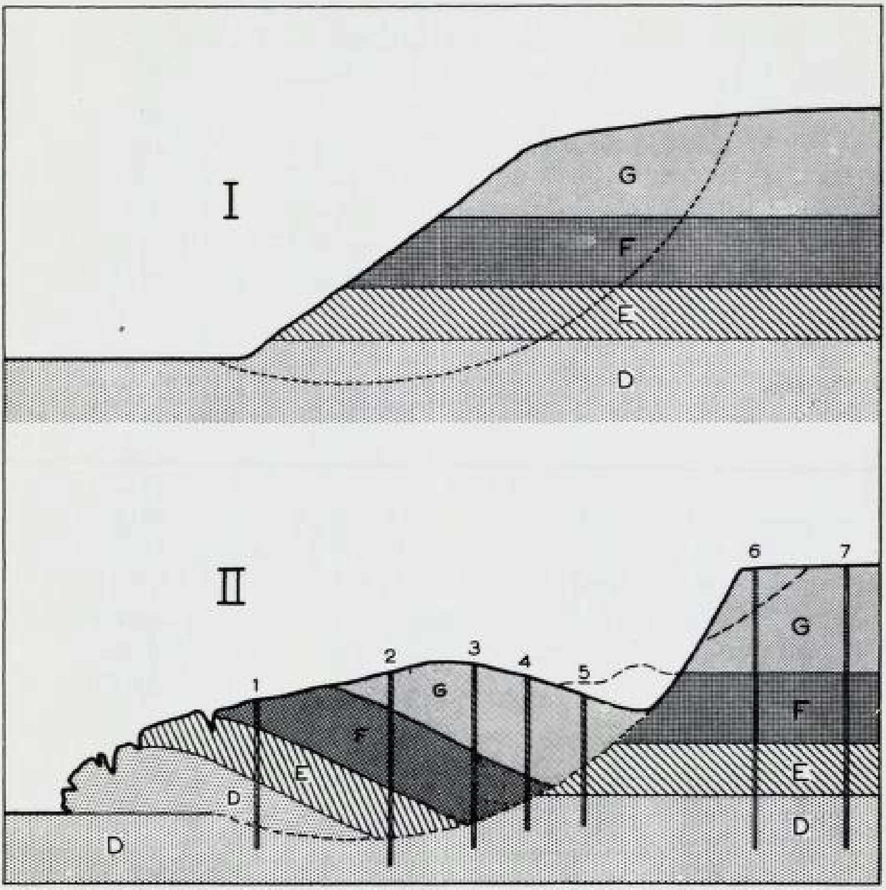

Fig. 17. Idealized profile through clay deposits in unstable equilibrium, I before, II after the slide. D, E, F and G indicate stratigraphical zones, the numbers 1 to 7 mark borings. Slide plane indicated by the dotted line in I.

*Idealisert profil gjennom leiravsetninger i ustabil likevekt, I før, II efter raset. D, E, F og G angir stratigrafiske soner, tallene 1—7 markerer boringer. Den prikkede linje representerer glideflaten.*

The traced part of the arc of the slip plane in the profil will, however, greatly facilitate the construction of the complete arc for stability computation. This will be particularly simple if the rear edge of the slide scar, by boring **6** in figure 17, is preserved. In the front part of the slide, to the left of boring 1, the presence of dry crust in the core will probably indicate the position of the previous clay surface which has been overrun by the slide.

Unfortunately, it may in some cases be impossible to determine the slip plane of a slide because the deposits have been involved in previous slides. The foraminiferal analyses will then reveal more than one break in the stratigraphical sequence of the different borings. In fact, several breaks and stratigraphic invertions may be recognized within one single core, the stratification having then been disturbed to such a degree that it has become impossible to point out any certain slip plane. To illustrate such a complicated case, the investigation of a landslide which took place at Lodalen in Oslo on October 6th, 1954, is recorded in the following.

The locality is situated approx. 1½ km east of the centre of Oslo at the main northern railway, and the slide was caused by extension of a marshalling yard. It is furthermore known that landslides have taken place within the same area previous to that of 1954 (Sevaldson 1956). A sketch map of the locality, with the limit of the slide and the placings of the borings indicated, is reproduced in figure 18, and a profile, section 2 in figure 18, showing the surface of the deposits before (dotted line) and after the slide, is illustrated in figure 19.

Core samples from six borings, boring nos. 1, 2, 3, 4, 6 and 7, were micropaleontologically investigated. Three of these borings, 2, 3 and 4 were from the slide whereas the other three were from adjacent parts of the deposits which were unaffected by the slide of 1954, boring 1 was situated above the slide and 6 and 7 west of it. Foraminifera occurred in all samples examined, and in accordance with the composition of the foraminiferal fauna from different samples it was possible to divide the sediments into four stratigraphical zones, D, E, F and G (in boring 2 even zone C was present). Zone D is characterized by the precense of few species, and usually also few specimens, *Elphidium clavatum* generally being the dominant one. The maximum number of species in one sample of this zone was 14. Zone E is characterized by the appearance of *Bulimina marginata* together with *Elphidium incertum*, *Elphidium clavatum* still being frequent. The maximum number of species in one sample was 28. In zone F *Bulimina marginata*

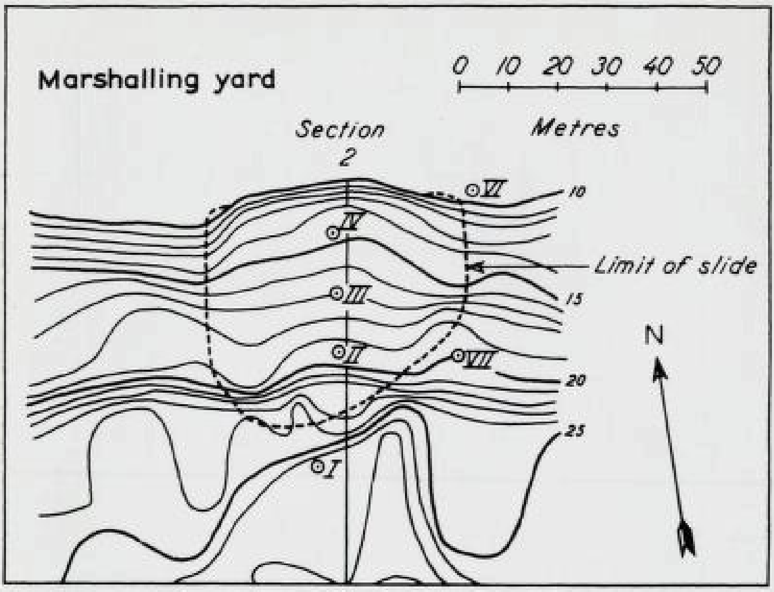

Fig. 18. Sketch map of the landslide at Lodalen, Oslo; limit of slide and position of borings indicated.

*Kartskisse over raset i Lodalen, Oslo, boringene og rasets begrensning er angitt.*

Fig. 19. Profile of the landslide at Lodalen, Oslo, section 2 in fig. 18.

*Profil av raset i Lodalen, Oslo.*

shows pronounced dominance, *Elphidium incertum* being second in number. The maximum number of species in one sample was 24. Zone G is characterized by quite frequent occurrence of *Eggerella scabra* and *Streblus beccarii;* the number of species was rather low in this zone, 11 being the maximum in one sample.

