

SVERIGES GEOLOGISKA UNDERSÖKNING

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AVHANDLINGAR OCH UPPSATSER

ÅRSBOK 76 NR 7

**ERIC OLAUSSON
EDITOR**

**THE PLEISTOCENE/HOLOCENE BOUNDARY
IN SOUTH-WESTERN SWEDEN**



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PREFACE

This publication was compiled by a number of scientists from various institutes in five countries under the leadership of Eric Olausson. It is based on comprehensive studies, research and field work.

Research workers from the Geological Survey of Sweden took an active part in the preparation of the manuscript. The Survey assumed the final, economic and editorial responsibility for the publication. Economic support for this was also given by the Swedish Natural Science Research Council.

The opinions and views expressed in this book are not necessarily authorized by the Geological Survey of Sweden. As usual each author independently will take the full responsibility for the presentation of scientific observations and conclusions made in the papers.

The Publication Board of the Geological Survey of Sweden.

CONTENTS

Abstract	5
1. In search of a stratotype locality	6
<i>E. Olausson</i>	
2. General comments on the Pleistocene/Holocene boundary	10
<i>E. Olausson</i>	
3. An outline of the marine stage of the Vänern basin	16
<i>C. Fredén</i>	
4. Field investigations, coring and sampling	27
<i>I. Cato</i>	
5. Geological notes of the Moltemyr, Brastad and Solberga areas	34
<i>C. Fredén</i>	
6. Description of the cores.....	36
<i>I. Cato</i>	
7. Grain-size distribution of the cores – with emphasis on the sedimentary patterns around the Pleistocene/Holocene boundary.....	54
<i>I. Cato</i>	
8. Water content, bulk density and organic carbon.....	66
<i>I. Cato</i>	
9. Clay minerals and chemistry	73
<i>A. M. Bruswitz</i>	
10. Stable isotopes	82
<i>E. Olausson</i>	
11. Magnetostratigraphy	93
<i>N. Abrahamsen</i>	
12. Molluscs and other megafossils	120
<i>R. W. Feyling-Hanssen</i>	
13. Ostracods.....	137
<i>A. R. Lord</i>	

14. Foraminifers	148
<i>K. L. Knudsen</i>	
15. Calcareous nannofossils	178
<i>N. Mikkelsen and K. Perch-Nielsen</i>	
16. Diatoms.....	187
<i>U. Miller</i>	
17. Dinoflagellate cysts	211
<i>R. Harland</i>	
18. Pollen	224
<i>A.-M. Robertsson</i>	
19. Radiocarbon dating.....	243
<i>I. U. Olsson</i>	
20. Summary of the investigation	253
<i>I. Cato, C. Fredén and E. Olausson</i>	
21. Proposal by the working-group	269
22. On the definition of the Pleistocene/Holocene boundary in deep-sea sediments.....	270
<i>W. H. Berger</i>	
23. The Holocene boundary stratotype: local and global problems.....	281
<i>R. W. Fairbridge</i>	
24. Some remarks and recommendations concerning a type- section of the Pleistocene/Holocene boundary.....	287
<i>B. Frenzel</i>	

THE PLEISTOCENE/HOLOCENE BOUNDARY IN SOUTH-WESTERN SWEDEN

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ABSTRACT

The boundary between the Pleistocene/Holocene epochs was placed at 10 000 ^{14}C years B.P. (Libby half-time) by the Holocene Commission. This corresponds to the Younger Dryas/Preboreal boundary in the European geochronology.

In search of a stratotype locality three cores from the province of Bohuslän, south-western Sweden, were scrutinized concerning different geophysical, geochemical and biostratigraphical parameters. The marine sequences of the cores from Moltemyr and Solberga reveal a distinct boundary and a transition zone respectively which meet the requirements laid down by the Holocene Commission. The cores are connected with the general chronology by *inter alia* the meltwater spike and the subsequent indications of the deglaciation of central and northern Fennoscandia and climatic improvement clearly registered by fauna and flora. The suggested age of the lithological boundary is *c.* 10 200–10 300 years B.P.

Either Moltemyr or Solberga can be chosen as a boundary stratotype and the other locality as a hypostratotype of the Pleistocene/Holocene transition. As regards the deep-sea deposits the recorded and pronounced Preboreal meltwater spike may be regarded as a synchronous global sign of the Pleistocene/Holocene boundary.

1. IN SEARCH OF A STRATOTYPE LOCALITY

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INTRODUCTION

At the Paris INQUA Congress in 1969 the Holocene commission defined the Pleistocene/Holocene boundary at 10 000 ¹⁴C years B.P. Libby half-time, which was accepted as the reference date for this boundary. This was an important step towards a Pleistocene/Holocene boundary stratotype.

In 1971 the INQUA Holocene Commission and the INQUA Subcommittee for NW European shore lines studied southern Sweden. During this field congress a proposed stratotype locality in Göteborg was demonstrated by N.A. Mörner.

At the INQUA Congress in Christchurch in 1973 the Holocene Commission decided that the proposed core from the Botanical Garden in Göteborg, Sweden, lacked some of the requirements for such a type section.

In 1973 the Holocene Commission asked me to select and evaluate a type locality along the Swedish West Coast which would fit the requirements for a type area better than the "Göteborg core" seemed to do. The requirements laid down for the type section by the Commission were as follows.

1. The locality must lie in an area as tectonically stable as possible.
2. A continuous sedimentation in a marine environment should have occurred during the uppermost Pleistocene – Lower Holocene.
3. It should be possible to date the layers with a high degree of precision using currently known dating methods.
4. The locality should be accessible for studies in the future.

FIELD AND LABORATORY WORK

A pilot study was planned and carried out in collaboration with Curt Fredén at the Geological Survey of Sweden and Ingemar Cato at the Geological Survey of Sweden and the University of Göteborg. During 1973, 27 cores were taken at 14 stations from Göteborg to Strömstad. The field work was led by I. Cato. Nearly 200 samples were collected for a rapid survey of the

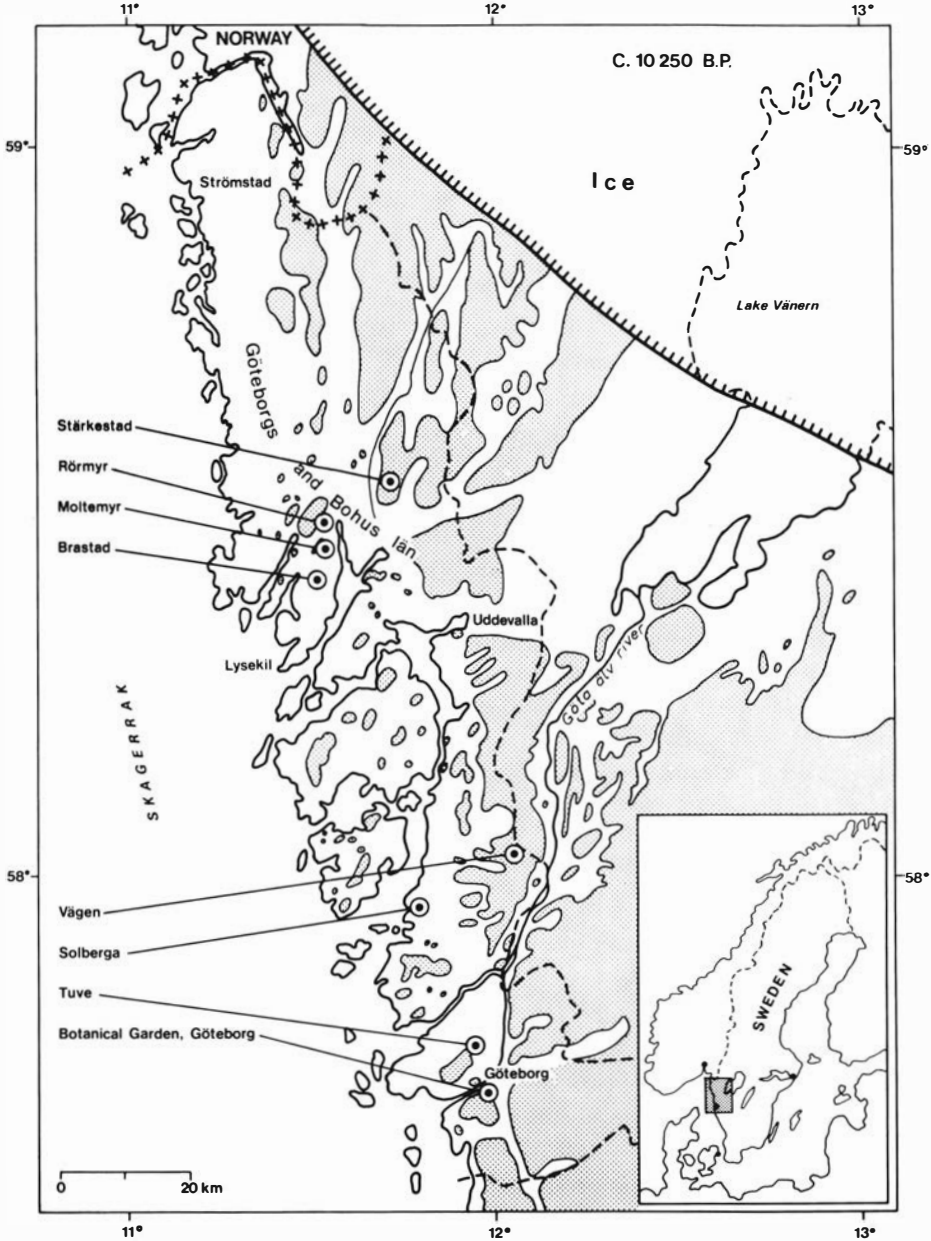


Fig. 1:1. The palaeogeography of south-western Sweden (Bohuslän with adjacent parts of Dalsland and Västergötland) about 10 200 years B.P. and the localities studied by the project.

cores. The diatom and pollen contents in these samples were then studied by Urve Miller and Ann-Marie Robertsson, both of the Geological Survey of Sweden.

The pilot study indicated that two of the stations were promising: Solberga and Brastad (Fig. 1:1). The leading group (Cato, Fredén and myself) decided that these two stations should be investigated further. A report on this preliminary study was given at the INQUA Congress in Christchurch in 1973.

In 1977 two cores were taken by a Foil Piston Corer at each station, one for various analyses, one for storage and/or future studies.

In order to obtain further details about the Late Weichselian-Preboreal development cores taken for different purposes by members of the working group were used. The extensive geological investigations carried out after the landslide at Tuve in 1977 were of great importance. Finally Moltemyr and Rörmyr, two small bogs with marine clay sequences, situated below the highest shore line, were investigated in 1980 since the Brastad core demonstrated an hiatus at the Pleistocene/Holocene boundary. The analyses made on the core from the Botanical Garden in Göteborg were reinterpreted. Older corings from adjacent areas were also taken into consideration. The map (Fig. 1:1) shows all the localities and the palaeogeography at 10 000 years B.P.

For geographical and palaeohydrographical reasons the localities studied by the project (*italics*) and others can be placed into two groups:

The Moltemyr group: *Moltemyr, Brastad, Rörmyr, and Stärkestad.*

The Solberga group: *Solberga, Vägen, Tuve, Ingebäck, Bäckebol, Tingstad,* and the Botanical Garden in Göteborg.

THE WORKING GROUP

The research group consisted of the following scientists whose contributions appear in Chapters 2–19:

Niels Abrahamsen, University of Aarhus: Magnetostratigraphy.

Ann Marie Brusewitz, Geological Survey of Sweden: Clay minerals and bulk chemistry.

Ingemar Cato, Geological Survey of Sweden and University of Göteborg: Member of the leading group, supervising the field and laboratory work; grain size, water contents, bulk density, and organic carbon analyses.

Rolf W. Feyling-Hanssen, University of Aarhus: Molluscs.

Curt Fredén, Geological Survey of Sweden: Member of the leading group, mapping of the Quaternary deposits in western Sweden.

- Rex Harland, Institute of Geological Sciences, Leeds: Dinoflagellate cysts.
Karen Luise Knudsen, University of Aarhus: Foraminifers.
Alan R. Lord, University College, London: Ostracods.
Naja Mikkelsen, Geological Survey of Denmark, Copenhagen: Coccoliths together with K. Perch-Nielsen.
Urve Miller, Geological Survey of Sweden: Diatoms.
Eric Olausson, University of Göteborg: Leader of the working group; stable isotope analysis.
Ingrid U. Olsson, University of Uppsala: ^{14}C datings.
Katharina Perch-Nielsen, Eidgenössische Technische Hochschule, Zürich: Coccoliths together with N. Mikkelsen.
Ann-Marie Robertsson, Geological Survey of Sweden: Pollen.
Kjell Björklund, University of Bergen, analysed some samples for Radiolaria but discovered no remains thereof.

The group has met several times. At the last workshop May 7–11 1981, officials of the Holocene Commission and the International Commission on Stratigraphy were invited together with a few specialists. We then presented our preliminary results, discussed our conclusions and during a field trip showed our localities. The specially invited experts were asked to give their impressions/advice in short papers. The contributions of three of them appear in Chapters 22–24.

The summary of the investigations and the proposal to the Holocene Commission (Chapters 20–21) were written by me in collaboration with I. Cato and C. Fredén.

ACKNOWLEDGEMENTS

First I thank the afore-mentioned scientists for very stimulating collaboration. Their enthusiasm and skill constituted a guarantee of good results, and of the resolution of unexpected difficulties. My special thanks go to Ingemar Cato and Curt Fredén for invaluable help during the years of field and laboratory work, and for their assistance in the editorial work. Thanks are due also to Barrie Dale, University of Oslo, and to Göran Kjellström, Dagmar Lundegårdh, Per H. Lundegårdh, Ernest Magnusson, Lars Nordberg, Erik Norling, Christer Persson and Roland Skoglund from the Geological Survey of Sweden, Uppsala, for making much appreciated suggestions for improvement and editing assistance.

The studies were financed by the Swedish Natural Research Council and the Geological Survey of Sweden and supported by the afore-mentioned universities, institutes and Geological Surveys. Financial support for the workshops was provided by the Nordic Cultural Council, the University of Göteborg, the Mannheimer foundation and the Marine Geological Laboratory, University of Göteborg. Travel expenses were paid by the members' own institutions, research councils and other local sources.

2. GENERAL COMMENTS ON THE PLEISTOCENE/HOLOCENE BOUNDARY

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REMARKS ON THE CHOICE OF PERIOD FOR THE BOUNDARY

The Pleistocene/Holocene boundary was defined by the Holocene Commission as 10 000 ^{14}C years B.P. Libby half-time. This is roughly the age of the Younger Dryas/Preboreal transition. A boundary of this type should be placed at the midpoint between glacial maximum and the postglacial temperature optimum, where most parameters exhibit changes. Sea-level curves (e.g. Bloom 1971, Mörner 1976) indicate that at least half of the ice stored in the continental ice sheets at the glacial maximum had melted by about 10 000 years B.P. The temperature curves (e.g. Flint 1971, Figs. 16–11) illustrate that the temperature rise was at the midpoint about the time of the Younger Dryas/Preboreal transition. However, the maximum Holocene warming in the Australia–New Zealand area occurred at 9 000 years B.P. and *c.* 6 000 years B.P. in the northern hemisphere (Salinger 1981). Considering these dates, the defined position is justified for the northern, but some 3 000 years too late for the southern hemisphere. The fact that temperature changes in the Australia–New Zealand area preceded changes in the northern hemisphere by about 3 000 years must be discussed in this context.

The extent of sea ice is a function of the salinity stratification. In earlier papers I discussed the last global deglaciation and its influence on the oceans and feed-back mechanisms. I suggested theoretical arguments for an open Arctic Ocean during the glacial maximum followed by a freezing over in deglacial times when the salinity stratification was re-established (Olausson and Jonasson 1969, Olausson 1972, Olausson 1981). The last change from open to ice-covered state in the Arctic could have been responsible for the Younger Dryas cooling, due to the great differences in the albedo between open and ice-covered seas.

A climatic deterioration during the Younger Dryas is well documented for the northern hemisphere, at least north of 30°N (Olausson 1969). The Weichselian deglaciation may therefore be divided into two phases in the

north, while elsewhere it may have been either a period of more or less continuous, or a sudden, more intense, warming followed by more gradual climatic amelioration. The last trend will be illustrated further.