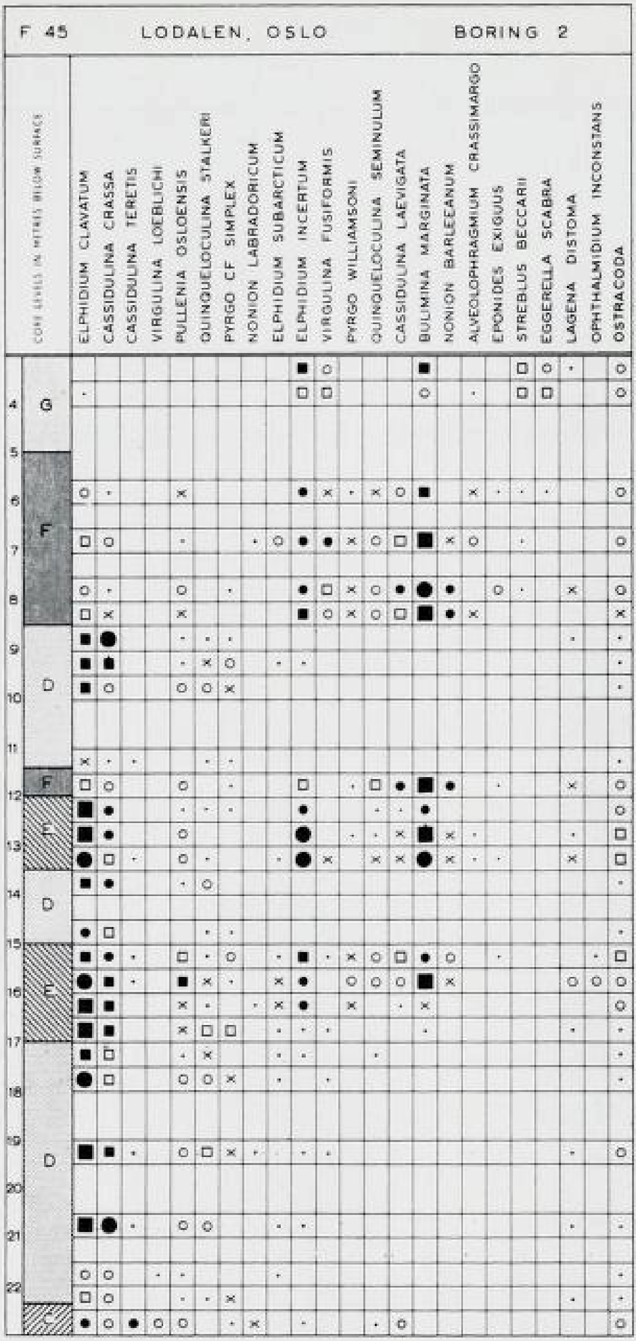

Fig. 20. Vertical distribution chart of boring 2, Lodalen, Oslo. For explanation of symbols see fig. 14.

*Vertikalfordelingsdiagram for de almindeligste foraminiferer i boring 2, Lodalen, Oslo (symbolforklaring i fig. 14).*

The analyses of four representative samples, one from each zone, are recorded below:

| Species | Zone D<br>Boring 2<br>Depth<br>20.6 m | Zone E<br>Boring 2<br>Depth<br>12.1 m | Zone F<br>Boring 2<br>Depth<br>8.2 m | Zone G<br>Boring 2<br>Depth<br>3.6 m |
|---|---|---|---|---|
| *Elphidium clavatum* ...... | 351 | 339 | 36 | 2 |
| *Cassidulina crassa* ........ | 84 | 69 | 3 | |
| *Quinqueloculina stalkeri* .. | 6 | 2 | | |
| *Pullenia osloensis* ........ | 5 | 2 | 4 | |
| *Fissurina semimarginata* .. | 3 | | | |
| *Quinqueloculina subrotunda* | 1 | 2 | | |
| *Lagena distoma* .......... | 1 | | | |
| *Cassidulina teretis* ........ | 1 | | | |
| *Cibicides lobatulus* ...... | 1 | | | |
| *Elphidium subarcticum* .... | 1 | | | |
| *Elphidium incertum* ...... | 1 | 89 | 126 | 24 |
| *Bulimina marginata* ...... | – | 83 | 720 | 68 |
| *Nonion* sp. .............. | – | 4 | | |
| *Liebusella goësi* .......... | – | 3 | 2 | |
| *Cassidulina laevigata* ...... | – | 2 | 42 | |
| *Quinqueloculina seminulum* | – | 1 | 11 | |
| *Pyrgo* cf. *simplex* ........ | – | 1 | | |
| *Globobulimina turgida* .... | – | 1 | | |
| *Elphidium excavatum* .... | – | 1 | | |
| *Nonion barleeanum* ...... | – | – | 78 | |
| *Virgulina fusiformis* ...... | – | – | 18 | 28 |
| *Nonionella auricula* ...... | – | – | 6 | |
| *Eponides exiguus* ........ | – | – | 5 | |
| *Pyrgo williamsoni* ........ | – | – | 3 | |
| *Lagena substriata* ........ | – | – | 2 | |
| *Lagena laevis* ............ | – | – | 1 | |
| *Buccella frigida* .......... | – | – | 1 | |
| *Eggerella scabra* .......... | – | – | – | 133 |
| *Streblus beccarii* .......... | – | – | – | 29 |
| *Alveolophragmium crassim*. | – | – | – | 2 |
| | 455 | 599 | 1058 | 286 |
| Ostracoda ................ | 1 | 16 | 4 | 9 |

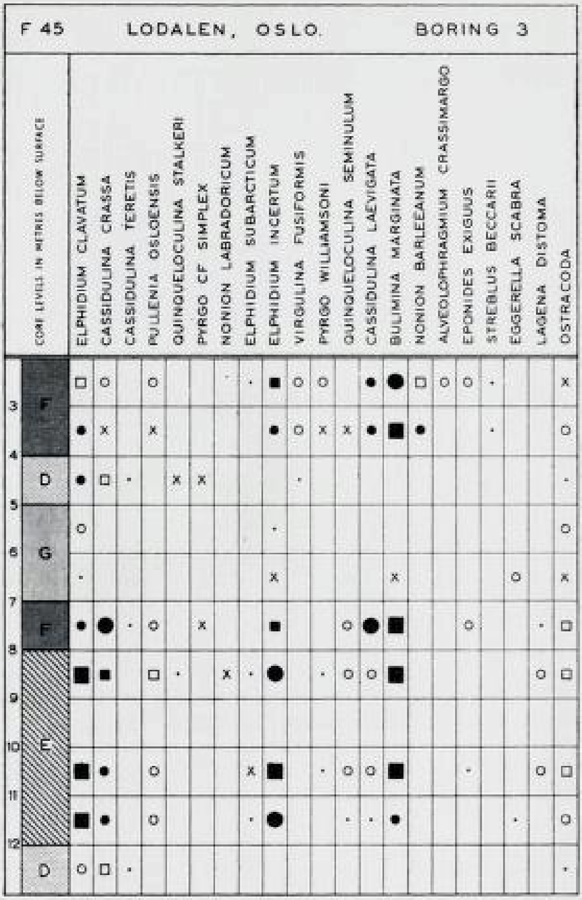

Fig. 21. Vertical distribution chart of boring 3, Lodalen.

*Vertikalfordelingsdiagram for boring 3, Lodalen, Oslo.*

To illustrate the variations in the composition of the foraminiferal fauna through the sediments, vertical distribution charts for the borings 2 and 3 have been reproduced in figures 20 and 21; rare species have been excluded. In boring 2 the zone D occur three times and zones E and F two times in the same core; in boring 3 the zones D and F occur twice.