A major source of cooling in the southern hemisphere is the Antarctic ice sheet and the surrounding sea ice. The former was only about 10 per cent larger than today during the ice ages and, thus, fairly comparable in size. However, the surrounding pack ice varies far more in size, ranging between $24 \cdot 10^6 \text{ km}^2$ (September) and $18 \cdot 10^6 \text{ km}^2$ (February) through the years. This pack ice is a result of the salinity stratification around the Antarctic. The stratification is weaker than that of the Arctic Ocean, allowing formation of only a meter (or so) of sea ice (Weyl 1968). The deep salinity maximum (<34.9 o/oo) at 1–2 km depth has its origin in the effluent, very dense, Mediterranean water. This water encompasses the Antarctic continent. The present volume of the Mediterranean outflow is $1.6 \cdot 10^6 \text{ m}^3 \text{ sec}^{-1}$. As shown in earlier papers, the eastern Mediterranean was stagnant c. 11 000–8 000 years B.P. (Olausson 1961, 1965, 1969). The western basin was, so far as is known, not stagnant and the bottom-water exchange with the Atlantic (and the subsurface outflow) was, thus, restricted to this basin. The western Mediterranean is, at present, responsible for only 25% of the bottom-water formation and some 30 % of the salinity increase of the Mediterranean surface water due to evaporation. Both the volume and salinity could have been appreciably lower, the last being also due to outflowing, rather low-saline surface water from the eastern Mediterranean. Therefore, the deep salinity maximum could have been more or less absent in the south Atlantic during a few thousand years around 9 000 years B.P. This lack of salinity stratification should, in turn, have appreciably reduced the area of the sea ice around the Antarctic and, due to changes in albedo (from about 70 to about 10 per cent) during southern summers, improved the climate in the southern hemisphere. The extent of the sea ice around the Antarctic is more than twice that in the Arctic Ocean and any changes would, thus, exert a stronger influence on the climate than would the Arctic sea ice. This is equal to a semiglobal temperature change of 2°C during the northern summer (cf. my explanation of the post-Messenian climatic deterioration, Fig. 2:1).

The climatic optimum occurring 10 000–8 000 years B.P. in Australia and New Zealand (see Summary by Salinger 1981) and the coeval isotope maximum in the Antarctic ice dome C (Lorius *et al.* 1979) could result from the eastern Mediterranean stagnation and, indirectly from the deglaciation in the north.

I therefore conclude that the hydrographical changes in connection with the deglaciation affected the amelioration and caused both cooling and warmings of nearly semiglobal extent. Within this deglacial period a global boundary can be placed independently of the consequences of the feed-back

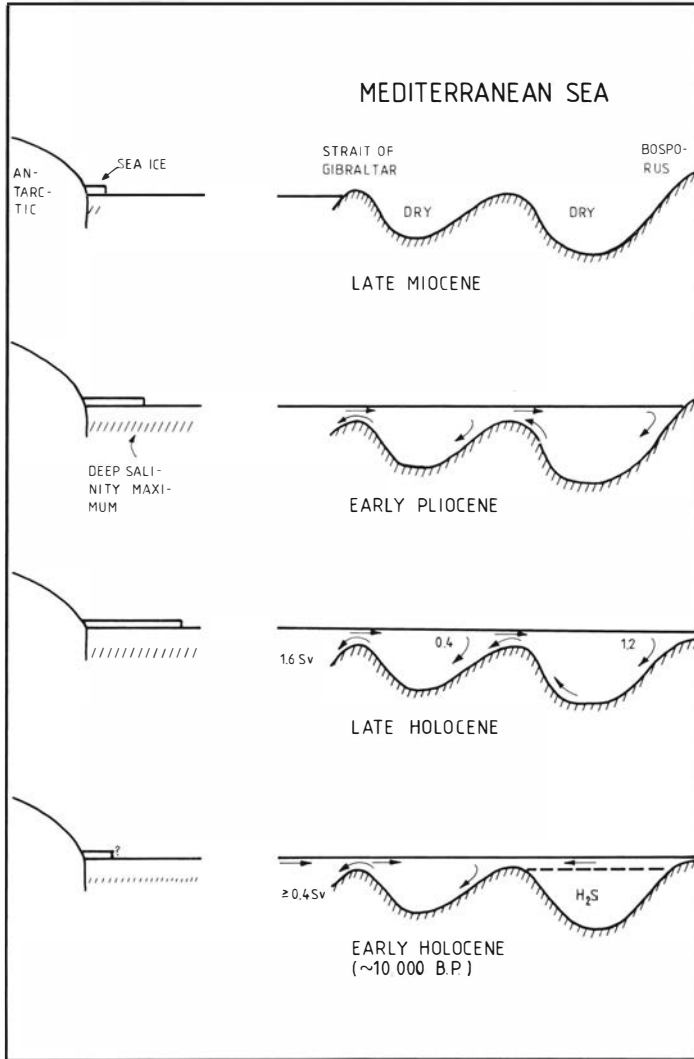


Fig. 2:1. The pack ice surrounding the Antarctic results from the salinity stratification in the underlying waters. The deep salinity maximum has its origin in the effluent, very dense, Mediterranean water. During the late Miocene (the Messinian "Salinity crisis") this efflux was stopped, and during the early Holocene stagnation in the eastern Mediterranean (Olausson 1961) the outflow diminished considerably.

When the water connection with the Atlantic was re-established after the "Salinity crisis" a salinity stratification around the Antarctic was developed. This led in turn to an increase in the extent of the sea ice there, and, by albedo changes, to a climatic deterioration. The early Pliocene cooling is proved by e.g. Kennett (1977).

During the afore-mentioned stagnant phase of the Mediterranean a considerable reduction of the sea-ice area took place. This is here judged to be the cause of the very early warming in the Australia-New Zealand area (Salinger 1981), preceding that in the northern hemisphere by about 3 000 years, and the abnormally early isotope maximum in the Antarctic ice dome C (Lorius *et al.* 1979).

$$1 \text{ Sv (Sverdrup)} = 10^6 \text{ m}^3 \text{ sec}^{-1}.$$

from the oceans. The age 10 000 years B.P. fits well with the beginning of the Preboreal and the onset of the warming in Australia and New Zealand. Various sea-level curves show that at least half of the ice volume had melted by 10 000 years B.P., and that the hydrographical conditions were, thus, closer to the present conditions than to those during the glacial maximum.

In a global perspective the choice of period for the Pleistocene/Holocene boundary is justified.

ON THE CHOICE OF TYPE LOCALITY AREA AND CRITERIA FOR THE BOUNDARY

It may be discussed whether a near-shore deposit is preferable as a stratotype section rather than deep-sea sequences. Referring to hydrographical changes and the rapid rise/decrease of many parameters in deep-sea cores, I formerly suggested that the boundary should be defined by means of deep-sea cores (Olausson 1969). However, as the resolution possible with near-shore deposits is much higher than in deep-sea oozes, they may be a better choice. My intention was then to find a marker, useful for the boundary definition in both areas. Meltwater injections could be such an instrument.

The meltwater spikes can be recognized in both shelf and deep-sea deposits. There are two large meltwater spikes in our cores, one in the Alleröd, and the other in the Preboreal substage. Only in near-shore deposits is this high resolution possible. The low resolution of deep-sea records (± 2 000 years, see Berger, Chapter 22) preclude discernment of the intervening short interval (Younger Dryas \sim 800 years) with a varied meltwater supply to the oceans.

The increased melting of the ice sheet at the onset of the Preboreal is a direct response to a temperature rise, and its result, a meltwater spike, is here considered as the prime signal of the Pleistocene/Holocene boundary. This signal can also be traced in deep-sea sediments (see Chapters 10 and 22). The second reaction to an amelioration is found in the fossil content (see, further, Chapter 20). However, various feed-back mechanisms can locally or semiglobally alter the general warming trend (see the discussion above).

DATING PROBLEMS

The dating of the Pleistocene/Holocene boundary is a problem. Many molluscs seem to be reworked and it may be difficult to select *in-situ* shells.

In the future, benthic foraminifers can perhaps be used for dating purposes with the help of an accelerator technique. Radiocarbon datings of the Pleistocene/Holocene interval may also deviate markedly from calendar years due to past changes in the ^{14}C activity.

It is probably possible to affix the boundary to the Swedish varve chronology, which is being revised. The ice recession from Stockholm to Medelpad and its connection with present time is under review. The duration of the former part of the varve chronology has increased by about 100 years (Strömberg 1981). The connection with present time is still problematic, with an estimated error of $+200 \pm_{200}^{300}$ years (Fromm 1970). The chronology of the ice recession from the Fennoscandian terminal moraines to the Stockholm area is complicated. A control of this portion of the Swedish varve chronology is in progress. An important event is the final drainage of the Baltic Ice Lake, which occurred when the ice receded from the Fennoscandian terminal moraines, opening the connection between the Baltic and the Skagerrak. The lowering of 26–28 m of the Baltic Ice Lake is presumed to have occurred at 10 163 years B.P. (Donner and Eronen 1981), or 10 200 years B.P. (see Fredén, Chapter 3).

During the drainage of the Baltic Ice Lake some 10^4 km^3 of water was discharged into the Skagerrak. The subsequent deglaciation, during the subsequent millennium, uncovered an area of about 10^6 km^2 of Scandinavia (Bloom 1971). If we assume that this ice sheet was 0.5 km thick on average, we arrive at an idea of the amount of meltwater ($\sim 5 \cdot 10^5 \text{ km}^3$) which was predominantly discharged through the Väner basin into the Skagerrak giving rise to the Preboreal meltwater spike in our cores.

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3. AN OUTLINE OF THE MARINE STAGE OF THE VÄNER BASIN

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INTRODUCTION

The main ice-marginal zones of western Sweden are well known. As the greater part of the landscape is dominated by bedrock hills and clay-covered lowlands, the moraine deposits in the ice-marginal zones are often pronounced. The previously established Late Weichselian deglaciation chronology in Sweden has been brought up for discussion by Berglund (1979). On the basis of radiocarbon determinations of molluscs, skeletal parts of vertebrates and gyttja samples from limnic deposits, a revision seems to be appropriate. The degree of revision suggested differs depending on the authors. However, all opinions seem to converge the closer one gets towards the end of the Younger Dryas Stadial. It should be noted that the present discussion about the deglaciation chronology deals not only with the stadials themselves but also with the duration of the stadials and interstadials.

DEGLACIATION CHRONOLOGY OF THE VÄNER BASIN

The main ice-marginal zones are shown in Fig. 3:1. At the present, it seems to be generally accepted that the Billingen moraines were formed at the end of the Younger Dryas Stadial. This is of course an advantage for the discussion of the Pleistocene/Holocene boundary. A review of the opinions of the deglaciation chronology of the Vänner basin is also seen in Fig. 3:1. The latest contribution to the discussion is published by Björck and Digerfeldt (1981). According to their opinion radiocarbon determinations from limnic sediments situated above the highest shore line, 133–134 m above sea level, on the Hunneberg hill support Berglund's proposal. The same authors have also established a curve for the shore-line displacement at Hunneberg (Björck and Digerfeldt 1982). Their stratigraphical investigations (diatom and pollen analyses and radiocarbon determinations) of 15 lakes between 129 and 91 m above sea level speak for Berglund's (1979) hypothesis.

The rate of sedimentation and the hydrographical environments for the

sedimentation along the western coast of Sweden are to a certain degree dependent on the deglaciation chronology, *i.e.* the distance to the ice front at the different distinguished interstadials and stadials as they are recorded in clay sequences. According to previous opinion, based on knowledge before the time of absolute dating, the Trollhättan terminal moraine was formed about 11 500 years ago, see Fig. 3:1. Berglund (1979) maintains that it was formed *c.* 12 300 years ago, according to radiocarbon determinations carried out on limnic gyttja samples. On basis of radiocarbon determinations of marine molluscs and skeletal parts of vertebrates and the stratigraphical position of these in the clay sequences, Fredén (1978) has suggested that the Trollhättan terminal moraine was formed about 11 800 years ago. With these determinations in mind we have a picture of the maximum (?) and minimum (?) time span, 2 000–1 200 years, between the formation of the Trollhättan and the Billingen terminal moraines, see Fig. 3:1.

The Skövde and the Billingen terminal moraines are part of the Fennoscandian terminal moraines. The continuation of the Skövde and Billingen moraines in Norway are the Ra moraines. Recently, Sörensen (1979) has questioned the previous chronology of the main ice-marginal deposits in the Oslo fiord area. On the other hand, the corresponding moraines in Finland – the Salpaussälkäs – are in good chronological accordance with recent Swedish opinions, see Fig. 3:1.

OCCURRENCE OF MARINE FAUNA IN THE VÄNER BASIN

To a large extent the present uncertainty of the deglaciation chronology depends on the limited opportunity to find suitable samples for radiocarbon determinations, especially samples in marine clay. The occurrence of molluscs in the clay of the Väner basin is shown in the inset profile of Fig. 3:1; mollusc shells are found at different levels depending on the terrain and it should be read stratigraphically in relation to the top and the bottom of the clay sequence. The same pattern applies for the finds of marine vertebrates. The known occurrences of shell-bearing layers may be summarized as follows (after Fredén, in prep.). In the southern part of the Väner basin the shell-bearing layers are usually 10–20 cm thick and they contain about ten or more species. It is not uncommon that more than one such layer occurs in the same clay sequence. Furthermore, radiocarbon determinations of shells of different species in small, surficial shellbanks show that these sites have been inhabited by different faunas at different times. The difference in radiocarbon age between different shell layers and faunas in the same area has been dated to be approximately 300 to 500 years. The number of species, the occurrence and the thickness of shell-

bearing layers decrease the closer one gets to the Skövde terminal moraine zone at the same time as the depth of occurrence increases. The profile in Fig. 3:1 is mainly valid for the vast field areas south-east of Lake Vänern. Note that the greater part of the clay south of the Skövde moraine lacks macrofossils.

North of the Billingen/Skövde terminal moraine zone, shells are only found on or in the most surficial part of the clay sequences west of Lake Vänern. The finds are mainly found in sandy deposits. Radiocarbon ages and localities are shown in Fig. 3:2. East and north of Lake Vänern no finds are known except one of a haddock about 20 km north of Billingen.

The habitats of molluscs reflect fairly stable hydrographical conditions. About 11 000 years ago, and during a period of more than 500 years, optimal conditions prevailed for Arctic and Arctic-Boreal faunas to flourish in the area between the Väner basin and the West Coast. Optimal conditions are defined by the temperature, salinity, clearness, water depth, currents, and nature of the bottom. The supply of nourishment is, of course, dependent upon the same factors. Stable conditions imply that meltwater discharge was low. At times, marine water with a relatively high salinity was most probably in contact with the ice front or quite close to it. The border to saline water both horizontally and vertically is primarily dependent on the meltwater supply and the course of land uplift, which determines the water depth and the palaeogeographical conditions.

A pronounced change of the hydrographical conditions is recorded by sedimentation of a clay which is devoid of macrofossils, see Fig. 3:1. Habitats of molluscs in the Väner basin area were buried with great volumes of clay, and the favourable conditions disappeared. Before this change in the deglaciation pattern the ice sheet had retreated to the Billingen terminal moraines during several thousands of years. Slightly more than one thousand years after the retreat from the northernmost Fennoscandian terminal moraine the Scandinavian ice sheet had disappeared entirely. In other words the ice retreat was very rapid without stops other than such caused by higher situated terrain, where the ablation pattern changed from a frontal and surficial to an entirely surficial melting. The discharge of meltwater was enormous during the Preboreal time.

PALAEOGEOGRAPHICAL CONDITIONS WITH RESPECT TO THE INVESTIGATED LOCALITIES

The palaeogeographical conditions of western Sweden at the end of the Younger Dryas stadial are shown in Fig. 3:3. The map is based upon only few available modern investigations. According to Björck and Digerfeldt (1982) the shore level of Hunneberg at that time would roughly correspond

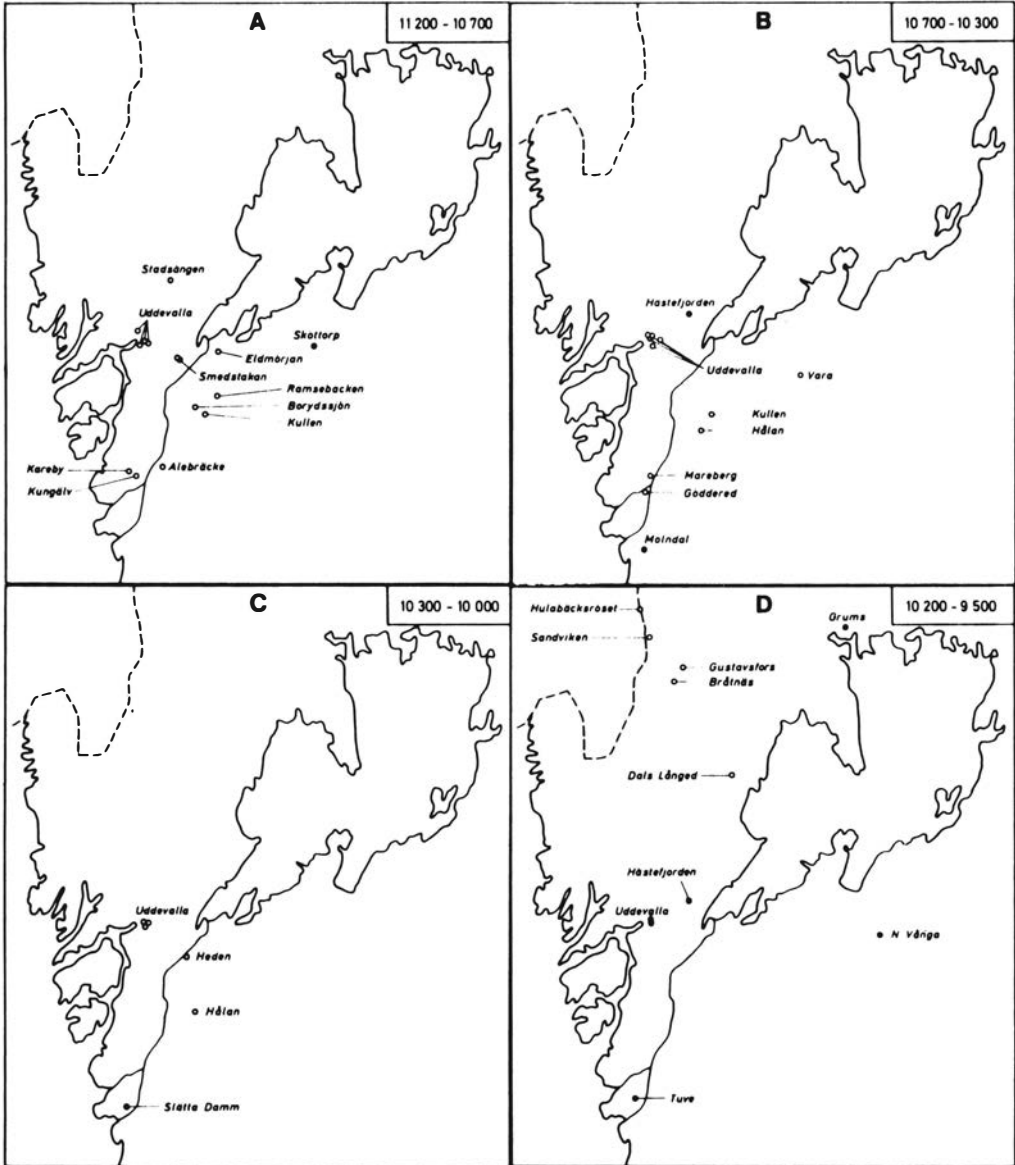


Fig. 3:2. Radiocarbon determinations of mollusc shells and skeletal parts of vertebrates. Sample sites are shown only from the Vänern basin and its straits during the time span 11 200–9 500 years B.P. The dates shown include a margin of error and correction for ^{13}C and the reservoir age of sea water. Localities of dated molluscs are shown with circles, vertebrates with dots. From Fredén (1975 and in prep.).

to 90–95 m above sea level. Approximate isobases – parallel to those of the highest shore line, (see Chapter 5) – give corresponding levels at Stärkestad of about 105 m and at Tuve of about 60 m above sea level. The purpose of the map is to show the main topographical features of the landscape with respect to the hydrographical conditions in the surroundings of the investigated localities.

The main connections between the Väner basin and the Skagerrak bay of the Atlantic Ocean consisted of the strait at Uddevalla and the Göta River valley. North of the Uddevalla strait a third connection existed, but of a minor importance since the threshold is situated in the eastern part of the valley at a level of 85–90 m above sea level.

In the Munkedal area the influence of meltwater from the two parallel valleys orientated NNE–SSW must have been fairly short-lived. In both valleys deposits of the Fennoscandian terminal moraine zone are built up to and above the highest shore line and form pronounced watersheds. In the valley mouth south of Stärkestad, Fig. 3:3, shells in sandy deposits on the south side have been dated at $10\,585 \pm 145$ years B.P. (St 7119–20). Twelve datings of samples – collected at different levels – in an exploited shellbank on the north side of the valley gave a mean age of $9\,980 \pm 135$ years B.P. (Fredén, unpubl.). The datings range from $10\,160 \pm 110$ (St 7552–53) to $9\,820 \pm 120$ years B.P. (St 7134–35). Both localities are situated at about 75 m above sea level.

BALTIC ICE LAKE

On the inset map of Fig. 3:4 the extension of the Baltic Ice Lake is shown. The traditional opinion is that the lake was dammed by the ice sheet and the topography until the icefront passed the northern point of the Billingen hill. There is a prevalent uncertainty about the circumstances concerning the draining event. However, the event as such is not questioned.

The uncertainty of the evolution at Billingen depends on several factors. According to the traditional opinion the youngest Fennoscandian terminal moraines are found at least 5 km south of the northern point, which implies that the event occurred some tens of years after the formation of the Billingen moraines. The relation between the northern point and the terminal moraines is shown on Fig. 3:1. Furthermore, the event implied a lowering of the lake surface of 26 m and a connection was established between the Baltic basin and the Atlantic Ocean. The circumstances about the so-called Billingen event itself have been discussed by Strömberg (1977). A review of the history of the Baltic Ice Lake was published in 1979 (Fredén).

On basis of pollen-analysed and radiocarbon dated isolation sequences of nine localities in south-eastern Sweden, Björck (1979) has recorded a sudden drop of the Baltic Ice Lake surface at about 10 300–10 200 years B.P. The lowering amount was recorded to be at least 26 m. A rapid lowering of the surface of the Baltic Ice Lake has been reported from many other places in the Baltic basin. In Finland (Alhonen 1979, pp. 103–107), for example, an approximate 28 m drop in the water level is recorded. It can be observed morphologically in several places on Salpaussälkä II, which was formed at the year ± 0 in the Finnish varve chronology – corresponding to the year 8 213 B.C. in the revised Swedish varve chronology.

The lowering of the Baltic Ice Lake surface has been related to the sudden outflow at the Billingen hill. However, at the northern part of the Billingen hill there is an annoying lack of erosional phenomena from this presumably dramatic and violent event. One may summarize that a regional lowering of the Baltic Ice Lake surface is recorded and that the event is dated to about 10 200–10 300 years B.P. Whether the total lowering, or part of it, occurred at the Billingen hill, or not, is not fully known.

YOLDIA SEA STAGE

When the land ice receded from the Billingen hill a new stage occurred in the evolution of the Baltic basin – the Yoldia Sea stage. A historical review of the stage was published in 1979 (Fredén). The palaeogeographical conditions of the Väner basin in the Preboreal times are illustrated in Fig. 3:4. The purpose of the inset map is to give the reader an idea of the volumes of meltwater which must have been transferred through the Väner basin during the stage, with the assumption of course, that no other outlet in the Baltic basin was accessible.

The Väner basin is relatively shallow – present maximum depth being 106 m. During the deglaciation large meltwater volumes were discharged into the Skagerrak. In some respects the straits of Uddevalla and the The Göta river valley can be regarded as large river mouths. Saline bottom water was pushed towards the sea by the supply of meltwater. When the Otteid strait was opened westwards, the Väner basin had a connection with saline water which was mixed with the meltwater in the basin. At about the same time the Närke strait was deglaciated. Both straits were approximately equal in dimensions, having a maximum width of *c.* 10 km and a maximum depth of *c.* 60 m.

The highest shore line was metachronic in nature. The straits south of Närke and Otteid straits had relatively small vertical areas and were laid dry

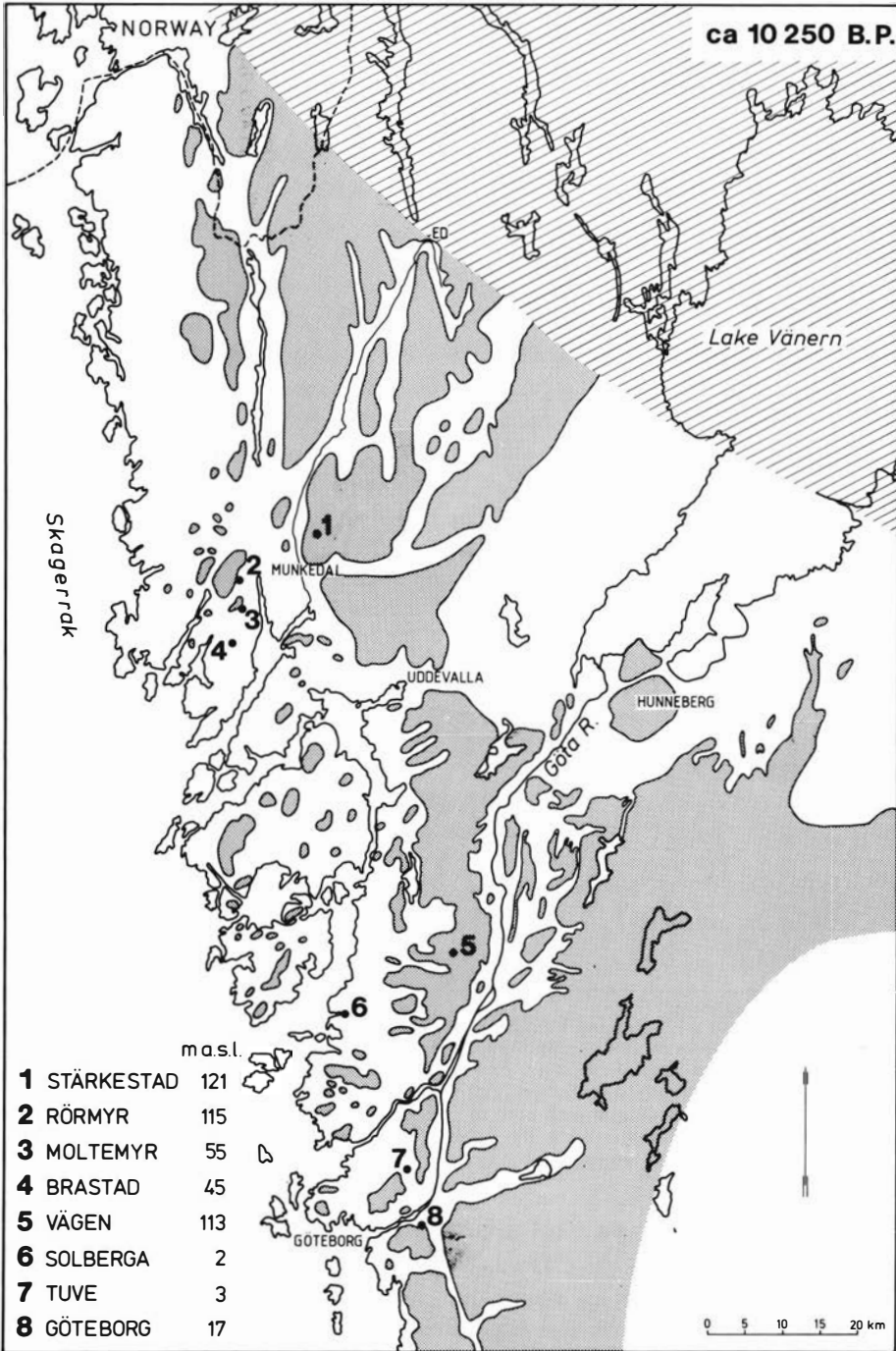


Fig. 3:3. Outline of the palaeogeography at the end of the Younger Dryas stadial. Slanting lines = land ice, grey areas = land.

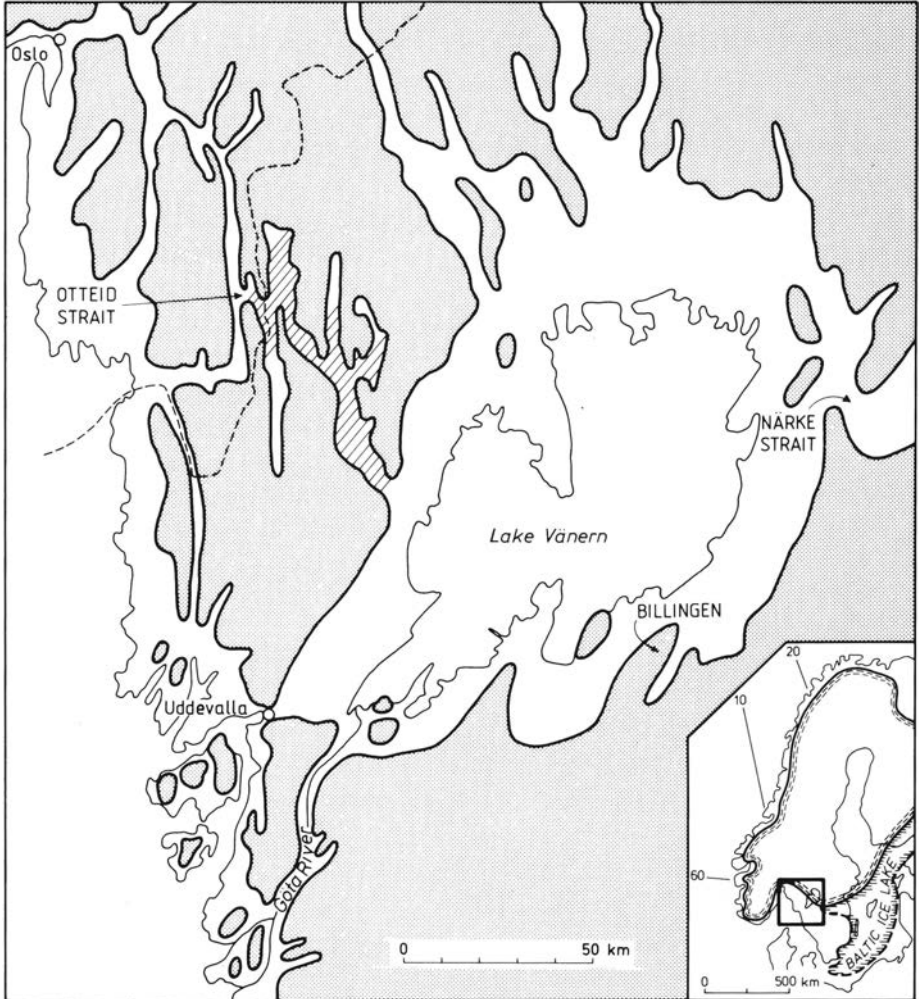


Fig. 3:4. Generalized outline of the land-sea conditions of the Vänern basin during approximately the mid-Preboreal times. Slanting lines show the distribution of found mollusc localities within the drainage area. Inset map shows the extension of the Baltic Ice Lake and the Scandinavian ice sheet at the end of the Younger Dryas Stadial. Slightly more than 1 000 years later the land ice had disappeared and all meltwater and freshwater in the Baltic basin is assumed to have been discharged to the Atlantic Ocean via the Vänern basin during this time.

fairly soon due to the land uplift. North of the Otteid strait another connection westwards has existed. No macrofossils are known in the valley.

During a time span of about 100 years the bivalve *Portlandia arctica* inhabited areas east of the Närke strait. The shells are found in the lowermost part of the clay sequences. West of the Närke strait the clays are mostly non-varved while east of the strait, *i.e.* within the Baltic basin, they

are mostly varved. These circumstances imply different sedimentation conditions – pronounced freshwater conditions in the Baltic basin while the salinity in the Vänern basin was sufficient to induce symmict sedimentation. A review of the Närke strait has been published by Fredén (1981). In this review it seems clear that – according to Finnish and Swedish investigations – the Närke strait was opened about 10 000 years ago.

When the clay sedimentation ceased in the archipelago environments of the Otteid strait, Boreal to Arctic-Boreal molluscs inhabited the slopes of the pronounced valleys. The distribution is seen on Fig. 3:4 (cf. inset profile on Fig. 3:1). Apparently there were favourable conditions for the fauna during a few hundred years; most of the radiocarbon dated samples gave ages about 9 800 to 9 700 years B.P., cf. Fig. 3:2 D.

Due to the land uplift the Otteid strait was laid dry at about the same time as the water exchange in the Närke strait ceased. This must have happened a hundred years, or so, before the Närke strait was laid dry, which occurred following calm conditions at least 9 000 years ago (Fredén 1981). Contemporaneously, the Vänern basin was isolated from the sea (Fredén, *op.cit.*).

A BRIEF AND TENTATIVE OUTLINE FOR THE MAIN EVENTS OF THE MARINE EVOLUTION OF THE VÄNER BASIN DURING THE PREBOREAL TIMES.

The outline is given in chronological order with assumed ages.

Ice retreat from the Fennoscandian terminal moraine zone	c. 10 250 years B.P.
The lowering of the Baltic Ice Lake surface. Beginning of the Yoldia Sea stage	c. 10 200 years B.P.
Närke and Otteid straits are opened. Saline waters enter the Baltic basin	c. 10 000 years B.P.
Molluscs inhabit the western part	c. 9 800 years B.P.
Molluscs fauna extinct	c. 9 600 years B.P.
Otteid and Uddevalla straits are laid dry	c. 9 300 years B.P.
The threshold of the Närke strait is laid dry. The Vänern basin becomes isolated from the sea	c. 9 000 years B.P.

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4. FIELD INVESTIGATIONS, CORING AND SAMPLING

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In the world-wide search for a type locality and sediment profile, which could serve as a world standard section for the Pleistocene/Holocene boundary, the Holocene Commission selected the isostatic uplifted area of south-western Sweden as probably ideal. As a result of this decision, a pilot study was first carried out in the broad region pointed out by the Commission in order to find the most suitable site for the final coring and closer investigations.

During May and June 1973, 27 probing holes were drilled at 14 sites, from Göteborg in the south to Strömstad in the north (Fig. 4:1, Table 4:1). Three of the sites were immediately found to be of no further interest. On the remaining sites about 160 samples from 13 holes were collected by means of an helical auger for a rapid survey at the Geological Survey of Sweden (Cato 1973). Lithostratigraphical and biostratigraphical (pollen and diatoms) results indicated that Solberga (hole 7, 57° 57' 05" N Lat., 11° 47' 42" E Long., 2 m above sea level) and Brastad (hole 12, 58° 23' 39" N Lat., 11° 31' 20" E Long., 45 m above sea level) were the most suitable sites for further studies (Miller and Robertsson 1974). The other sites were rejected in consequence of the occurrence of disturbed layers, sandy layers, sequences consisting of highly sensitive (quick) clay, artesian pressure at the soil-bedrock contact, lack of Pleistocene sediments, or other unsuitable conditions (Table 4:1).