From micropaleontological examination of other borings through clay deposits in Oslo it is, as we have seen, known that the normal

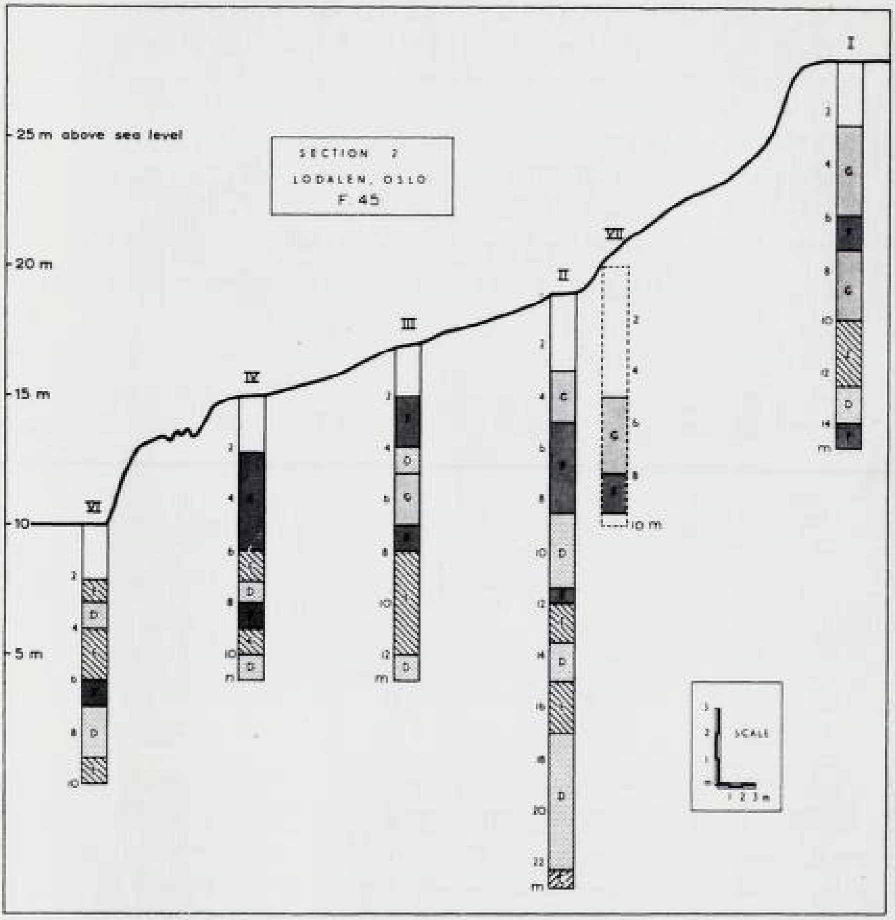

Fig. 22. The borings at Lodalen, stratigraphically divided, projected into one profile (section 2 of fig. 18).

*De stratigrafisk inndelte boringer i Lodalen projisert inn i profil 2 (seksjon 2 på fig. 18).*

succession of the stratigraphical zones which occur in Lodalen is D, E, F, G—D being the oldest zone and G the youngest. None of the borings from Lodalen showed this normal succession. Even the cores from those parts of the deposits which were not involved in the slide of 1954, borings 1 and 6, show a disturbed stratification (fig. 22). Boring 7, which was also taken outside the latest slide, showed normal succession of zones F and G; this boring was, however, not deep and only the two youngest zones were present in the core.

On the whole, the micropaleontological investigation of the landslide of 1954 in Lodalen revealed several breaks in the stratigraphical sequence, indicating that the sediments have been involved in several slides previous to the 1954 one. To point out any certain slip plane seems, however, to be very unsafe in a case like this.

## Conclusions.

1. The advancing fronts of the Pleistocene ice sheets of Scandinavia carried away most of the unconsolidated sediments which they met on their way. The marine clays which are the subject of the present paper, were deposited at the retreating front of the latest glaciation (Würm-Wisconsin) during periods of climatic amelioration. As the weight of the ice masses lessened, isostatic elevation of the previously glaciated region took place. In consequence, a great part of the marine sediments were raised above sea level. The retreat of the ice was interrupted by stagnations or oscillations which are marked by marginal moraines, the most prominent of which is the Ra. Other well-known morainic stages are the Ås-Ski stage, the Aker stage and the Minnesund stage (fig. 1).

2. On the basis of their content of fossil Foraminifera it has been possible to divide the marine clays of the Oslofjord area into seven stratigraphical zones: A, B, C and D being of Late Glacial age, E, F and G of Post Glacial. Zone A comprises the oldest strata of the Late Pleistocene, they were deposited under high-arctic climatic conditions in sea-water of rather high salinity. Zone B comprises sediments deposited during climatic amelioration when the water of the Oslofjord was much diluted by melt-water and, accordingly, had a rather low salinity. The sediments of zone C were deposited under marine-ecological conditions distinctly better than those of the previous zones; the salinity must have been high. At the beginning of the period of zone D the climate had once again become arctic and the glaciers had readvanced to the position marked by the moraines of the Aker stage; a considerable decrease in salinity took place when the glaciers receded anew. With the deposition of the zone E layers the marine-climatic conditions had changed to boreal and we have arrived into Post Glacial age; the salinity of the contemporaneous fjord water was rather high. Zone F comprises sediments deposited under optimum climatic conditions; water temperature and salinity seem to have been higher than

during any other Late Pleistocene period. Deterioration of the climate took place during the deposition of the zone G layers, and the contemporaneous salinity of the water was quite low.

3. The foraminiferal zone A is correlated with the *Yoldia* clay of Brøgger's classical division, zone B roughly with the *Arca* clay, zone F corresponds to the *Isocardia* clay and zone G to the *Scrobicularia* clay. Zone C is correlated with Øyen's *Mytilus* stage and D with his *Portlandia* stage (fig. 4).

4. A close correlation exists between the stratigraphical zones and the shear strengths of a clay deposit. In borings through homogenic sediments, showing discontinuous variation of shear strength with depth, the breaks in the variation of shear strength occur at the transitions from one stratigraphical zone to another (figs. 5-7). Thus, in clays of approx. equal mineral composition and grain size distribution any one stratigraphical zone can be related to a certain value of the ratio shear strength to effective overburden pressure, $s/\sigma_e$. Among the zones occurring in the Oslo region zone D is characterized by the lowest value of $s/\sigma_e$.

5. In most cases any one stratigraphical zone has a greater value of $s/\sigma_e$ in deposits close to sea level than the corresponding zone in deposits situated at greater elevation (fig. 8 a). This demonstrates the general relation between geotechnical properties and reduced salt concentration in the pore water of the clay. Small values of the ratio shear strength to effective overburden pressure occur in relatively salt-free clays whereas high $s/\sigma_e$-values are found in clays which have, more or less, kept their original salt concentration. The degree of leaching, resulting in reduced salt concentration, depends upon the hydraulic gradient which, as a rule, is larger in places where the sediments have been raised above the erosion base than in places where they have remained below or close to this level.

6. The leaching process takes place at different rate from one place to another and varies considerably with the permeability of the sediment; at any particular locality, however, it is a function of time. It is known, from other investigations, that the changes in geotechnical properties, caused by leaching, are negligible as long as the reduction in salt content has not reached a value of approx. 10 gram per litre, but that they become extremely important when

this critical value is surpassed. A clay belonging to zone D, which was deposited in water of low salinity, will, during the process of leaching, probably reach this critical value some thousand years before a clay which had a high original salt content in its pore water (fig. 10).

7. It is, in most cases, easily demonstrated by micropaleontological methods whether a sediment has remained undisturbed or if it has been subjected to previous slides; to trace the position and form of the real slip plane is, however, a much more difficult task.

# Sammendrag.

## Mikropaleontologi anvendt på geotekniske problemer i Norge.

### Innledning.

En hovedoppgave for den geotekniske forskning i Norge er å utrede våre leiravsetningers egenskaper og på den måten hjelpe til ved løsningen av praktiske spørsmål, f. eks. i forbindelse med byggeprosjekter. Hovedmassen av de leirer som kommer på tale i denne forbindelse er såkalte marine leirer, dvs. de er avsatt i sjøvann, og skriver seg fra den tid da siste istids bredekker efterhvert smeltet ned og trakk seg tilbake innover landet. At en så stor del av avsetningene senere er kommet til å ligge tørt, har sin årsak i den landstigning som har funnet sted under og efter avsmeltningen.