Hence, two azimuthally oriented cores were taken at each of the sites Solberga (27.3 m long) and Brastad (15.1 m long) in April 1977 (Cato 1977), one for various analyses, one to be stored at 91 % humidity and constant temperature at the Department of Marine Geology, Göteborg. The cores, 66 mm in diameter, were taken by a Swedish Foil Piston Corer (Kjellman *et al.* 1950), which permits taking continuous cores of up to 30 m length (Figs. 4:2 and 4:3). This is possible only because the friction between core and pipe is reduced partly by the 0.1 mm steel foils, partly by hydraulic injection of paraffin oil into the system.

The 1–2 m thick dry crust of the clay was removed before coring, in order not to create a hard plug in the head of the corer. A few meters from, and on each side of the corer, two pollen-traps (Tauber 1967) were mounted 80 cm

TABLE 4.1. Summary of results and information from the pilot study along the Swedish West-Coast in 1973.

		Position				Lithostratigraphical notes					Biostratigraphical notes					
Locality	Hole No	Lat	Long	Dates of coring	Ground surface (m above sea level)	Pene-traiton (m)	Clay (m)	Dry crust (m)	Layers of sand/gravel (cm)	Shell-fragments, shell-layer	Peat/gyttja	Bot-tom	No of Samp-les	Sampled levels (cm)	Probable age of sampled levels	Observed reposition or disturbed layers
Harestad	1	57°48'57"N	11°51'48"E	1973-05-22	5-10	22.8 x	2.0	140-145				hard	1	1083	Not det.	
	2	57°49'37"N	11°50'05"E	1973-05-22	5-10	>30.5 x	1.8									
Lycke	3	57°51'57"N	11°43'20"E	1973-05-23	0-5	>31 x	2.0									
Solberga	4	57°55'49"N	11°47'45"E	1973-05-23	5-10	15.7 x	2.0					hard	9	1045-1515	Pleistocene	x
	5	57°56'36"N	11°47'48"E	1973-05-24	5-10	>31.5 x	1.2									x
	6	57°56'46"N	11°48'34"E	1973-05-24	0-5	5.5 x	1.2			440		sand	7	320-440	Not det.	x
	7	57°57'05"N	11°47'42"E	1973-05-25	0-5	27.2 x	1.2					sand/fill	18	1738-2698	Pleistocene/Holocene	x
					-28											
Tegneby	8	58°10'00"N	11°34'27"E	1973-05-29	25-30	24.9 x	-					hard				x
	9	58°09'57"N	11°34'27"E	1973-05-29	25-30	19.9 x	-	700-730				hard				x
	10	58°09'56"N	11°33'42"E	1973-05-30	25-30	20.8 x	1.5					hard	9	155-2070	Holocene	x
Morlanda	11	58°10'57"N	11°30'23"E	1973-06-04	5-10	19.4 x	2.0		700-750 980-1000 980-1000 1460-1480 1520-1570 etc.			hard	12	143-1938	Holocene (?)	x
Brastad	12	58°23'39"N	11°31'20"E	1973-06-05	40-45	17 x	0.5					hard	13	170-1674	Pleistocene/Holocene	
Bro	13	58°25'39"N	11°28'00"E	1973-06-06	5-10	12 x	1.5			215-220		sand	21	145-1240	Holocene	
Härnäsät	14	58°21'15"N	11°22'24"E	1973-06-07	10-15	>30.4 x	2.0									x
	15	58°21'55"N	11°23'21"E	1973-06-07	0-5	11.5 x	1.8		910-955			gravel	15	145-1025	Holocene	x
	16	58°21'57"N	11°23'25"E	1973-06-07	0-5	7.8 x	-					hard				x
Askum	17	58°25'34"N	11°19'45"E	1973-06-08	15-20	>21.3 x	1.5									x
Tossene	18	58°26'49"N	11°22'48"E	1973-06-08	35-40	4.0 x	2.5					hard				x
	19	58°26'54"N	11°23'00"E	1973-06-08	35-40	7.8 x	1.5					hard				x
	20	58°26'54"N	11°22'58"E	1973-06-08	35-40	8.4W x	1.5		805-815			hard	17	138-838	Holocene	x
Gullov	21	58°31'41"N	11°23'21"E	1973-06-12	35-40	>25 x	2.0					sand				x
	22	58°31'18"N	11°23'02"E	1973-06-12	35-40	>21 x	-									x
Gerum	23	58°40'26"N	11°22'00"E	1973-06-13	10-15	21.7 x	1.8					hard	15	138-2135	Holocene	
	24	58°41'55"N	11°21'42"E	1973-06-14	15-20	>23.6 x	-									x
	25	58°41'16"N	11°22'00"E	1973-06-14	15-20	28.3 x	-					sand				x
Långeby	26	58°43'39"N	11°11'51"E	1973-06-15	0-5	12.6 x	-		50-385	x	0-35	sand	18	135-1182	Holocene	x
Råssö	27	58°50'18"N	11°11'20"E	1973-06-15	0-5	8 x	-		290-363 705-etc.	x	0-200 490-562	sand	8	290-790	Holocene	x

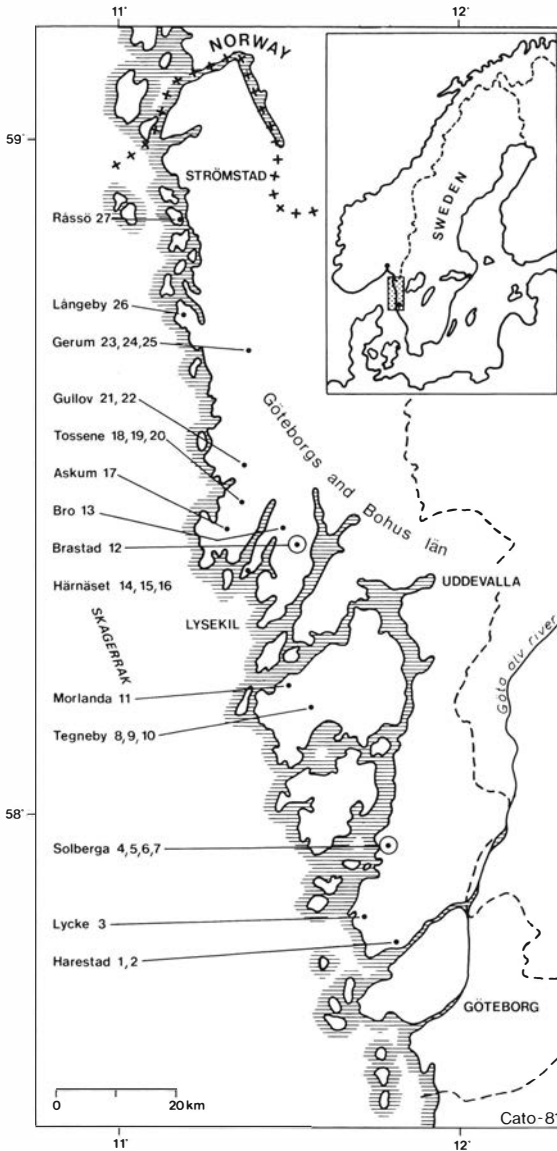


Fig. 4:1. Sites investigated during the pilot study in south-western Sweden, 1973.

above the ground. The purpose was to detect the composition of the recent pollen rain.

During the coring, the corer was carefully held in position. Every 5 m, a new 5 m tube was mounted on top of the descending pipe, without interrupting the coring process. The coring process did not stop until firm bottom (till, glaciofluvial deposits, bedrock *etc.*) was reached. Afterwards the whole corer was withdrawn and dismantled in the splices between the 5

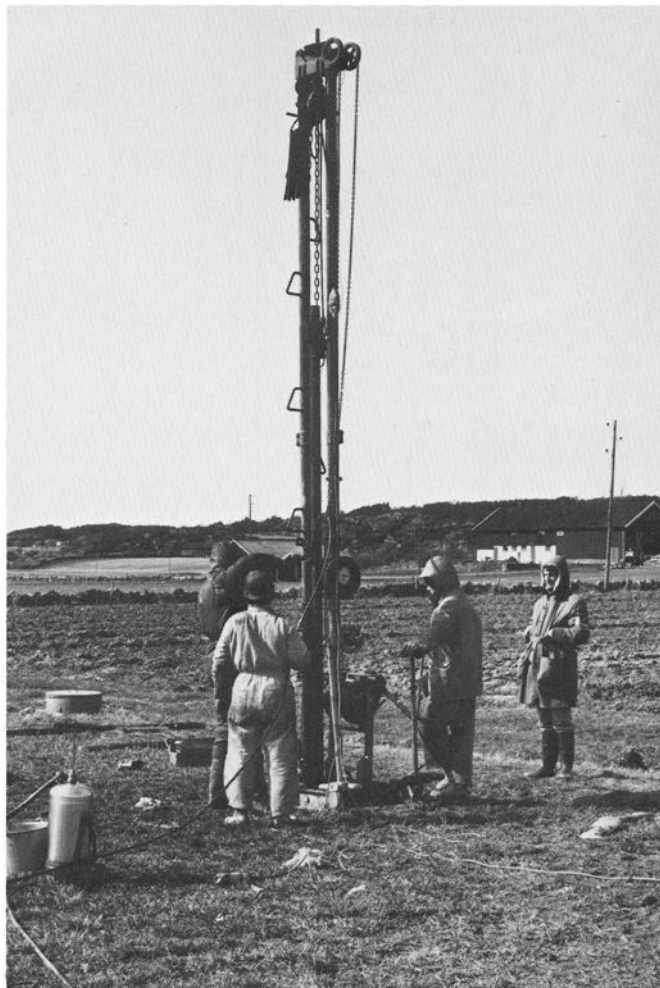


Fig. 4:2. Taking of one of the Foil Piston Cores at Solberga (N. Knaverstad) on April 14th, 1977.

m sections. The pipes were sealed with muffs and the sediments from the splice muffs were kept separately in plastic foil. The bearing north on every 5 m tube was then transferred, to the 5 m sections, and indicated by means of small plastic plugs ($\pm 2^\circ$) in the sediment. The 5 m sections were then finally cut into 3–4 core sections, and sealed in airtight plastic (polyethyl) foil at the site before further transport to the laboratory.

At the Prehistoric Museum, Moesgård, Denmark, radiography was performed on the Solberga and Brastad cores, followed by preliminary measurements of the natural remanent magnetization (NRM) at the



Fig. 4:3. Processing of one of the Foil Piston cores at Solberga (N. Knaverstad) on April 14th, 1977.

Geophysical Laboratory, University of Aarhus, Denmark. These records were then used as structural and lithological indicators during the subsequent opening and sampling of the cores at the Department of Micropalaeontology, University of Aarhus. The cores were photographed (both in colour and in black and white), examined, described, and classified before the bulk density and water content were determined and the final palaeomagnetic subsampling was carried out. The colour descriptions were made with the help of the GSA Rock-Color Chart. Finally the core sections were cleaned of paraffin oil and cut into 5 cm pieces, which were subsampled for physical, geochemical and biostratigraphical studies together with ^{14}C -datings. Altogether, about 1 100 subsamples from 110 levels of the Solberga and Brastad cores were taken and distributed among members of the project. The remaining samples were stored at the Department of Marine Geology in Göteborg.

Since the preliminary results show that a long break in sedimentation probably occurred in the Brastad core, this site had to be supplemented. Therefore in September 1980 three 6.5 m long cores were taken by means of a modified Russian Peat Sampler with 60 mm diameter (Tolonen 1968) at

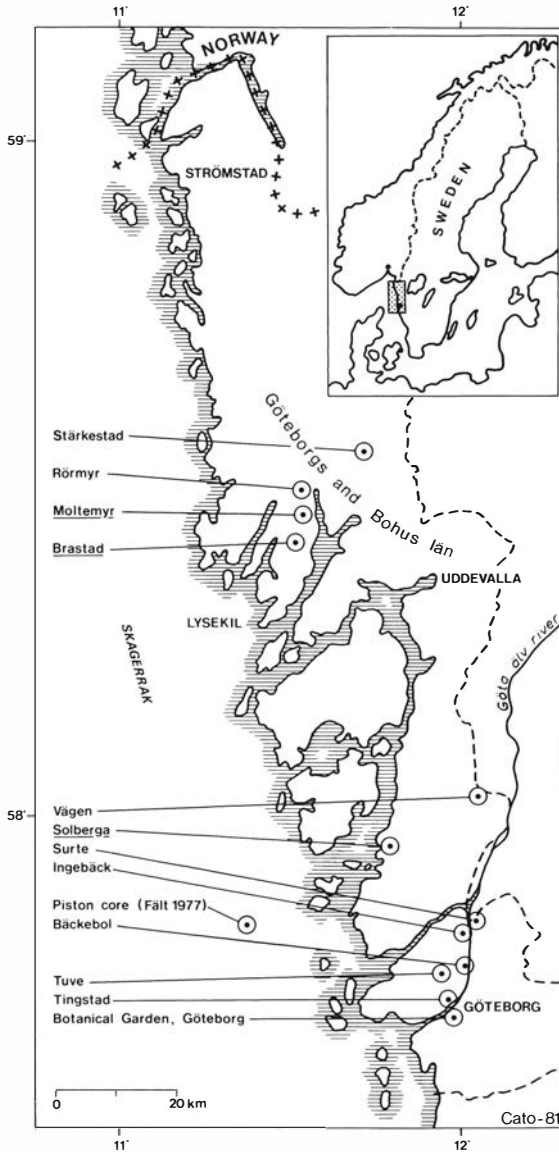


Fig. 4:4. Foil Piston Core stations 1977 and 1982 (underlined) and other sites in south-western Sweden mentioned in the forthcoming papers.

one of Fries' sites (Fries 1951:80), Moltemyr ($58^{\circ} 26' 45''$ N Lat, $11^{\circ} 32' 36''$ E Long, 55 m above sea level, Fig. 4:4). The core sections were transported to the Geological Survey of Sweden, where they were subjected to the same process as the Solberga and Brastad cores. Subsamples 2.5 cm thick were distributed among members of the project, to be studied for geochemistry, ^{14}C -age, micro- and macropalaeontological successions. Palaeomagnetic studies were also carried out on one part of the core. At a later workshop

members of the project group decided that Moltemyr should be included in the programme. In June 1981 a 16.3 m long (probing depth >27 m) and azimuthally orientated core was therefore taken by means of the smaller Swedish Piston Corer (37 mm in diameter). New palaeomagnetic determinations and supplementary chemical, physical and micropalaeontological studies at deeper levels are now in progress. These additional analyses will not be presented in this context.

Knowledge of the vegetational succession around the Pleistocene/Holocene boundary of neighbouring terrestrial areas was essential for a correct, conventional zonation by pollen analysis in marine cores, as represented by Solberga, Brastad and Moltemyr. Two corings in limnic sediments at Vägen (58° 01' 05" N Lat., 12° 02' 35" E Long., 113 m above sea level) and Rörmyr (58° 28' 55" N Lat., 11° 31' 30" E Long., 115 m above sea level, Fig. 4:4) were therefore carried out, using a modified Russian Peat Sampler (see above), in August 1978 and September 1980. These cores were used for ¹⁴C-datings, diatom and pollen analyses.

ACKNOWLEDGEMENTS

I am indebted to Börje Färestad, Lars Blomkvist (both at the Swedish Geotechnical Institute), Gunnar Ekman, and Sverker Larsson (both at the Geological Survey of Sweden) for their most efficient co-operation during the field-work.

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5. GEOLOGICAL NOTES OF THE MOLTEMYR, BRASTAD AND SOLBERGA AREAS

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A generalized distribution of the Quaternary deposits around the investigated localities and the main features of the Late Quaternary evolution of western Sweden is shown in Fig. 5:1.

The Moltemyr basin is situated between 55 and 60 m above sea level surrounded by bedrock hills – reaching about 90 to 130 m above sea level – and valley slopes which consist mainly of fine-grained glacial clay. The most pronounced valley has a north-south direction. The basin is drained northwards through this valley.

The raised bog is surrounded by a narrow fen. The bog has been exploited to such a degree that only small parts of the original surface remain.

Shell and shell fragments are found in sandy deposits and in small lenses in the clay around the basin. On the south-western bedrock hill, remains of a small shellbank are situated at a level of about 75 m above sea level in a small fissure valley. A radiocarbon determination of shells and shell fragments yielded an age (uncorrected) of $10\,700 \pm 180$ years B.P. (St 5377). It is assumed that the mollusc fauna in the area is contemporary. Following species of molluscs and barnacles have been identified: *Astarte borealis* (common), *Chlamys islandica*, *Hiatella arctica*, *H.a. uddevallensis*, *Macoma calcarea*, *Mya truncata*, *Mytilus edulis*, *Balanus crenatus*, and *Balanus hammeri*.

The Brastad locality is situated in an extensive, flat-lying clay area, 40–45 m above sea level surrounded by bedrock hills reaching 50–75 m above sea level. The area is drained westwards. Clay sequences of more than 30 m are known.

The Solberga locality is located in a broad valley a few metres above sea level and quite close to the present shore line. The relative relief between the clay surface and the surrounding bedrock hills is 20 to 25 m. Clay thicknesses of more than 30 m are recorded in the broad valley. The surficial clay usually has a postglacial origin at levels below about 20 m above sea level.

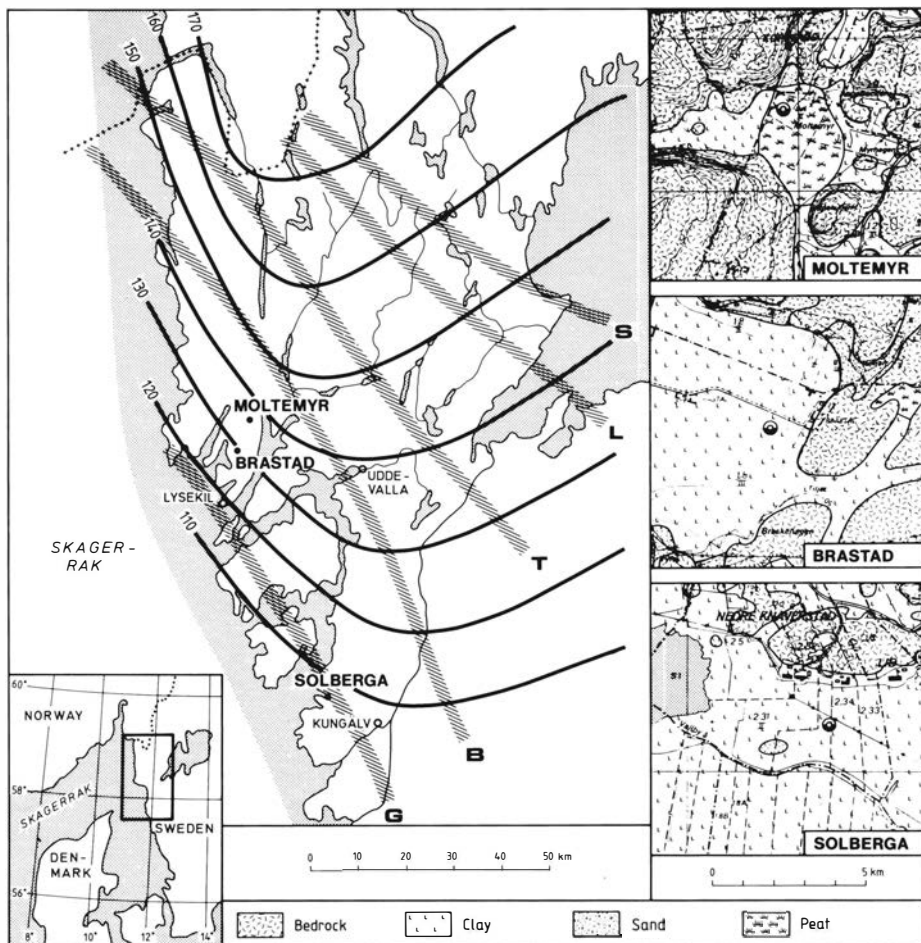


Fig. 5:1. Main features of the Late Quaternary evolution in western Sweden and of the distribution of Quaternary deposits at the investigated localities. The isobases for the highest shoreline in m above sea level are given in rough outline. The main terminal moraine zones are (G) Göteborg moraine, (B) Berghem moraine, (T) Trollhättan moraine, (L) Levene moraine, and (S) Skövde/Billingen moraines.

The geological maps are based upon the economic map sheets 8B 7a, 8A 6j and 7B 6c (*Lantmäteriverket, Gävle*). Contour interval is 5 m. The drilling holes are shown by the circular symbol for Foil Piston Corer.

The Solberga locality is situated on the geological map sheet Göteborg NV, which is to be published in 1983.

6. DESCRIPTION OF THE CORES

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STRATIGRAPHY

The Solberga and Brastad cores were photographed by Søren Bo Anderssen and Sven Korsgaard, both of the Geological Institute of Aarhus. Karl-Erik Alnavik, Geological Survey of Sweden, photographed the Moltemyr core. The films used for the Solberga and Brastad cores were 1 series Kodachrome 64, 1 series Ectachrome High Speed (B) and 1 series Kodak Panatomic -X. The Moltemyr core was photographed with 1 series Kodachrome 64 and 1 series Kodak Plus-X. The fresh sediment of the core sequences was exposed via the removal of an upper longitudinal border slice. Immediately afterwards they were photographed from a distance of about 2 m and described by some group-members.

Figures 6:2a through 6:2f below show the results, and give details of the individual core sections. The cores are reproduced in scale 1:10. A cm-scale from the top of each core gives the depth below ground surface. Notes on the lithology, organic content, occurrence of shells, shell fragments, pebbles, grit *etc.* can be found below (Tables 6:1–3). Colours are stated with reference to the GSA Rock-Color Chart while the nomenclature of sand, silt and clay mixtures follows the Shepard (1954) system. As the figures illustrate all sediment core-sections were oxidized at the border as a consequence of exposure to the air.

The clastic sediment of the cores was rather homogeneous, and with the exception of the silt layer at Brastad, no distinct limits between the sediment types given below were observed.

As can be seen from the description of the cores laminae with dark and light bands occur between 486 cm (distinct laminae from 591 cm) and 1 810 cm depth in the Solberga core, *i.e.* the clay-rich sequence (see Chapter 7). These dark and light bands may correspond to winter and summer units in varves or reflect reduced and oxidized bottom conditions during winter and summer respectively. However, it must be stressed that visual examination of the laminae revealed no difference in the grain-size composition between the dark and light bands. The diagram (Fig. 6:1), shows both the thickness of the laminae, dark plus light bands and the thickness of the dark bands. If

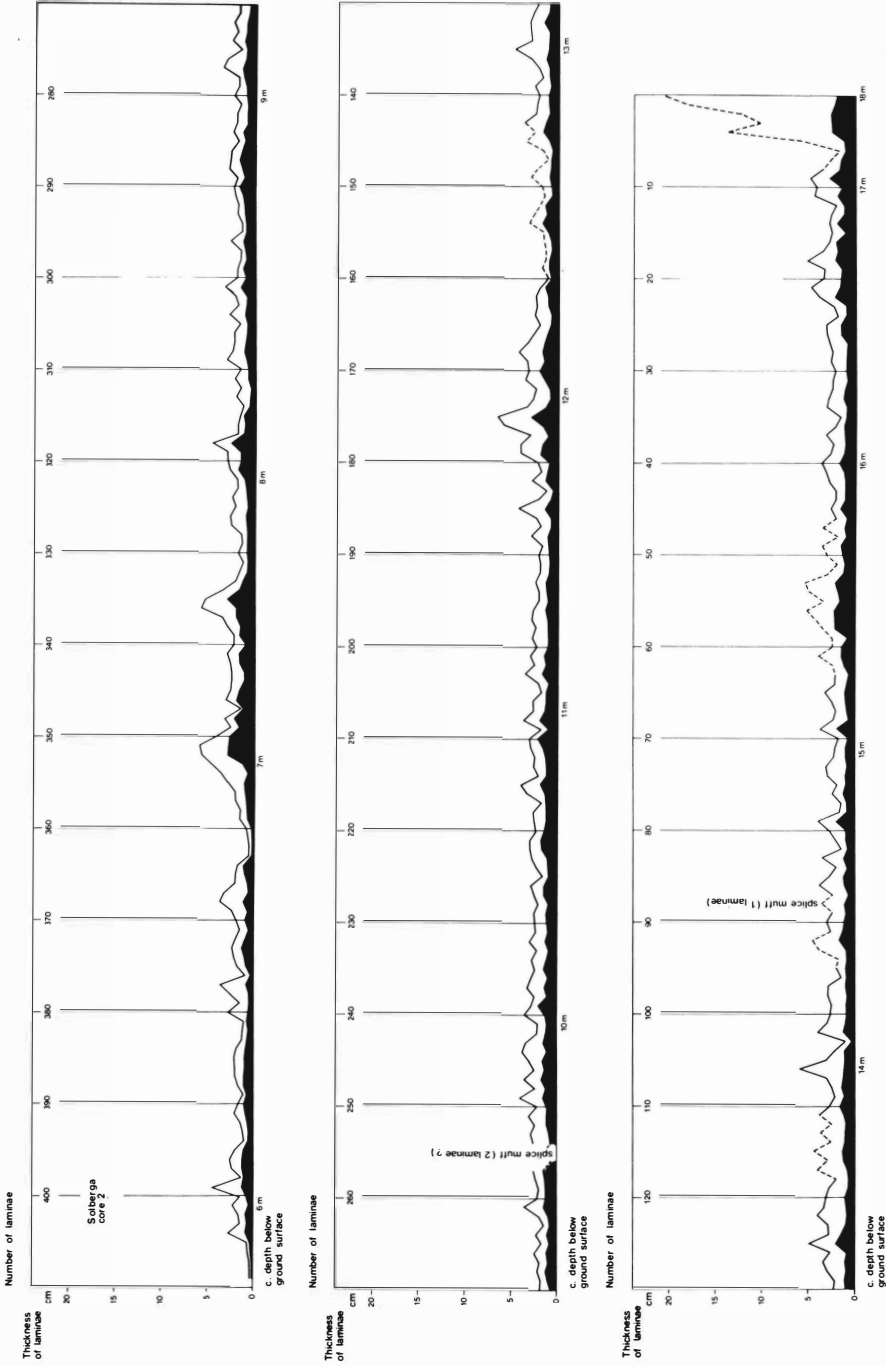


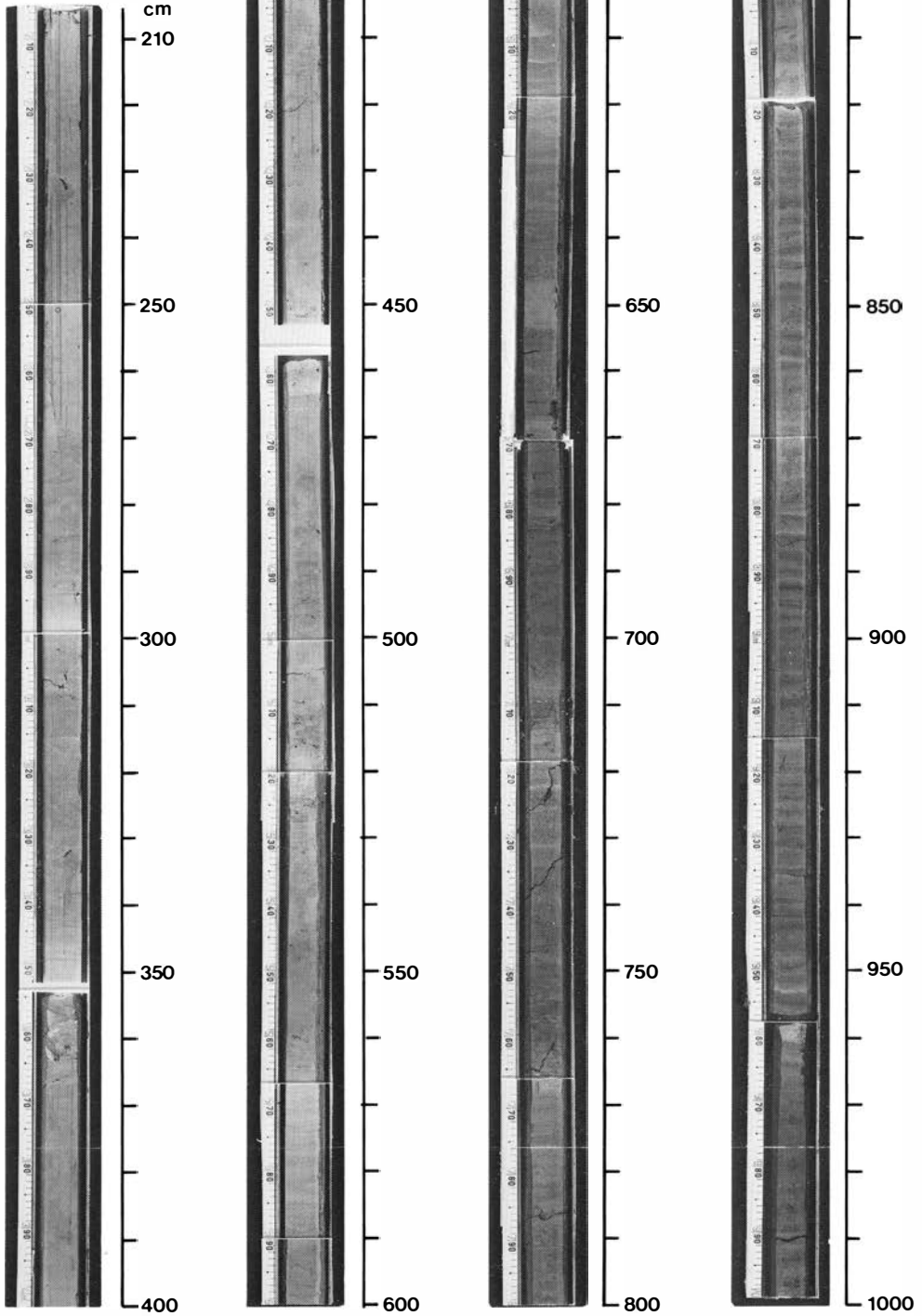
Fig. 6:1. The laminated ("varved") sequence (5.9–18.1 m) of the Solberga core. Upper curves give the total thickness, filled curves the thickness of the dark bands ("winter units"). Hatched sequences mark diffuse laminae.

one dark and one light band correspond to one year, the 409 "varves" may give the approximate duration of the meltwater discharge through the Väner basin into Skagerrak during the Preboreal times. As can be seen in Fig. 6:1, the thickness of the "varves" is greatest around 18 m depth, *i.e.* in the beginning of the sequence, and smallest around 6 m, *i.e.* at the end of the sequence.

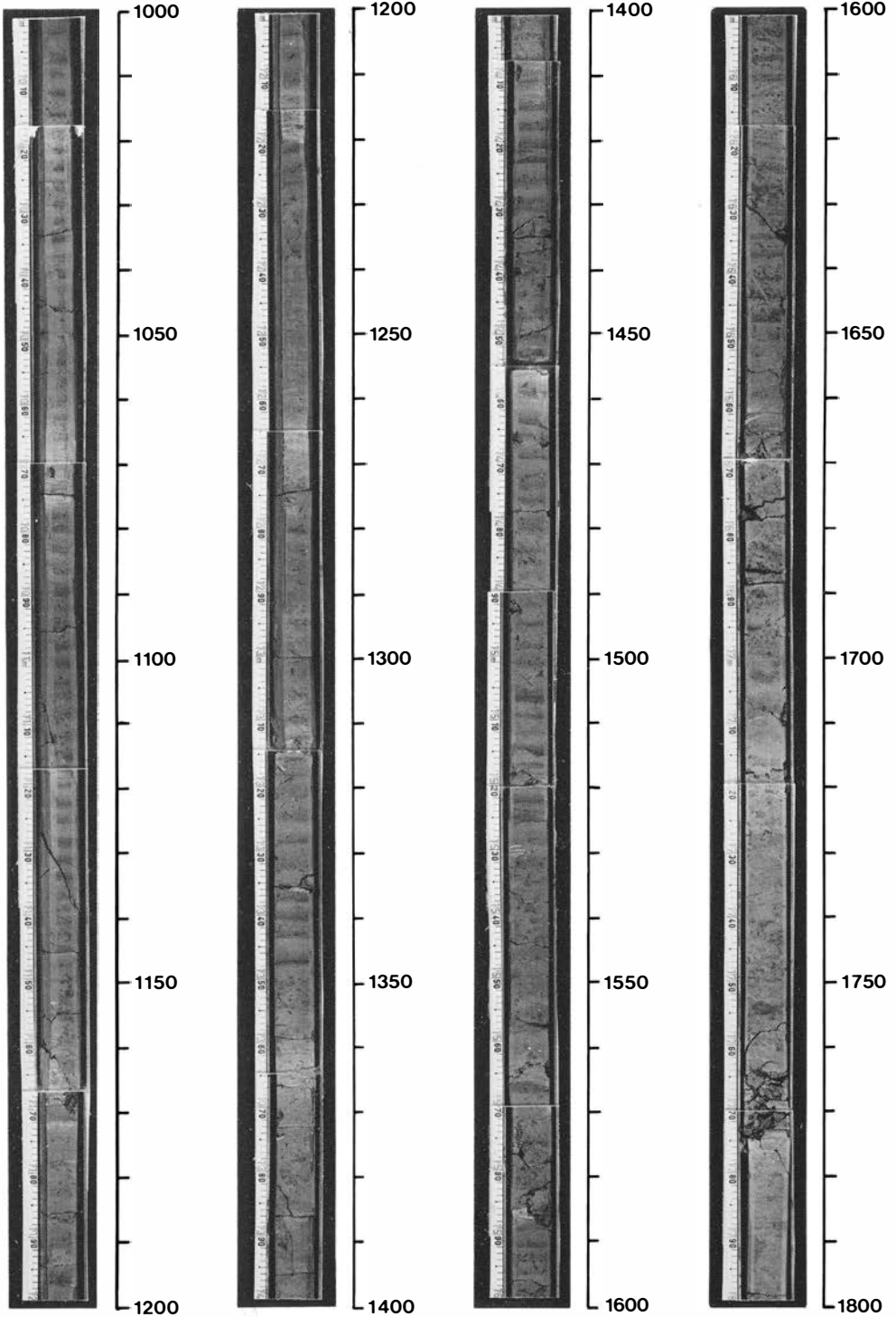
It is also worthy of note that dark and light bands between 6.5 and 8.5 m in the Tuve core and between 5.5 and 13.4 m in core B 873 (Botanical Garden, Göteborg) were observed by Häger (1981) and by Mörner (1976) respectively. These sequences were according to other facts assumed by Cato *et al.* (1981) and by Cato and others (this volume) to have been formed as a consequence of the above-mentioned meltwater discharge.