Nærværende arbeide er et forsøk på å dra nytte av mikropaleontologien ved løsningen av praktiske geotekniske problemer.

Mikropaleontologien arbeider med fossiler som er så små at man må bruke mikroskop for å studere dem nærmere. I våre marine leiravsetninger tilhører de aller fleste mikrofossiler gruppen Foraminifera, encellede dyr med skall som oftest er bygget opp av kalk. Det er skallene vi finner i avsetningene og størrelsen av dem er som regel 0.2—0.3 mm. Ut fra kjennskapet til hvordan forskjellige arter av foraminiferer lever i våre dager, om denne eller hin art krever kaldt eller temperert vann, stort eller lite dyp, høy eller lav saltholdighet, kan man dra slutninger om hvilke klimatiske forhold de forskjellige leirlag ble avsatt under og dermed om lagenes relative alder.

For å skaffe prøver fra undergrunnen, må man i stor utstrekning benytte seg av kjerneboringer. Hvis man bare hadde de vanlige skall av muslinger og snegler å holde seg til ved utredningen av lagfølgen i en slik boring, ville holdepunktene være få og usikre. For slike relativt store skall (megafossiler) vil sjelden eller bare helt tilfeldig forekomme i borkjernene, mens mikrofossilene i almindelighet vil være til stede i store mengder selv i tynne borkjerner. Istedenfor spredte eksemplarer eller bruddstykker, får man av mikrofossiler hele faunaer, eller populasjoner, å arbeide med. Og da må resultatet kunne bli langt sikrere. Der kan iallfall være opptil 30 000 foraminiferer i en leirprøve som i tørr tilstand veier 100 gram. De aller fleste foraminiferer lever i saltvann, noen få arter forekommer i brakkvann og nesten ingen i ferskvann.

## Geologisk historie.

Under kvartærtiden (Pleistocene) var Skandinavia iallfall tre ganger dekket av enorme ismasser som under sin vekst skjøv unna nesten alt som fantes av løsmateriale i området. De løsmasser (i motsetning til fast fjell) som vi finner under marin grense i Norge i dag er derfor vesentlig slike som ble avsatt foran isdekkets vikende fronter under siste istids avsmeltningsperiode.

Ansamlingen av sne og is i Fennoskandia (Finnland og Skandinavia) resulterte i en nedtrykning av landmassen slik at kystene lå dypere neddukket i sjøen enn de gjorde før nedisningen. Under den derpå følgende forbedring av klimaet letnet trykket av ismassene, og følgen var en langsom stigning av de tidligere nedisede landområder. På den måten ble en stor del av de marine sedimenter løftet opp over havnivået slik at de i dag utgjør byggegrunnen i noen av våre tettest befolkede områder, f. eks. omkring Oslofjorden og Trondheimsfjorden. I Oslo finnes den høyest hevede strandlinje i dag 221 m over nuværende havnivå.

Tilbakerykningen av isen ble fra tid til annen avbrutt av stillstand eller små fornyede fremrykninger. Iskantens stilling til disse tider finner vi merker efter i store randmorener. I Oslofjord-området er den mest fremtredende av disse den velkjente Ra-morene som kan følges fra Halden over Sarpsborg til Moss, og fra Horten til Larvik—Helgeroa og som fortsetter både i Sverige og vestover utenfor vårt område. Lagdelingen i Raet samt dets innhold av marine fossiler viser at det opprinnelig er avsatt i sjøen. Senere gjorde isen en stans, med små frem- og tilbakerykninger, ved linjen Mysen, Ås—Ski, Storsand. I nordkanten av Oslo by, ved Linnerud, Grefsen, Sognsvann, Bogstadvann og lenger vest ved Egge i Lierdalen, ligger morener som viser fremstøt av bremassene (Akertrinnet), og på Romerike finnes israndddannelser ved Berger, Jessheim, Hauerseter, med Minnesundtrinnet som den siste stagnasjon av isranden i dette område (sml. fig. 1). Marine avsetninger er funnet så langt nord som ved sydenden av Mjøsa, og i Glåmas dalføre nordover til omkring Våler (fig. 2).

## Stratigrafi.

Ved studium av foraminiferinnholdet i leirprøver fra en lang rekke boringer i Oslofjord-området viser det seg at de marine avsetninger kan inndeles i syv soner: A, B, C, D, E, F og G, med A som den eldste og G som den yngste. Sonene A, B, C og D skriver seg fra senglacial tid da en innlandsis ennu fantes i landet, mens E, F og G ble avsatt i postglacial tid da all is var smeltet bort. Avsetninger tilhørende sone A er i Oslo-feltet bare funnet syd for Raet, de ble avsatt under høyarktiske klimaforhold da et ishav skyllet mot innlandsisens kalvingsfront i områdene omkring det som nu er ytre Oslofjord. Sone F derimot, omfatter avsetninger som skriver seg fra postglacial varmetid, stenalderen, da klimaet over hele Norges land var gunstigere enn det er i dag. Foraminiferinnholdet i de forskjellige soner vil bli utførlig behandlet i et senere arbeide.

I figur 4 er våre mikropaleontologiske soner sammenholdt med Brøggers tidligere inndeling som grunner seg på innholdet av muslingskall i leirene, og med Øyens strandlinjenivåer som har navn efter muslinger og snegler i strandavsetninger. Strandlinjenes høyde i Oslo til de forskjellige tider er også angitt, og helt til høyre i skjemaet er anført avsetningenes tilnærmede alder.

## Stratigrafi og geoteknikk.

For en lang rekke leirprøver fra boringer i Oslofjord-området er der iakttatt en sammenheng mellom stratigrafi og geotekniske egenskaper, slik at overgang fra én stratigrafisk sone til en annen som regel følges av en forandring i geotekniske egenskaper. Dette gjelder i særlig grad leirens skjærfasthet, som er den motstand en leirsylinder av bestemt tverrsnitt gjør mot å slites over på tvers.

I figurene 5—7 er sammenhengen mellom stratigrafi og noen geotekniske egenskaper vist ved to boringer fra Bjørvika og en fra Majorstuen, Oslo. Tendensen i forandringen i skjærfasthetene (skjærfasthetene fremstilt ved ringer og kryss til høyre i diagrammene) er illustrert ved rette linjer (sml. Bjerrum 1955). Innenfor hver enkelt stratigrafisk sone tiltar skjærfastheten forholdsvis jevnt med dypet i avsetningen, men ved overgangen fra en sone til den neste er der et mer eller mindre plutselig brudd i denne jevne økning.

Vi holder oss her bare til skjærfastheten, og for i våre betraktninger å eliminere dens økning med dypet, dividerer vi skjærfastheten s med det effektive overlagringstrykk $\sigma_e$ og får dermed et forhold $s/\sigma_e$ som er noenlunde konstant for hver sone innenfor en og samme boring. I tabellen side 26 er sammenstillet resultatene av mikropaleontologiske og geotekniske undersøkelser for 10 boringer fra 5 forskjellige steder i Oslo. Forholdet skjærfasthet til effektivt overlagringstrykk, $s/\sigma_e$, viser innenfor hver enkel boring påfallende sammenheng med boringens stratigrafiske soner. Således viser det seg at sone D i alle boringer har den laveste $s/\sigma_e$-verdi. Disse forhold gjelder selvfølgelig bare i den utstrekning kornstørrelsesfordeling og mineralsammensetning er konstant gjennom hele den betraktede del av avsetningen.