Figs. 6:2a–f. Photographs of the continuous cores from Solberga, Brastad and Moltemyr. The black arrows between 18.4 and 19.3 m in Solberga and at 3.5 m depth in Moltemyr mark the Pleistocene/Holocene transition zone/limit respectively. At 2.3 m depth in Brastad the limit between silt and silty clay is marked ("hiatus").

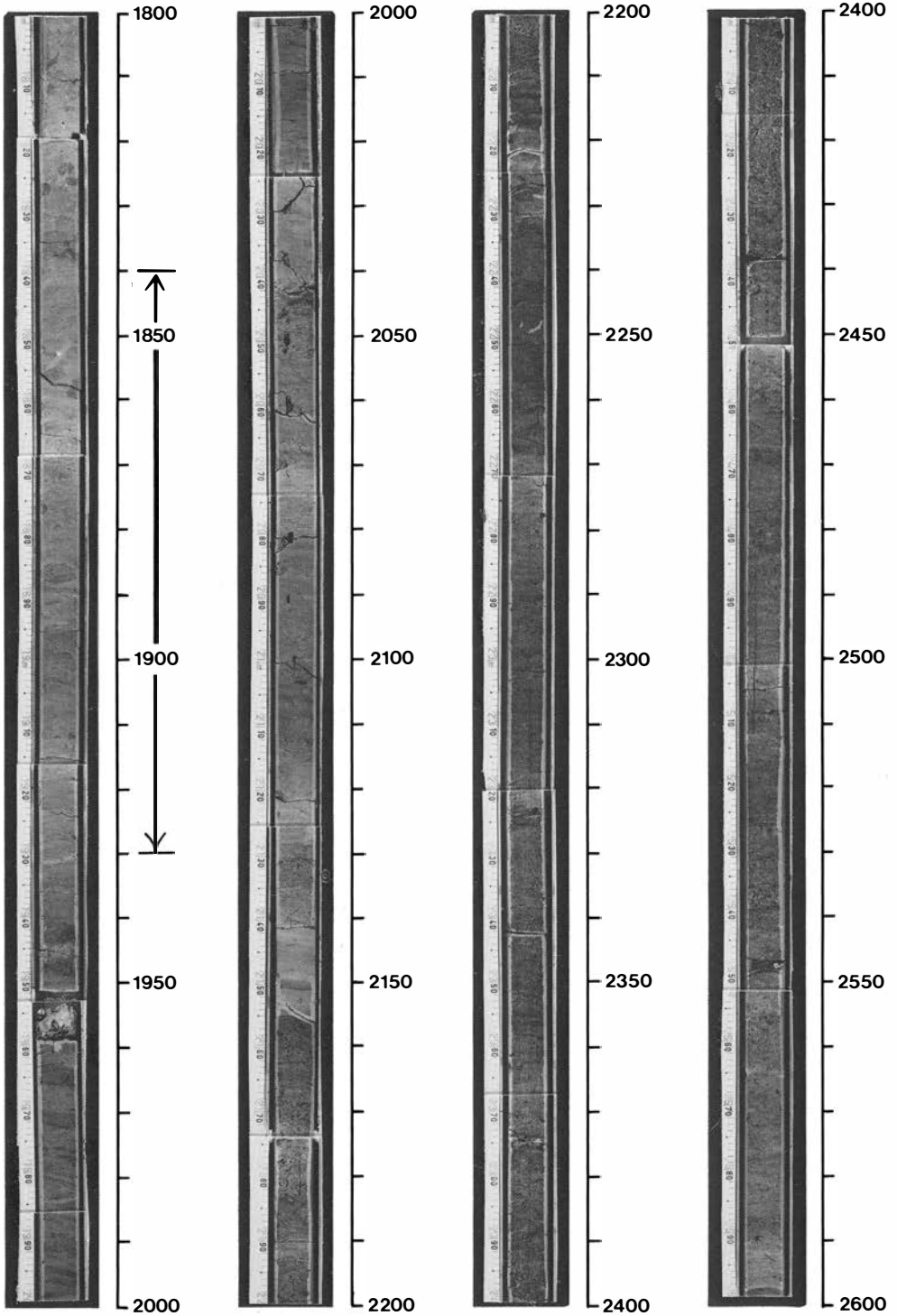
**SOLBERGA
core 2**



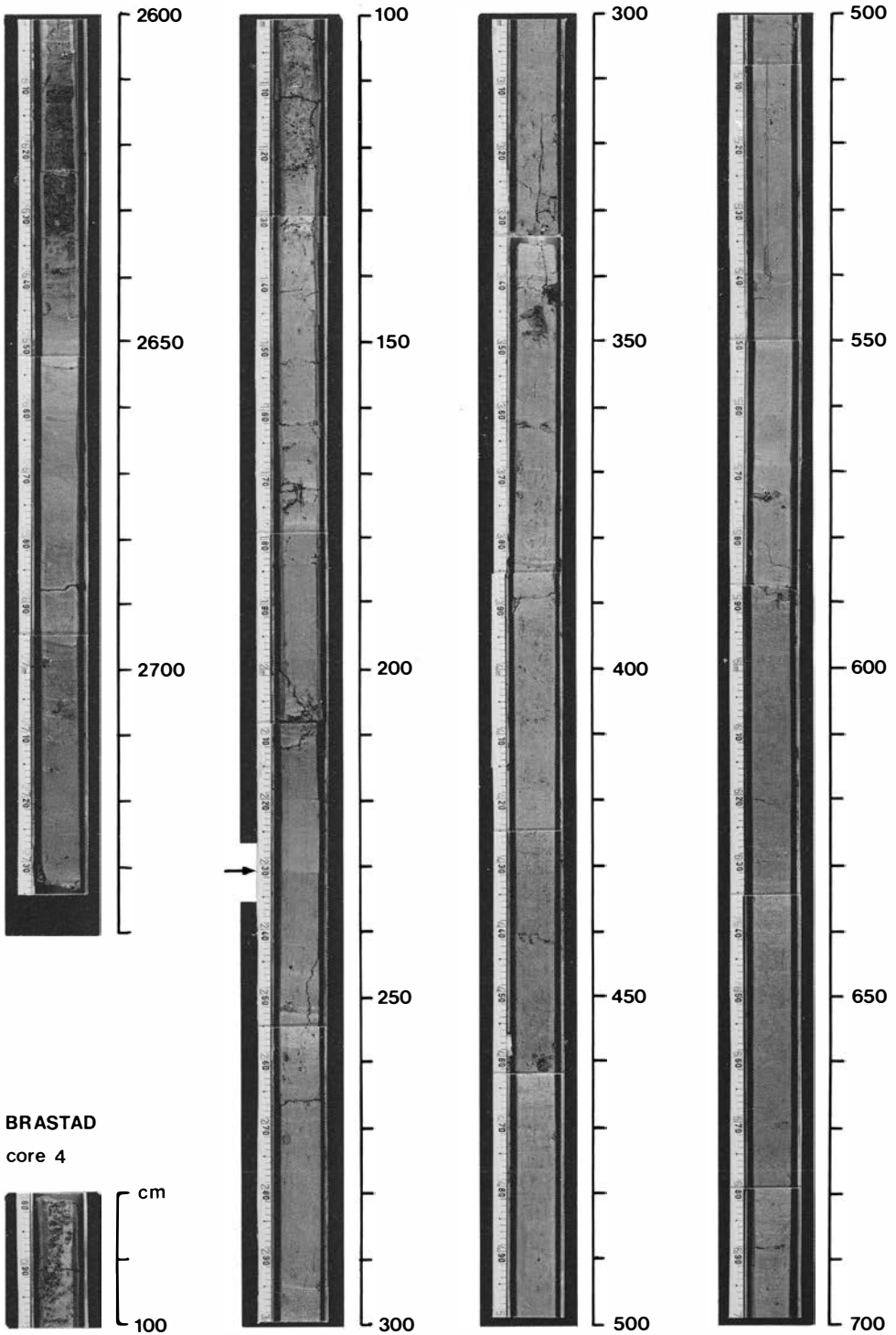
a



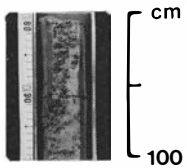
b



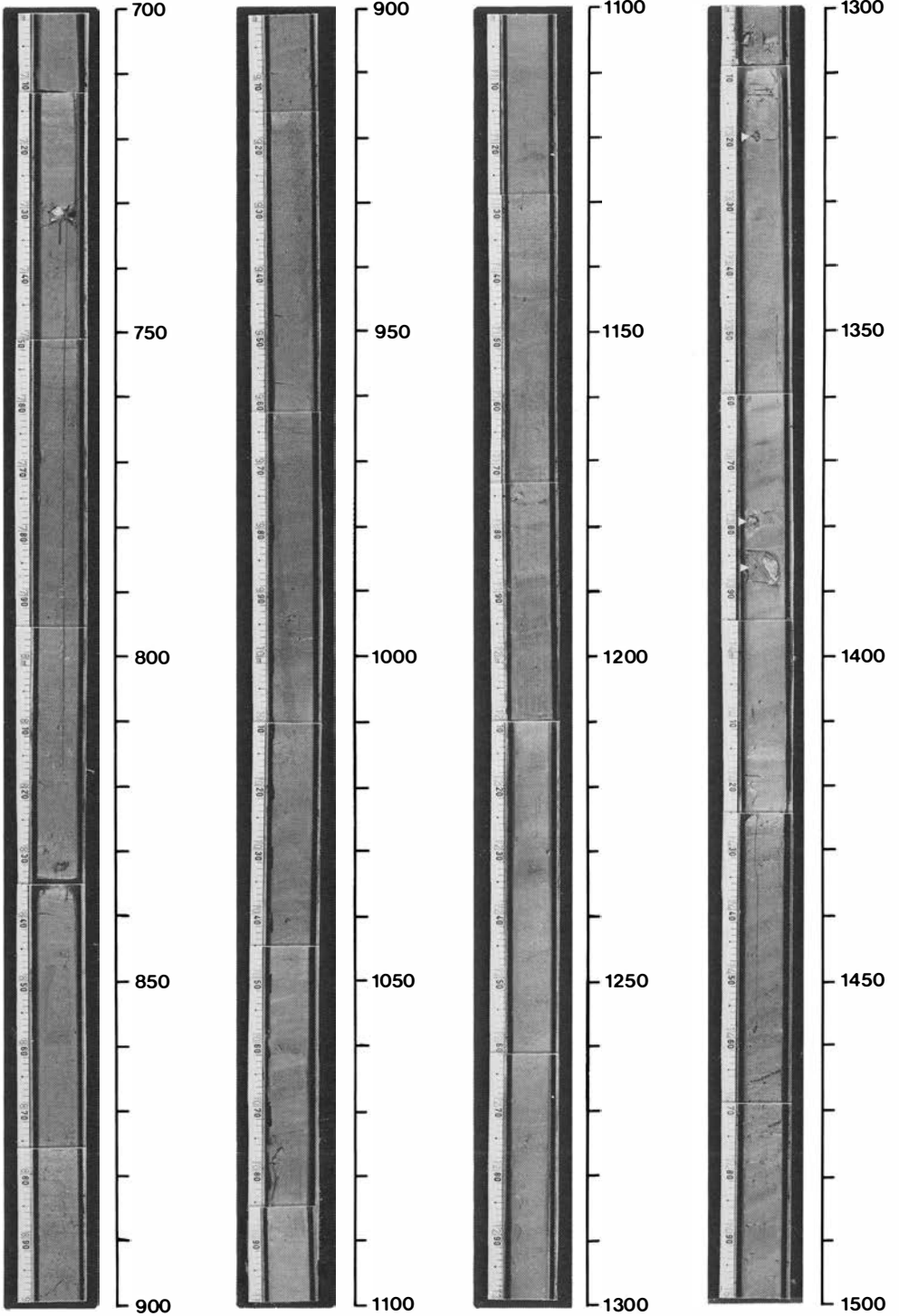
C



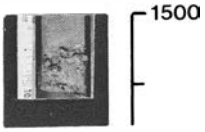
BRASTAD
core 4



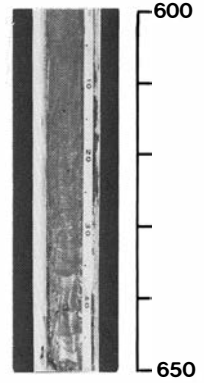
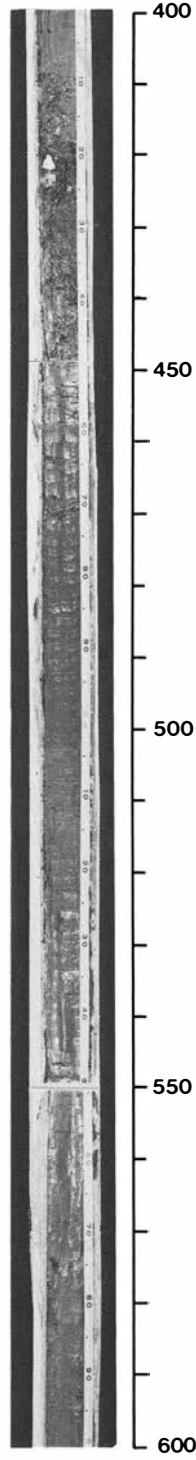
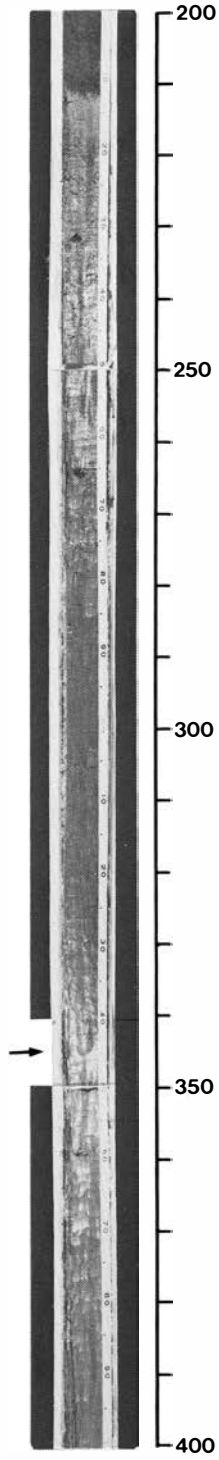
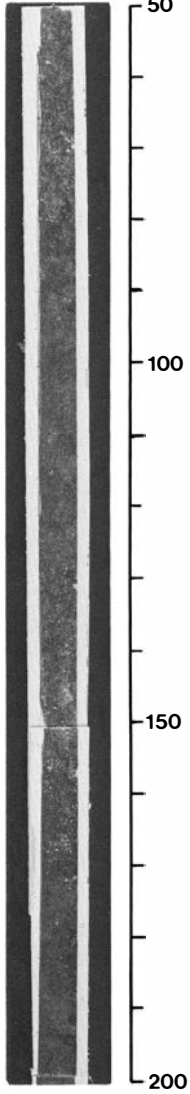
d



e



MOLTEMYR
core



f

TABLE 6:1. Stratigraphy of the Solberga core.

Depth below ground surface	Notes on the stratigraphy
205–400 cm.	<p>Gyttja silty-clay, medium dark greenish grey (5 GY 4/1), homogeneous, containing shell fragments at 286, 341, 365, 390, and 403 cm and rootlets at 295 and 314 cm depth.</p> <p>Between 430–460 cm there is a gradual colour transition downwards to dark greenish grey (5 GY 3/1).</p>
400–670 cm.	<p>Silty clay, dark greenish grey (5 GY 3/1), with very few shell fragments and no rootlets. From about 486 cm diffuse laminae and from 591 cm downwards more or less distinct laminae of dark and light bands occur.</p>
670–1 790 cm.	<p>Clay, dark greenish grey (5 GY 3/1), without shell fragments. The laminae of dark and light bands became less diffuse downward. Between 780 and 1 710 cm depth the laminae are distinct. The dark bands are greenish grey in colour (5 GY 3/1). When exposed to air, the laminae became gradually diffuse, due to oxidization. From about 1 710 cm downwards the laminae again became diffuse. Independent of the laminae 13 areas covered with sulphide spots occur from 1 060 cm downwards, e.g. at 1 103–1 115, 1 230–1 240 and 1 594–1 707 cm. A burrow fill occurs at 1 640–1 645 cm level.</p>
1 790–2 733 cm.	<p>Silty clay, dark greenish grey (5 GY 3/1), containing shell fragments (observed at 59 levels). Below 2 481 cm depth the thickness of the shell fragments increases. Between 1 967 and 2 015 cm the colour changes to greyish black (N2) – greenish black (5 GY 2/1) with several black (N 1) bands. At 2 155 cm depth the colour changes to black (N 1). The above given sequence of laminae occurs down to 1 810 cm, but also deeper diffuse laminae appear at several levels. From 2 640 cm downwards the colour is greenish grey (5 GY 3/1).</p> <p>Grit was observed at 2 654 and 2 670 cm depth and frequently below 2 730 cm.</p>

TABLE 6:2. Stratigraphy of the Brastad core.