## Redusert saltinnhold.

Det viser seg videre at de geotekniske egenskaper stort sett er avhengige av leiravsetningens høyde over havet. Idet vi stadig holder oss til skjærfastheten, representert ved forholdet $s/\sigma_e$, ser vi at hver sone (C, D, E, F, G) har en større verdi av $s/\sigma_e$ i avsetninger nær havnivå enn i avsetninger som befinner seg høyere opp. Denne avhengighet er, for boringene i tabellen side 26, illustrert i diagrammet på figur 8 a, og i virkeligheten demonstrerer den den almindelige sammenheng mellom geotekniske egenskaper og redusert saltkonsentrasjon i leirenes porevann.

Systematiske undersøkelser over saltinnholdet i norske marine leirer har vist at en betraktelig reduksjon har funnet sted siden de ble avsatt. Og det er videre blitt klart at redusert saltinnhold medfører f. eks. redusert skjærfasthet (Rosenqvist 1946 a, Bjerrum 1955). Dette forhold er illustrert i figur 9. Lave $s/\sigma_e$-verdier finnes i relativt saltfrie leirer mens høyere verdier finnes i leirer som mer eller mindre har beholdt sitt opprinnelige saltinnhold. Reduksjonen i geotekniske egenskaper foregår ikke i samme forhold som reduksjonen i saltinnhold. Selv en betydelig reduksjon av saltinnholdet medfører bare helt ubetydelige reduksjoner i leirens geotekniske egenskaper så lenge saltkonsentrasjonen holder seg over 10 gram pr. liter. Men blir saltinnholdet lavere enn denne verdi, påvirkes de geotekniske egenskaper i betraktelig grad.

Reduksjonen av en leires opprinnelige saltinnhold er avhengig av grunnvannssirkulasjonen i avsetningen. Og grunnvannsbevegelsen vil meget ofte, men slett ikke alltid, være livligere i avsetninger som er hevet opp i større høyde over havets nivå enn i slike som er blitt liggende i eller nær ved sjøen. Derfor finner vi ofte lavere saltholdigheter og lavere skjærfastheter i høytliggende leirer enn i lavtliggende.

## Saltkonsentrasjon og stratigrafi.

Reduksjonen i saltinnhold avhenger også av det tidsrom som har stått til rådighet for grunnvannets utlutende virksomhet. En ung leiravsetning vil derfor ha høy $s/\sigma_c$-verdi av to grunner, for det første fordi den er ung og ikke har hatt tid nok på seg til noen nevneverdig reduksjon av saltinnholdet, og for det annet fordi den bare har fått være med på en liten del av landstigningen. Grunnvannssirkulasjonen har derfor ikke kunnet økes i noen betraktelig grad og altså har ikke noen nevneverdig utlutning av saltinnholdet kunnet finne sted.

I en homogen leiravsetning (hvor vi ser bort fra tørrskorpefenomenene) der de stratigrafiske soner G, F, E, D, C forekommer, skulle verdien av $s/\sigma_c$ således være mindre i sone F enn i sone G, og mindre i E enn i F, man skulle vente en kontinuerlig minking i forholdet fra yngre til eldre lag i avsetningen. Men som vi har sett varierer ikke $s/\sigma_c$-verdien på den måten. Visstnok er $s/\sigma_c$-verdien mindre i sone F enn i G, mindre i E enn i F og mindre i D enn i E, men i sone C er den igjen større. Dessuten er der en mer eller mindre brå forandring i $s/\sigma_c$-verdien ved overgangen fra en sone til en annen. I en bestemt boring har hver sone sin bestemte $s/\sigma_c$-verdi.

For å prøve å finne en forklaring på dette påtagelige forhold mellom skjærfasthetens størrelse og leiravsetningens geologiske historie, for de stratigrafiske soner avspeiler jo den geologiske historie, er det naturlig å se nærmere på den totale saltholdigheten av det sjøvann som leiren opprinnelig ble avsatt i. Vi antar da at den opprinnelige saltkonsentrasjon i leirens porevann var den samme som saltholdigheten i dette sjøvann (sml. G. Holmsen 1930, Rosenqvist 1955). Som vi har sett under omtalen av våre mikropaleontologiske soner, ble avleiringene innen de forskjellige soner avsatt i perioder med skiftende klimatiske forhold som igjen medførte forandringer av saltholdigheten i det tilhørende sjøvann. Indikasjoner på lav saltholdighet ble funnet i forbindelse med sonene D og G, mens mikrofaunaen i sone C og sone E tyder på temmelig høy saltholdighet. Sone F ble dannet i sjøvann med stor saltholdighet, omtrent 35 gram pr. liter.

Våre sen- og postglaciale leirer ble avsatt i sjøvann som antagelig aldri hadde saltholdighet lavere enn ca. 20 ⁰/₀₀. Det vil si at den opprinnelige saltkonsentrasjon i leirens porevann for alle stratigrafiske soner har vært vel over den kritiske verdi 10 gram pr. liter, og der synes å være lite håp om å finne en forklaring på de forskjellige skjærfastheter ut fra den opprinnelige saltholdighet i leirene fra de forskjellige soner. Man skulle tvert imot vente å finne konstant $s/\sigma_c$-verdi gjennom hele serien av stratigrafiske soner i en homogen leiravsetning. Dette er også tilfelle — så lenge ikke saltkonsentrasjonen i leirene er blitt betraktelig redusert ved utlutning.

Utlutningsprosessen foregår med forskjellig hastighet på forskjellige steder, og varierer i høy grad med kornstørrelsen i avsetningene. Men i hvert enkelt tilfelle vil den være avhengig av tiden. På hvilken måte utlutningen avhenger av tiden vites ikke, for mange detaljer i prosessen er utilstrekkelig kjent (sml. Rosenqvist 1955). Men for å forenkle fremstillingen antar vi her at reduksjonen i saltkonsentrasjonen, utlutningsprosessen, er direkte avhengig av tiden, slik at altså dobbel tid gir dobbel utlutning. En slik antagelse har ingen prinsipiell innflytelse på forklaringen av forholdet mellom skjærfasthet og stratigrafiske soner. Den antatte reduksjon av saltinnholdet er fremstillet på fig. 10, hvor grunnlinjen i diagrammet er delt inn i hypotetiske tidsintervaller på 1000 år. Vi antar altså at leire som engang ble avsatt i sjøvann med total saltholdighet på 35 ⁰/₀₀ og senere utsatt for utlutning, efter 10 000 år vil ha saltinnholdet i sitt porevann redusert til 15 ⁰/₀₀. En annen leiravsetning med opprinnelig saltinnhold på 30 ⁰/₀₀ vil, ifølge samme hypotetiske diagram, ha sitt saltinnhold redusert til 10 $^0/_{00}$ etter 10 000 år.

Som før nevnt forårsaker utlutningen av saltet i leirenes porevann forandringer i deres geotekniske egenskaper. Videre vet vi at disse forandringer er helt ubetydelige så lenge saltinnholdet fremdeles er høyere enn ca. 10 gram pr. liter, men at de blir skjebnesvangre når saltinnholdet reduseres ytterligere og bringes ned under denne kritiske verdi.

Idet vi atter betrakter det hypotetiske diagram (fig. 10), skal vi følge to leirer gjennom utlutningsprosessen. Den ene ble avsatt i sjøvann og fikk en saltkonsentrasjon på 35 gram per liter i porevannet, den annen ble avsatt i brakt sjøvann og fikk en opprinnelig saltkonsentrasjon på bare 25 gram per liter. Hvis mineralsammensetningen, kornstørrelsesfordelingen og andre forhold er like for de to avsetninger, så vil de, før utlutningen, antagelig også ha samme skjærfasthet, eller rettere samme $s/\sigma_c$-verdi, selv om der altså er en forskjell på hele 10 gram pr. liter når det gjelder saltinnholdet i deres porevann. Imidlertid, hvis de ble avsatt samtidig og senere utsatt for utlutning overensstemmende med diagrammet (fig. 10), så ville saltinnholdet i den brachyhaline avsetning, opprinnelig 25 gram per liter, nå den kritiske verdi 10 gram per liter 5000 år før leiren med opprinnelig saltinnhold på 35 gram per liter. Når saltinnholdet i 35 $^0/_{00}$-leiren var blitt redusert til 15 gram per liter, og altså avsetningen fremdeles var en normal leire med lav sensitivitet, ville saltkonsentrasjonen i den brachyhaline leire samtidig være redusert til 5 gram per liter, og denne avsetning ville antagelig da være forandret til en kvikkleire med høy sensitivitet.

Av boringene i tabellen side 26 fremgår det at verdien av $s/\sigma_c$ er større i sone G enn i sone F selv om det opprinnelige saltinnhold i sone F må ha vært adskillig større enn i sone G. På den annen side er imidlertid G-leirene de yngste i den stratigrafiske rekkefølge og har således hatt liten tid til utlutning, mens F-leirene kan ha vært utsatt for utlutning gjennom et tidsrom av omkring 5000 år. Den store forskjell i $s/\sigma_c$ mellom sone F og sone D, $s/\sigma_{cF}$ ser ut til å være omtrent det dobbelte av $s/\sigma_{cD}$ i en og samme boring, forklares både ved at sone D er omtrent 4000 år eldre enn F og ved den høyere opprinnelige saltholdighet i sone F. Årsaken til at $s/\sigma_{cF}$

er større enn $s/\sigma_{eD}$, selv om sone C antagelig er 1000 år eldre enn D, ligger i den høyere opprinnelige saltkonsentrasjon i C-leirenes porevann, denne faktor overskygger virkningen av den forholdsvis lille tidsforskjellen.

Homogene leiravsetninger som ikke har vært utsatt for utlutning i nevneverdig grad, viser liten eller ingen diskontinuitet i skjærfastheten på overgangen mellom to stratigrafiske soner. Slike leirer har i stor utstrekning beholdt sitt opprinnelige saltinnhold, og selv om dette er forskjellig for forskjellige stratigrafiske soner, påvirker ikke det skjærfastheten i nevneverdig grad så lenge konsentrasjonen er høyere enn 10 gram pr. liter. Således viser boringer gjennom uforstyrrede leiravsetninger i Drammen skjærfastheter som tiltar jevnt med dypet og altså gir et konstant forhold mellom skjærfasthet og effektivt overlagringstrykk gjennom hele profilet (fig. 11) selv om flere stratigrafiske soner forekommer. Disse leirer viste seg å ha en saltkonsentrasjon på mellom 26.7 og 13.4 gram pr. liter i porevannet. Slike leirer finnes i alminnelighet nær nuværende havnivå eller andre steder der grunnvannsbevegelsen er liten. På den annen side viser avsetningene ved Vaterland og i Bjørvika i Oslo at også leirer som befinner seg nær, eller endog under, nuværende havnivå kan ha fått sitt opprinnelige saltinnhold redusert.

I de omtalte boringer fra Oslo (tabellen side 26) viser det seg altså at sone D innenfor hver enkelt boring har den laveste $s/\sigma_e$-verdi, og dette forhold vil nok gjenfinnes i de fleste uforstyrrede avsetninger i Oslofjord-området. Men det vil ikke si at kvikkleirer nødvendigvis må tilhøre sone D. For, som vi har sett, kvikkleirene fremkommer ved at en opprinnelig forholdsvis høy saltkonsentrasjon i leirenes porevann reduseres i betraktelig grad. Og dette kan skje med leirer innen hvilken som helst stratigrafisk sone. I overensstemmelse hermed anfører P. Holmsen (1949) at kvikkleirene i Norge ikke er spesielt knyttet til postglaciale leirer, flere av de største leirfall har foregått i senglaciale leirer.

## Gamle skred.

Leiravsetninger som har deltatt i skred, har i almindelighet fått helt andre geotekniske egenskaper enn den uforstyrrede avsetning hadde. Derfor er det av interesse for geoteknikeren å vite om han har med forstyrrede eller uforstyrrede lag å gjøre. Allerede den mikropaleontologiske påvisning av lag som kan kjennes igjen fra det ene borhull til det andre vil her være til hjelp, selv om disse lagene behandles som helt lokale foreteelser og ikke knyttes til noen regional stratigrafi. Hvis boringene er tallrike nok og fornuftig plasert, vil den normale lokale lagfølge snart vise seg, og uoverensstemmelser lar seg lett oppspore.

Slik anvendelse av mikropaleontologien til oppsporing av gamle utglidninger er illustrert ved et eksempel fra Høyskoleplatået (Gløshaugen) i Trondheim. På kartskissen, figur 12, er vist plaseringen av boringene, 2, 4, 8 og 13, og på figur 13 er disse boringer, stratigrafisk inndelt, projisert inn i profil II. På figurene 14—16 er vist hvordan forekomst og hyppighet av endel foraminiferarter er lagt til grunn for en stratigrafisk inndeling (se også tabellen side 40). Samtlige lag er av senglacial alder. Sone A er karakterisert ved en fattig fauna; sone B har flere arter, *Virgulina loeblichi* opptrer og *Pyrgo williamsoni* er ganske hyppig; sone C er karakterisert ved forholdsvis stort artsantall, ved rikelig forekomst av *Virgulina loeblichi* og ved opptreden av *Cassidulina teretis;* sone D har som regel færre arter enn C, og viser en utpreget dominans av *Cassidulina crassa.*

Som vi ser er rekkefølgen av lagene den samme i alle boringer, men lagenes store forskjell i tykkelse tyder på glidninger i materialet. I øverste del av boring 13 har vi dessuten en gjentagelse av lagene C og D som viser at denne del har sklidd ned fra skrenten av det høyere platå (se fig. 13).

## Glideflaten.

Når det gjelder å bestemme posisjonen av glideflaten ved skred i leiravsetninger, kan mikropaleontologien i noen tilfelle yde assistanse. Figur 17 viser et skjematisk profil gjennom en leiravsetning i ustø likevekt, I før, II efter raset. Den prikkede kurve angir glideflaten. Hvis der ikke har gått ras tidligere, kan lagdelingen være slik som angitt på figuren med f. eks. fire soner, D, E, F og G. Mikropaleontologisk undersøkelse av boring 6 og 7, altså i den uforstyrrede del av avsetningen, klarlegger den stratigrafiske rekkefølge av de fire nevnte soner. Når dette er gjort, kan sonene finnes igjen i boringene innen rasområdet. I boring 1 vil foraminiferene vise tilstedeværelsen av sonene F, E og D i samme rekkefølge som i den uforstyrrede del av avsetningen, glideflaten vil ikke åpenbare seg. I boring 2 vil hele rekkefølgen fra G til D være representert, men ingen indikasjoner av glideflaten, sone E i det utraste materiale hviler på sone D, og det er den normale rekkefølge. Men boringene 3, 4 og 5 vil gi utmerkede holdepunkter for glideflatens bestemmelse; i boringene 3 og 4 mangler sone E, og glideflaten vil være å finne på overgangen mellom F og D. I boring 5 mangler sone F, og glideflaten finnes mellom G og E.