Depth below ground surface	Notes of stratigraphy
80–220 cm.	Clayey silt, moderate olive brown (5 Y 4/4), with light olive brown (5 Y 5/6) precipitates down to about 140 cm depth. The precipitates gradually disappear between 140–174 cm. Between 174–206 cm the colour is olive grey (5 Y 4/1), but changes gradually to dark yellowish brown (10 YR 4/2), which occurs between 212–220 cm. The sediment contains rootlets at 88, 105 and 180–190 cm and other plant fragments (40 mm × 3 mm) at 210 cm depth. A 7 cm long silt lens occurs at 211–212 cm and a 1 cm large silt “ball” at 215 cm depth. There are no shell fragments in this sequence.
220–231 cm.	Clayey silt to silt, yellowish brown (10 YR 4/2), with increasing silt content downwards. A fault occurs along the limit between this and the under-lying sediment. There are no shell fragments in this sequence.
231–1 502 cm.	Silty clay, dark greenish grey (5 GY 4/1), which is distinct from the sediment above (see arrow Fig. 6:2d) and contains shell fragments at 18 levels (between 320 and 994 cm), grit at 22 levels (between 299 and 1 447 cm) and stones at the following depth: 940 cm biotite mica (1.5 cm, 1 g), 1 065 cm quartz, biotite (4.5 cm × 3 cm, 28 g), 1 124 cm gneiss (3 cm × 1.5 cm, 6 g), 1 230 cm gneiss (1 cm × 2 cm, 9 g), 1 374 cm gneiss (1 cm × 1.5 cm, 3 g), 1 379 cm gneiss (3 cm × 3 cm, 32 g; see arrows Fig 6:2e) and 1 485 cm gneiss (4.5 cm × 2 cm, 28 g). Plant fragments occur at 265, 270–280, 285, 357 cm, and burrow fills at 415, 504 cm and between 770–1 000 cm depth. The burrow fill at 504 cm depth is surrounded by a pipe-like iron oxide concretion. The silty clay is soapy between 345 and 835 cm depth. More or less faint dark and light laminae occur from 960 cm depth downwards. Between 1 130–1 220 cm the thickness of the laminae is about 6 cm. The dark bands are brownish grey (5 YR 4/1) or medium dark olive grey (5 Y 4/1). Below 1 331 cm depth are 8 thin silt layers at (1 332, 1 452, 1 456, 1 460, 1 465, 1 473, and 1 478 cm).
1 502–1 509 cm.	Clayey sand to sand, olive grey (5 Y 4/1), without shell fragments.

TABLE 6.3. Stratigraphy of the Moltemyr core.

Depth below ground surface	Notes on the stratigraphy
50–165 cm.	Fen peat, brownish black (5 YR 2/1), incorporating many pieces of wood. From about 150 cm depth rich in <i>Phragmites</i> and <i>Equisetum</i> .
165–212 cm.	Coarse detritus gyttja, olive black (5 Y 2/1) between 203–212 cm and fine detritus gyttja between 165–203 cm.
212–300 cm.	Gyttja silty-clay, sharp limit, light olive grey (5 Y 5/2) and banded down to 222 cm depth where it changes to greyish olive (10 Y 4/2). Between 251 and 265 cm depth light olive grey (5 Y 5/2) bands occur. Below 265 cm depth the colour is greenish grey (5 G 6/1). Shell fragments occur at 5 levels.
300–465 cm.	Silty clay, greenish grey (5 G 6/1), containing shell fragments at 9 levels.
465–508 cm.	Clayey silt, greenish grey (5 G 6/1), containing some shell fragments.
508–650 cm.	Silty clay, greenish grey (5 G 6/1), homogeneous, rich in shell fragments, except for the sequence below 570 cm depth.

X-RADIOGRAPHY

(BY INGEMAR CATO IN COOPERATION WITH NIELS ABRAHAMSEN)

The Solberga and Brastad cores were submitted to radiographical examination by Jesper Trier at the Prehistoric Museum, Moesgård, Denmark. For this purpose a Federex portable X-ray set was used. The X-ray tube was fixed at a distance of 2 m from the core sections. The cores, still sealed in plastic foil and PVC-liners, were oriented with north to the left of the film. Before exposure the coring depth and core sections were marked with lead figures and every 10 cm with nails. Five exposures with overlap were taken on Agfa-Gevaert D7pDW film (24 cm × 30 cm) for each section. During the 17 min long exposure time, the X-ray tube was run at 85 KV and 4 mA.

Absorption of X-ray is dependent not only upon the wavelength of radiation and the atomic number of the absorbent material, but also on the

density and thickness of the sediment. The latter varies as a consequence of the cylindrical cores, which results in increased blackening laterally from the centre towards the core border.

Important internal structures of the sediment cores were revealed by radiography, which simplified the description of the stratigraphy and facilitated the subsampling procedures together with the interpretation of the depositional environment. Some results are exemplified by Figs. 6:3a–3d, which are reproduced in scale 1:2.5. As can be seen from the sequence shown, 1 678–2 020 cm at the Solberga core, shells are clearly reflected in the radiograms, e.g. at the levels 1 729, 1 833, 1 848, 1 874, 1 888, 1 907 cm as well as fractures, here with more or less horizontal axial planes. The latter appeared, when the sediment core was withdrawn from the pipe. At the levels 1 819 cm and 1 951 cm the core has been cut in sequences. The sediment of the splices between the core pipes has not been X-rayed. A gap was therefore left in the radiogram, between 1 951–1 954 cm in Fig. 6:3c. From 1 954 cm depth and 5 cm downwards the folded plastic foil, sealing the core, can be seen.

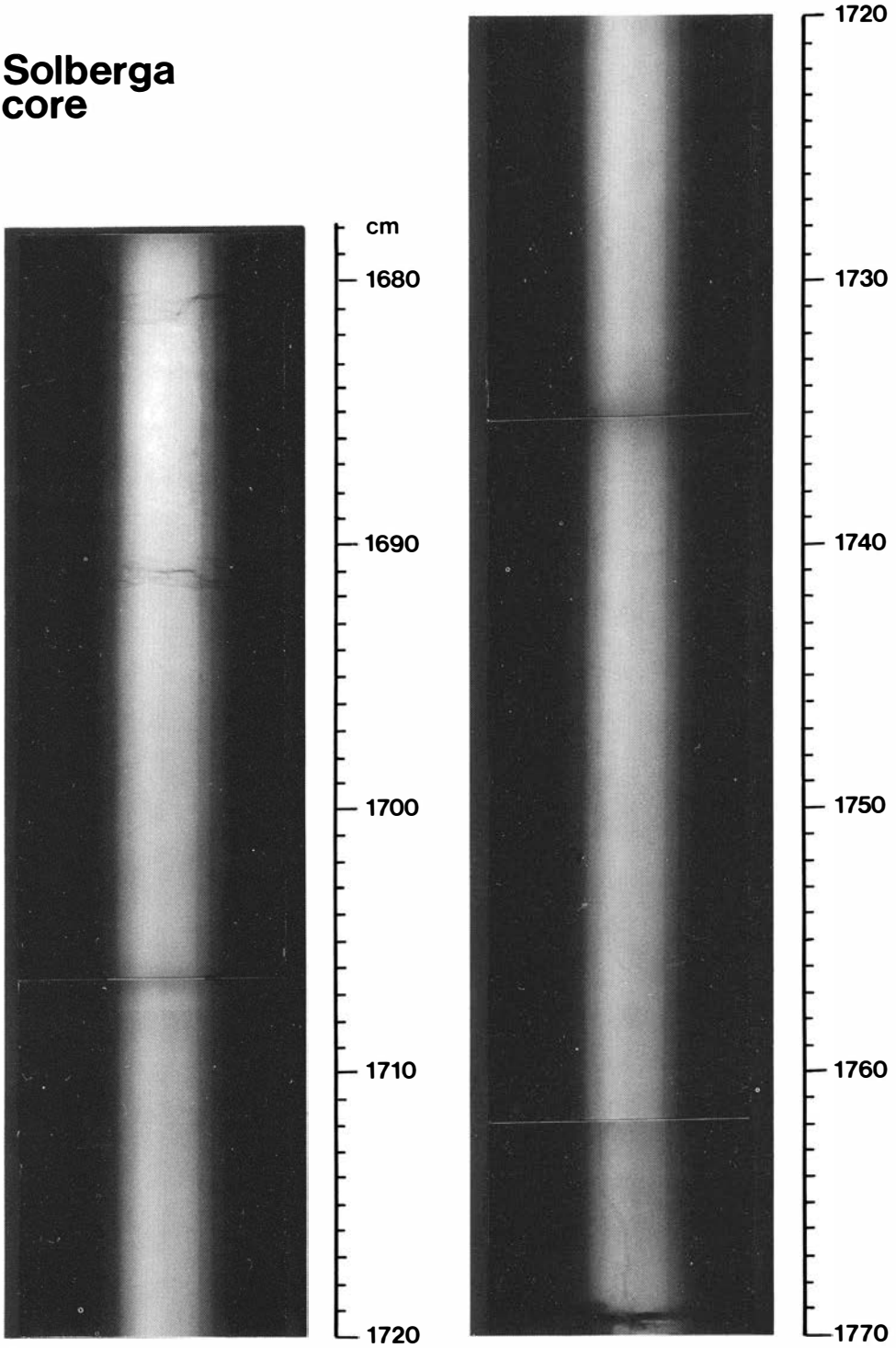
The overlap of the X-ray films during exposure created faint light-grey bands at about the levels 1 701, 1 736, 1 763, 1 790, 1 841, 1 897, 1 925, 1 969, and 1 997 cm in the Solberga core and at 226 cm in the Brastad core. These limits should not be confounded with lithological boundaries such as the one seen at 2.31 m depth in the Brastad core. This boundary in the grey scale reveals the distinct change from a silty clay sediment below into a silt layer above this level.

The strong change in the grain-size distribution from about 18.4 m upwards to about 17.7 m in Solberga core is reflected in the radiogram by a faint upwards blackening of the core.

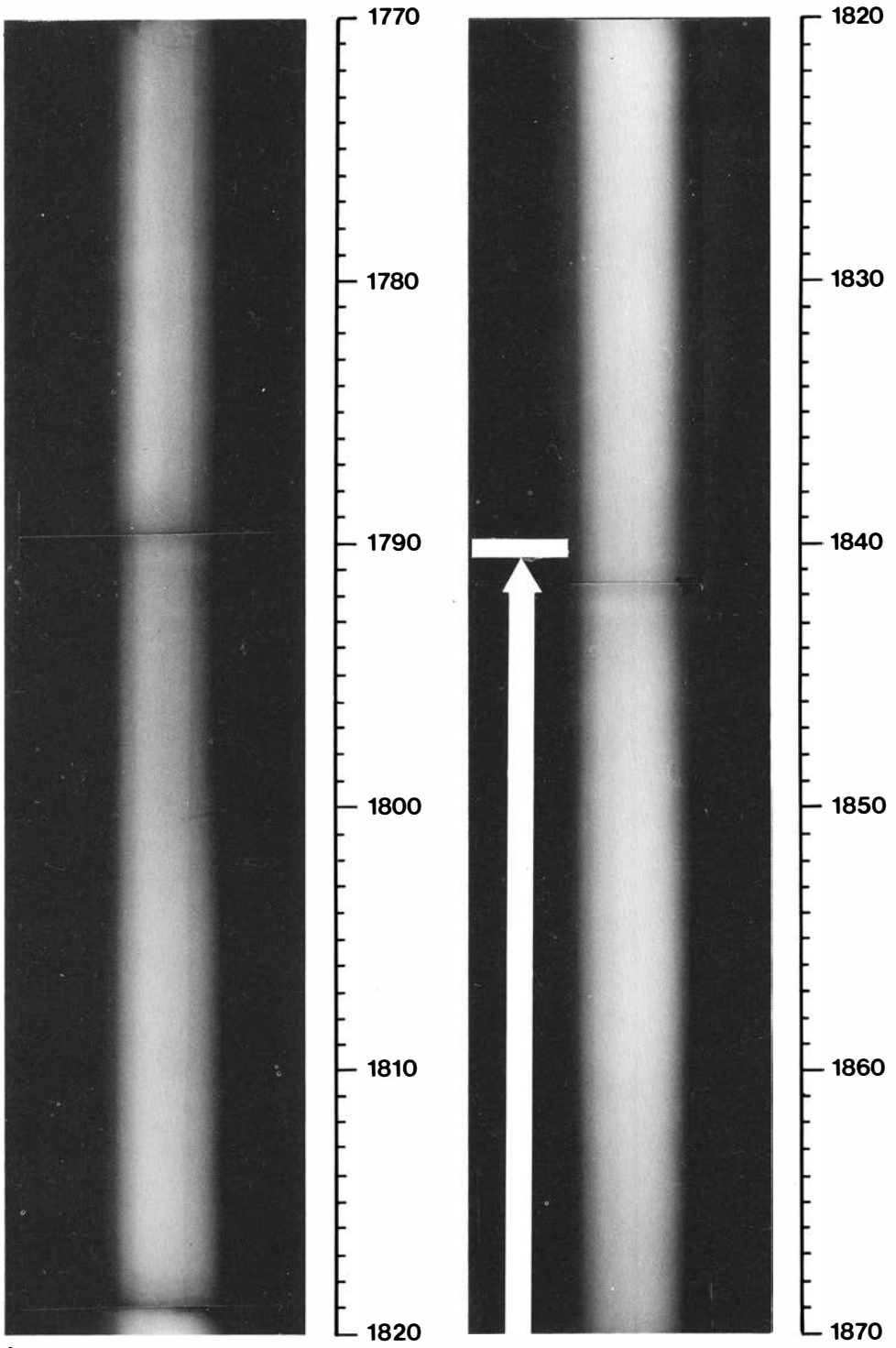
The radiograms give an idea of the very homogeneous cores with sparsely embedded macroscopic shells and pebbles. The latter occur only at the bottom of the cores, not shown here. The abrupt lithological change in Brastad at 2.31 m depth indicates that only the Solberga core reveals a continuous sedimentation during the end of the Pleistocene and the beginning of the Holocene epochs.

Figs. 6:3a–d. X-radiogram of sections from the Solberga and Brastad cores. The white arrow between 18.4–19.3 m in Solberga marks the Pleistocene/Holocene transition zone. At 2.3 m depth in Brastad the limit between silt and silty clay is marked (“hiatus”).