I mange tilfelle vil det imidlertid være umulig å bestemme glideflatens beliggenhet fordi avsetningen har vært innviklet i tidligere skred. Foraminiferundersøkelsen vil da vise mer enn ett brudd i den stratigrafiske rekkefølge. Til illustrasjon av et komplisert tilfelle anføres skredet i Lodalen, Oslo, den 6. oktober 1954. På figur 18 er vist en kartskisse over området med skredets begrensning og boringenes plasering. Figur 19 viser i profil overflaten av skredområdet før og efter raset. Prøver fra seks boringer ble undersøkt mikropaleontologisk, tre av disse, 2, 3 og 4, var fra selve rasområdet, mens de andre tre var fra det tilgrensende område som ikke deltok i raset av 1954. På grunnlag av foraminiferinnholdet kunne avsetningen deles i fire karakteristiske soner, D, E, F og G, i boring 2 er til og med en sone C representert (se tabellen side 51). I boring 2 (fig. 20) opptrer sone D tre ganger og sonene E og F to ganger i samme borkjerne, i boring 3 (fig. 21) forekommer sonene D og F to ganger. Til og med boringer fra de deler av avsetningen som ligger utenfor raset av 1954 viser forstyrret lagfølge. I figur 22 er de stratigrafisk oppdelte boringer innført i profil 2, og viser så mange brudd i den stratigrafiske rekkefølge at det ville være et meget usikkert foretagende å forsøke å peke ut bestemte glideflater.

# References.

Bjerrum, L. 1954 a. Geotechnical properties of Norwegian marine clays. — Norw. Geotechn. Inst. Publ. No. 4, pp. 1-21. Oslo. (Also Géotechnique *4*, No. 2).

Bjerrum, L. 1954 b. Theoretical and experimental investigations on the shear strength of soils. — Norw. Geotechn. Inst. Publ. No. 5, pp. 1-113. Oslo.

Bjerrum, L. 1954 c. En geotekniker ser på byplanen. — Norw. Geotechn. Inst. Publ. No. 6, pp. 1-10. Oslo. (Also Kommunalt tidsskr. *41*, No. 7.)

Bjerrum, L. 1955. Norske marine leirers geotekniske egenskaper. — Norw. Geotechn. Inst. Publ. No. 7, pp. 1-16. Oslo. (Also Tekn. Ukeblad 1955, Nos. 35 and 37. Oslo.)

Brotzen, F. 1951. Bidrag till de svenska marina kvartäravlagringarnas stratigrafi. — Geol. Fören. Förhandl. *73*, pp. 57-68. Stockholm.

Brøgger, W. C. 1900-1901. Om de senglaciale og postglaciale nivåforandringer i Kristianiafeltet (Molluskfaunan). — Norges Geol. Unders. No. 31, pp. 1-731. Kristiania.

Cushman, J. A. 1940. Foraminifera, their classification and economic use. Pp. 1-535. Harward Univ. Press. Cambridge, Massachusetts. (First ed. 1928.)

Feyling-Hanssen, R. W. 1954 a. Late Pleistocene Foraminifera from the Oslofjord area, Southeast Norway. — Norsk Geol. Tidsskr. *33*, pp. 109-152. Oslo.

Feyling-Hanssen, R. W. 1954 b. The stratigrafic position of the quick clay at Bekkelaget, Oslo. — Norsk Geol. Tidsskr. *33*, pp. 185-196. Bergen.

Feyling-Hanssen, R. W. 1955. Dominating Foraminifera from the Late Pleistocene of the Oslofjord area, Southeast Norway. Actes IV Congr. Intern. Quaternaire, Rome-Pise, 1953. Pp. 1-8. Roma.

Glaessner, M. F. 1948. Principles of micropaleontology. Pp. 1-296. Melbourne Univ. Press. Melbourne. (Also Cambridge Univ. Press. First ed. 1945.)

Holmsen, G. 1929. Lerfaldene ved Kokstad, Gretnes og Braa. — Norges Geol. Unders. No. 132, pp. 1-45. Oslo.

Holmsen, G. 1930. Grundvandet i vore leravsætninger. — Norges Geol. Unders. No. 135, pp. 1-92. Oslo.

Holmsen, G. 1934. Lerfall i årene 1930—1932. — Norges Geol. Unders. No. 140, pp. 1-36. Oslo.

Holmsen, G. 1938. Våre leravsetninger som byggegrunn. — Norges Geol. Unders. No. 151, pp. 1-95. Oslo.

Holmsen, G. 1954. Oppland. Beskrivelse til kvartærgeologisk landgeneralkart. — Norges Geol. Unders. No. 187, pp. 1-58. Oslo.

Holmsen, G. 1955. Norske jordarter og geotekniske problemer knyttet til dem. — Norw. Geotechn. Inst. Publ. No. 7, pp. 1-5. Oslo.

Holmsen, G. and Holmsen P. 1946. Leirfall i årene 1940—1945. — Norges Geol. Unders. No. 167, pp. 1-71. Oslo.

Holmsen, P. 1946. Om leirfallene i Norge og kvikkleirenes betydning. — Statens vegvesen, Veglab. Meddel. No. 4, pp. 3-4. Oslo.

Holmsen, P. 1949. Om kvikkleire og betingelsene for dens dannelse. — Geol. Fören. Förhandl. *71*, pp. 616-619. Stockholm.

Holtedahl, O. 1953. Norges geologi. *2*. Norges Geol. Unders. No. 164, pp. 585-1118. Oslo.

Larssen, Kari Egede. 1950. Pollenanalytiske undersøkelser i indre Østfold. — Universitetet i Bergen, Årbok 1949. Nat.-vit. rekke No. 13, pp. 1-19. Bergen.

Moum, J. and Rosenqvist, I. Th. 1955. Kjemisk bergartsforvitring belyst ved en del leirprofiler. — Norsk Geol. Tidsskr. *34*, pp. 167-174. Bergen. (N. G. I. No. 8.)

Rosendahl, H. 1955. Geochronologia Norvegica. — Actes IV Congr. Intern. Quaternaire, Rome-Pise, 1953. Pp. 1-8. Roma.

Rosenqvist, I. Th. 1946 a. Om leires kvikkaktighet. — Statens vegvesen, Veglab. Meddel. 4:5, pp. 5-12. Oslo.

Rosenqvist, I. Th. 1946 b. Om leires plastisitet. — Statens vegvesen, Veglab. Meddel. 4:12, pp. 12-16. Oslo.

Rosenqvist, I. Th. 1953. Considerations on the sensitivity of Norwegian quickclays. — Géotechnique *3*, pp. 195-200. (N. G. I. publ. No. 2.)

Rosenqvist, I. Th. 1955. Investigations in the clay-electrolyte-water system. — Norw. Geotechn. Inst. Publ. No. 9, pp. 1-125. Oslo.

Sevaldson, R. A. 1956. Raset i Lodalen 6. oktober 1954. — Norw. Geotechn. Inst. Publ. No. 19, pp. 1-16. Oslo. (Also Tekn. Meddel. Norges Statsbaner.)

Skempton, A. W. 1948. A study of the geotechnical properties of some Post Glacial clays. — Géotechnique *1*, pp. 7-22.

Strøm, K. 1936. Land-locked waters. Hydrography and bottom deposits in badly-ventilated Norwegian fjords with remarks upon sedimentation under anaërobic conditions. — Skr. Norske Vid. Akad. i Oslo. I. Mat.-Nat. Kl. No. 7, pp. 1-85. Oslo.

Wenner, C.-G. 1951. Data on Swedish landslides. — Geol. Fören. Förhandl. *73*, pp. 300-308. Stockholm.

Øyen, P. A. 1915. Kvartærstudier i Trondhjemsfeltet III. — Kgl. Norske Vid. Selsk. Skr. 1914. No. 6, pp. 1-506. Trondhjem.

Øyen, P. A. 1917. Korrelationsopgaver i nordvesteuropæisk kvartærforskning. — Arch. Mat. og Naturv. *15*, Nr. 3, pp. 1-12. Kristiania.

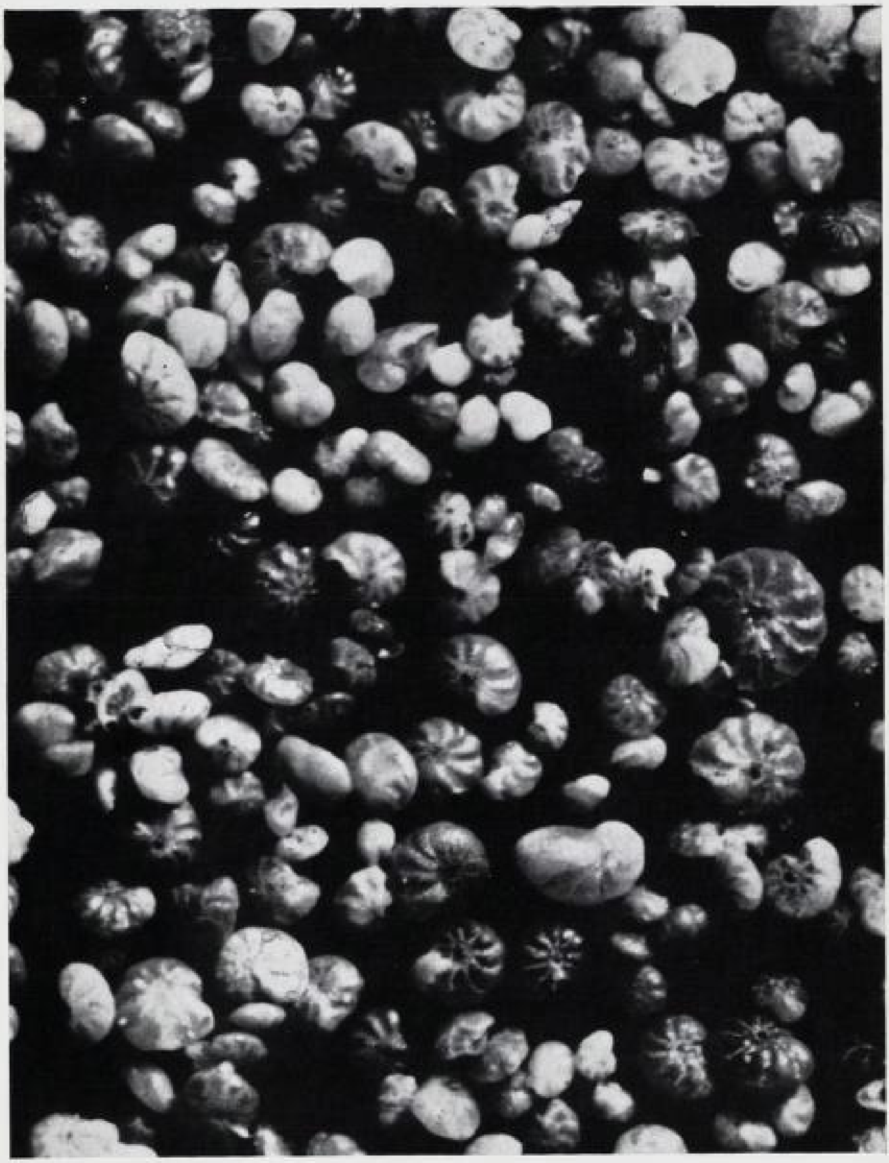

Plate 1. Zone A. Fossil fauna of Foraminifera from a boring at Sarpsborg, 15.5 m below the surface. *Elphidium clavatum* dominating.

*Sone A. Fossil foraminiferfauna fra en boring ved Sarpsborg, 15.5 m under overflaten. Elphidium clavatum dominerer.*

Plate 2. Zone C. Foraminiferal fauna from boring 4, Høyskoleplatået, Trondheim, 3.3 m below the surface. *Virgulina loeblichi* frequently represented.

*Sone C. Fossil foraminiferfauna fra boring 4, Høyskoleplatået, Trondheim, 3.3 m under overflaten. Rikelig forekomst av Virgulina loeblichi.*

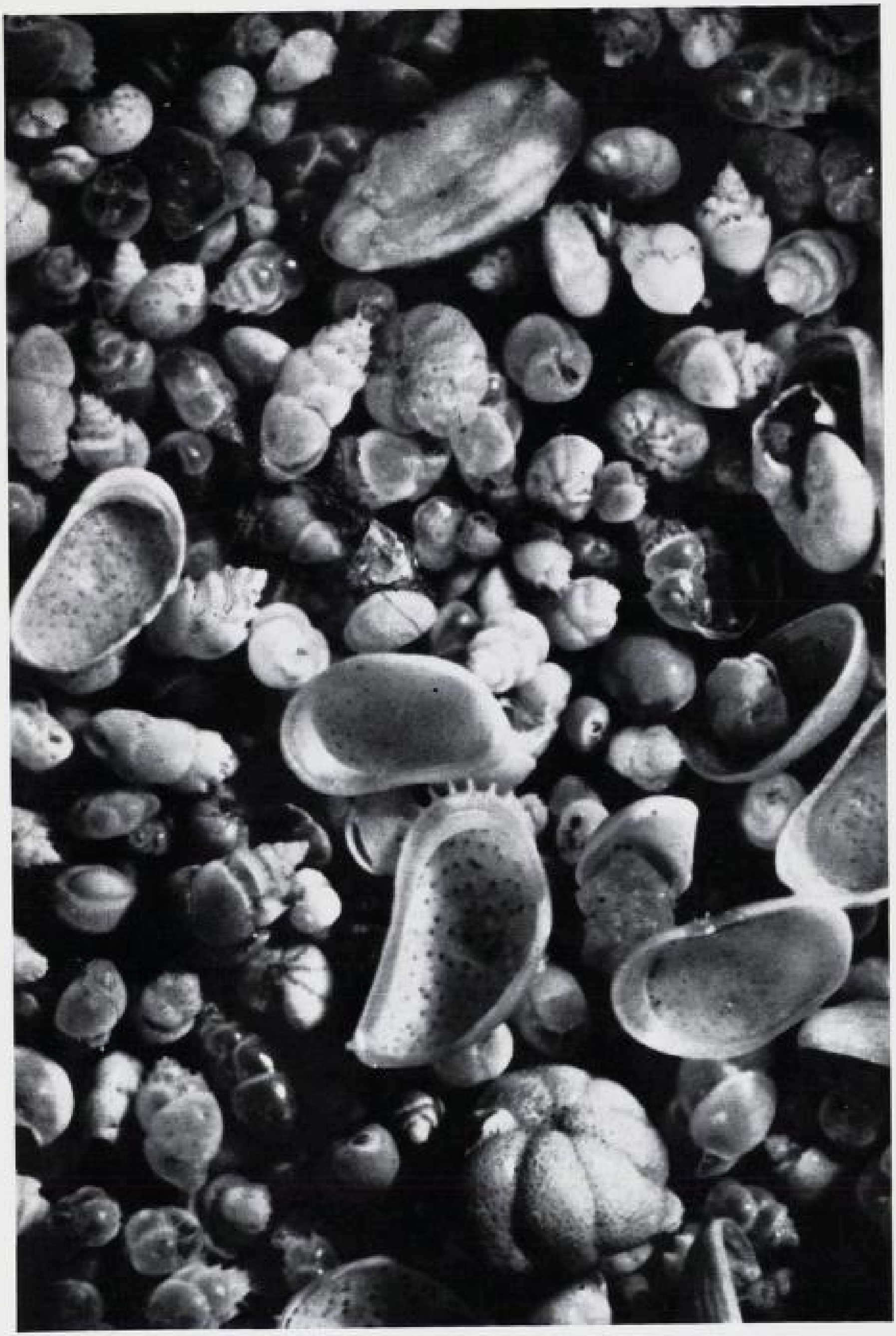

Plate 3. Zone F. Foraminifera and some Ostracoda from a boring at Nationaltheateret, Oslo, 11.3 m below the surface. *Bulimina marginata* dominating.

*Sone F. Fossile foraminiferer og noen ostracoder fra en boring ved Nationaltheateret, Oslo, 11.3 m under overflaten. Bulimina marginata dominerer.*