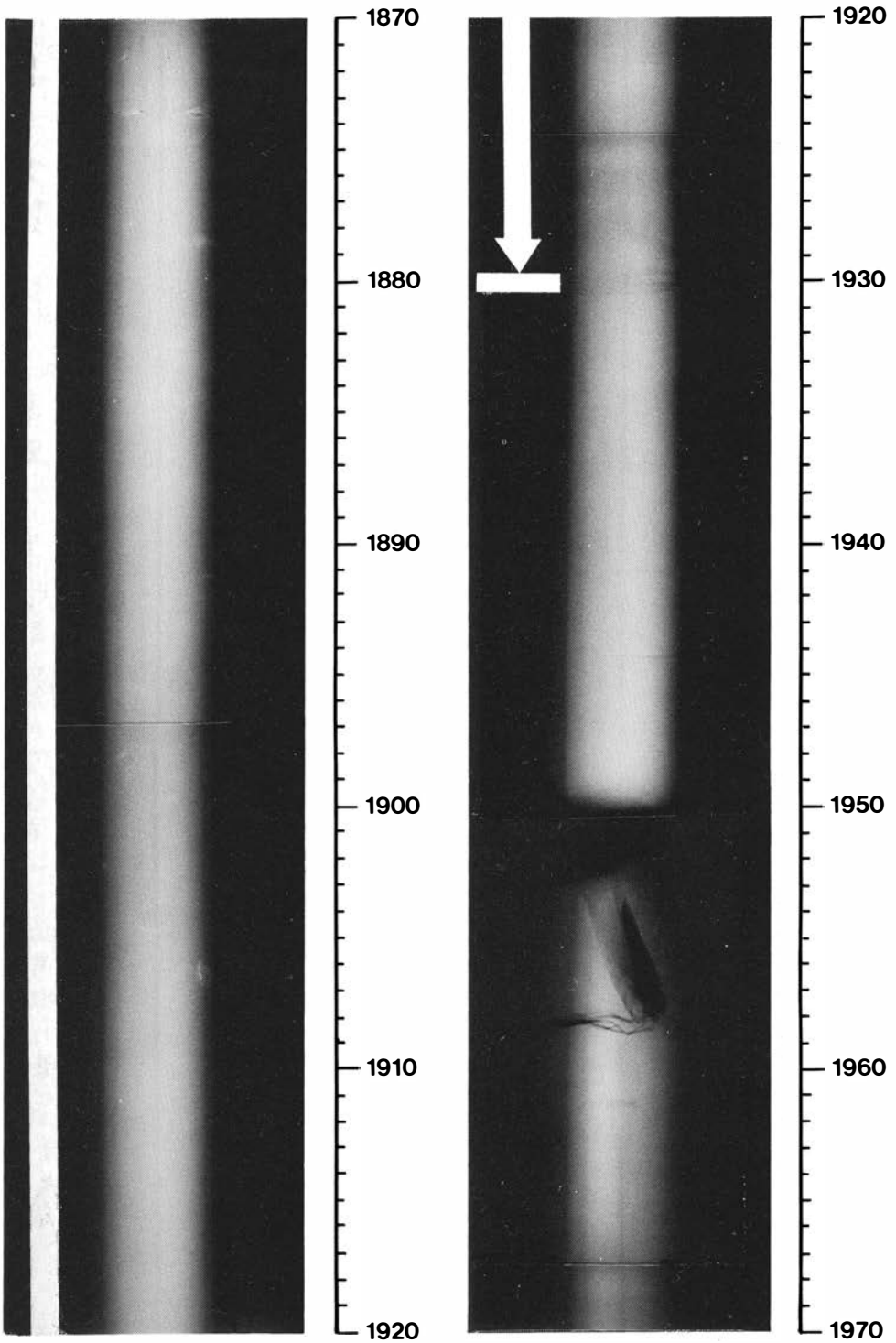
**Solberga
core**



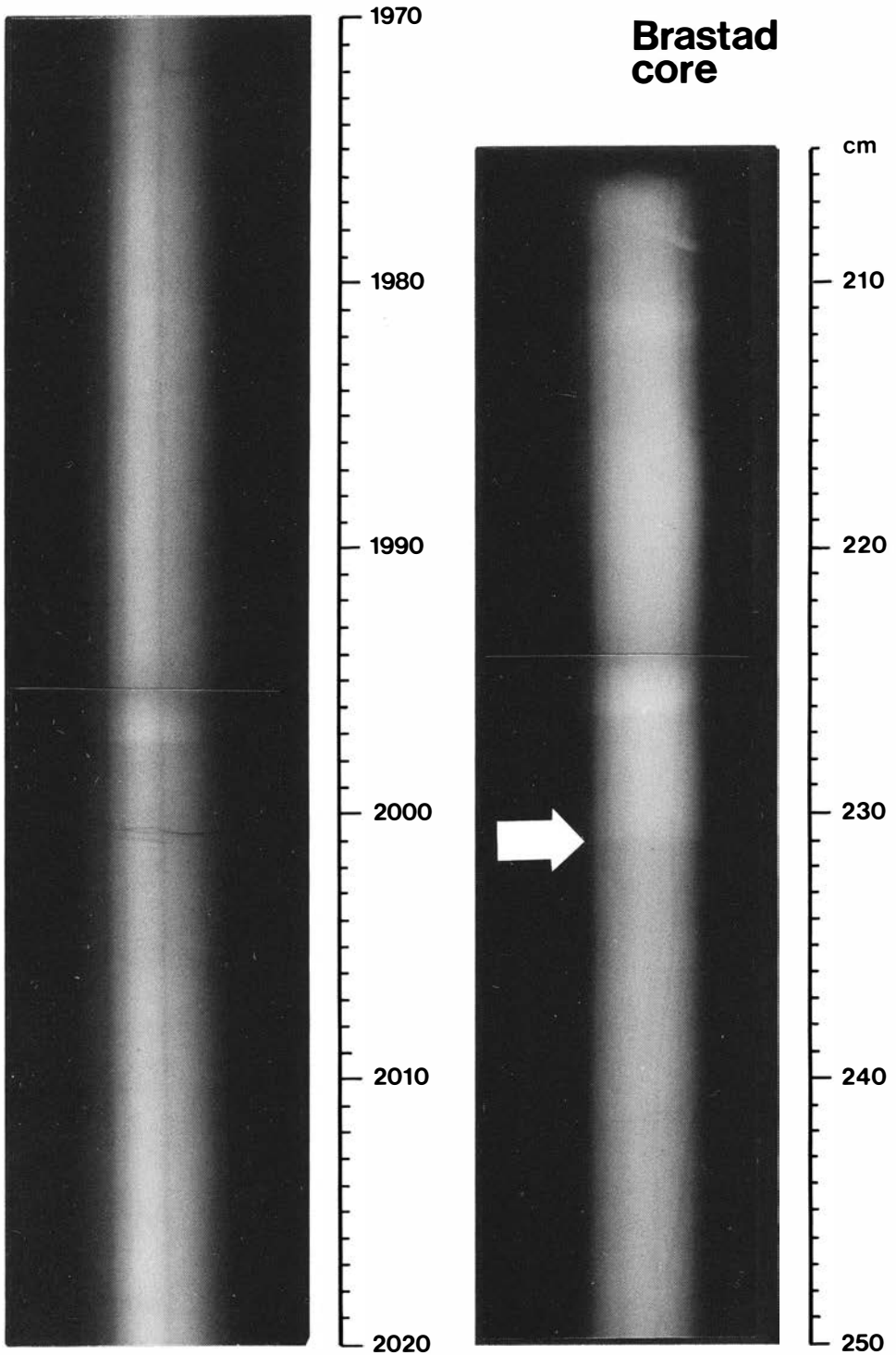
a



b



c



d

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7. GRAIN-SIZE DISTRIBUTION OF THE CORES – WITH EMPHASIS ON THE SEDIMENTARY PATTERNS AROUND THE PLEISTOCENE/HOLOCENE BOUNDARY

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METHODS

The methods used for grain-size analysis followed standard procedure. Organic matter was first removed with hydrogen peroxide according to Jackson (1965) whereupon the water-soluble salts were washed out with distilled water. In order to avoid the crust on sediment dried at 105°C, the pretreated samples were freeze-dried at a pressure of about 0.02 torr and a temperature of -35°C. The water content in the freeze-dried sediment samples was less than 1 %. The granulometric analyses were performed with the hydrometer method (Gandahl 1952) for particle sizes smaller than 0.062 mm, and by sieving the dried sediment (Knutsson and Ljunggren 1960) for particle sizes coarser than 0.062 mm. The sieves used had square meshes with the widths of the 1922 Wentworth scale (Wentworth 1922).

The nomenclature of the grain-size distribution follows the size limits of the Massachusetts Institute of Technology, M.I.T. Scale, of 1931 (Terzaghi and Peck 1960). For the nomenclature of sand, silt and clay mixtures, the system of Shepard (1954) was used (see Fig. 7:4). The quartile Q_{75} and median Md are the size values used by Pettijohn (1957). In the interpretation of the cumulative curves, no importance was attached to the interruptions at 0.062 mm, caused by the difference between sieving and sedimentation analysis.

RESULTS

Results from each sample are plotted *versus* depth in Figs. 7:1–3 and in triangle diagrams in Fig. 7:4.

Solberga core – The coring at Solberga started below the dry crust – 1.2 m thick – in a silty clay at a depth of 2.1 m and reached down to firm bottom at a depth of 27.3 m below ground surface (situated about 2 m above sea level). From the top of the core there is a gradual increase in the clay

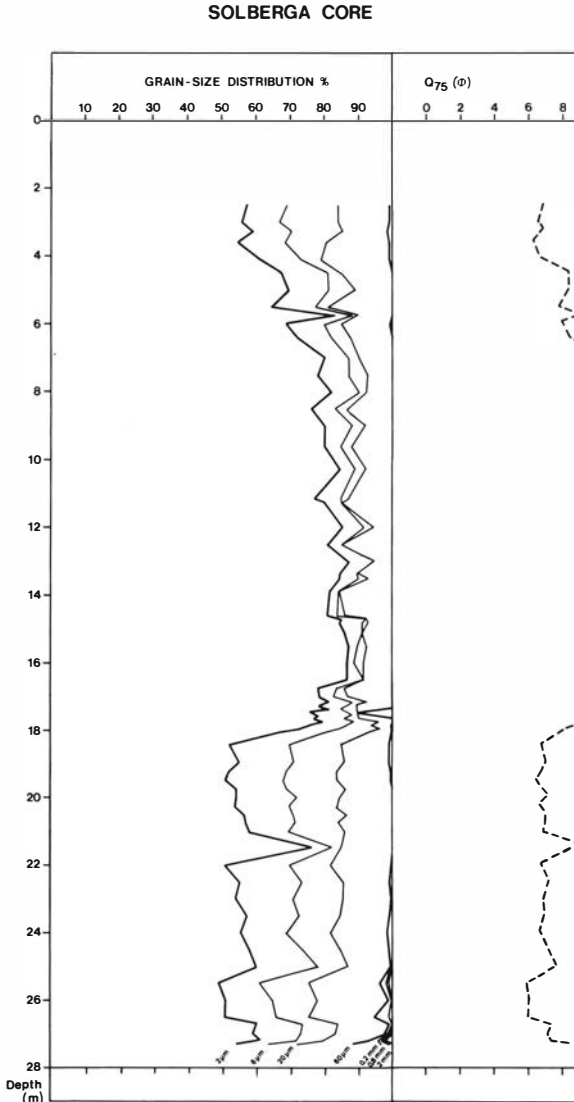


Fig. 7:1. Grain-size distribution and variation of the quartile Q_{75} versus depth in the Solberga core.

content from about 55 % to about 75 % at a depth of 6.7 m (Fig. 7:1), where the silty clay yields to a very fine-grained homogeneous clay (75–85 % $< 2 \mu\text{m}$) reaching down to about 17.5 m depth.

The sand fraction, comprising only a few per cent of the silty clay, disappears in the homogeneous clay. At a depth of 17.5 m the sand fraction appears again with a distinct peak of 10 %, but falls immediately to a few per cent and remains fairly constant to the bottom of the core.

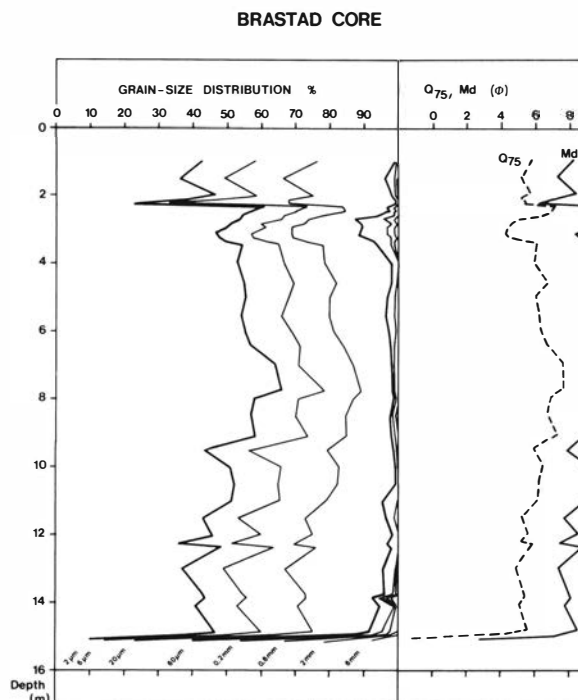


Fig. 7:2. Grain-size distribution, variation of the quartile Q_{75} and the median value *versus* depth in the Brastad core.

From the sand peak and downwards there is a simultaneous sudden drop in the clay content. The clay content decreases from about 80 % to a little more than 50 % in less than 1 m at a depth of 18.4 m. The homogeneous clay becomes a silty clay, which forms the sediment in the lower part of the core above the firm bottom. The distinct peak of the clay fraction at a depth of 21.40–21.45 m is also worthy of note.

Brastad core – The coring at Brastad started below the dry crust – 0.5 m thick – in clayey silt at a depth of 0.8 m and reached down to sand and gravel at 15.1 m below ground surface (situated about 45 m above sea level). The clayey silt at the top of the core abruptly yields to a thin silty layer (75 % silt) at 2.20–2.31 m depth (Fig. 7:2). Below this layer the core consists of silty clay, which has a maximum clay content of 65 % at 7.8 m. From this maximum, the clay content decreases progressively downwards to about 40 % and the sediment becomes a clayey silt from about 11 m down to the bottom of the core.

The sand content is with one exception fairly constant (1–4 %) from the top of the core down to a depth of about 11 m, where there is a slow increase

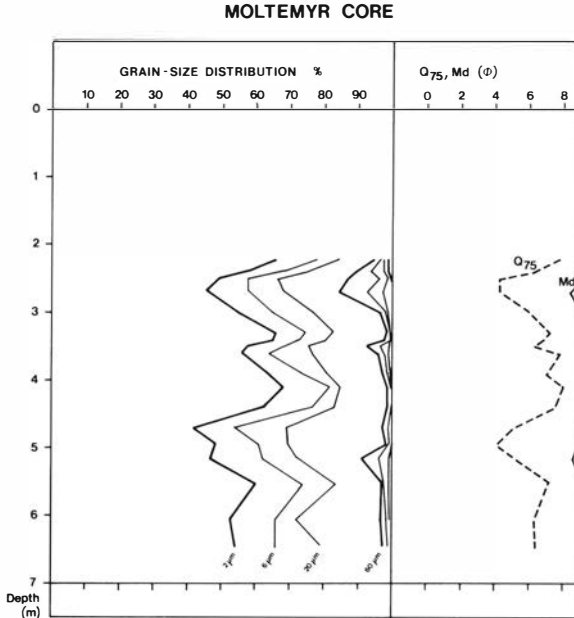


Fig. 7.3. Grain-size distribution, variation of the quartile Q_{75} and the median value *versus* depth in the Moltemyr core.

to 10 % at the bottom of the core. Below the silty layer at a depth of 2.5–3 m, the sand fraction has a peak of about 13 per cent. In the very lowest part of the core, *i.e.* the transition zone to the basal sand and gravel, the grain size increases and the deepest sample is classified as a silty sand. However, this sample was taken from the mouth piece of the Foil Piston Corer so the possibility cannot be excluded that during the coring this sediment was artificially formed by mixture of the basal sand and overlying clayey silt.

Moltemyr core – The coring at Moltemyr started in a fen peat at a depth of 0.5 m below ground surface (situated about 55 m above sea level), continued through a layer of detritus gyttja (1.65–2.12 m) down into silty clay and stopped at 6.5 m depth (clay thickness >27 m; see Chapter 4).

With the exception of a strong minimum at 2.5 m depth the clay content varies between 55 and 70 % in the upper clastic part of the sediment core (Fig. 7:3). A sudden drop in the clay content occurs at a depth of about 4.1 m. Over little more than 0.5 m the clay content decreases from nearly 70 % to about 40 % at a depth of 4.7 m. The silty clay becomes a clayey silt, which passes downwards into silty clay.

The sand fraction varies between 2 and 4 %, but three peaks occur at 2.7, 3.5 and 5.2 m depth. The sand content in the upper peak reaches 15 %, while the others contain little less than 10 % sand.

DISCUSSION OF THE SEDIMENTARY PATTERNS

The three cores Solberga, Brastad and Moltemyr contain sediments ranging from clayey silt through silty clay to clay (Fig. 7:4). The Solberga core is the most fine-grained, with a median diameter (Md) less than $2\ \mu\text{m}$ (9ϕ) throughout, while between 7 and 18 m depth the quartile Q_{75} shows that as many as 75 % of the sediment particles have a diameter less than $2\ \mu\text{m}$ (9ϕ). (See Fig. 7:1.) In general the quartile Q_{75} approaches $16\ \mu\text{m}$ (6ϕ) in the Brastad and Moltemyr cores (Figs. 7:2 and 7:3).

The grain-size composition of the cores clearly shows (with one exception in Brastad, see below) that the three sites represent stable depositional environments in the past. However, variations in the fine-grained texture *versus* depth indicate that the patterns of sedimentation changed with time. The most pronounced changes are as follows.

- 1, a distinct change in the grain-size distribution between 17.7 and 18.4 m in the Solberga core, resulting in a very homogeneous clay (80 % $< 2\ \mu\text{m}$) sequence between 17.7 and 5 m,
- 2, a sudden occurrence of a thin silt layer between 2.20 and 2.31 m in the Brastad core and
- 3, a marked change in the grain-size distribution between the levels 2.5–3 m and 3.3–3.5 m and 4.1–4.7 m in the Moltemyr core, resulting in homogeneous clay sequences.

Focussing at first on the Solberga core, the rapid but gradual decrease in the grain size from below upwards and the occurrence of a sand peak in the above-mentioned zone indicate changes in the supply and type of sediment and in the mechanisms of transportation. The different size fractions were not transported by the same means. Clay, fine and medium silt were transported in suspension while the coarser fractions travelled along the bottom.

As can be seen from the diagram (Fig. 7:1), the change from 18.4 m depth upwards starts from below with a strong increase in the clay content of the sediment, while the other fractions diminish. The first substep in the dramatic change of the grain-size composition indicates an increased supply and sedimentation of the suspended load during the period of deposition. The next substep is the occurrence of a sand peak followed by increased clay and coarse silt fractions with a simultaneous diminution of the fine- and medium-silt fraction upwards. This suggests a suddenly increased bottom transport simultaneously with the suspended load transport, which in turn indicates a sudden occurrence of currents at the time of deposition. The disappearance of the sand fraction, which is replaced upwards by coarse silt, shows that the strength of the currents was strongest at their onset.

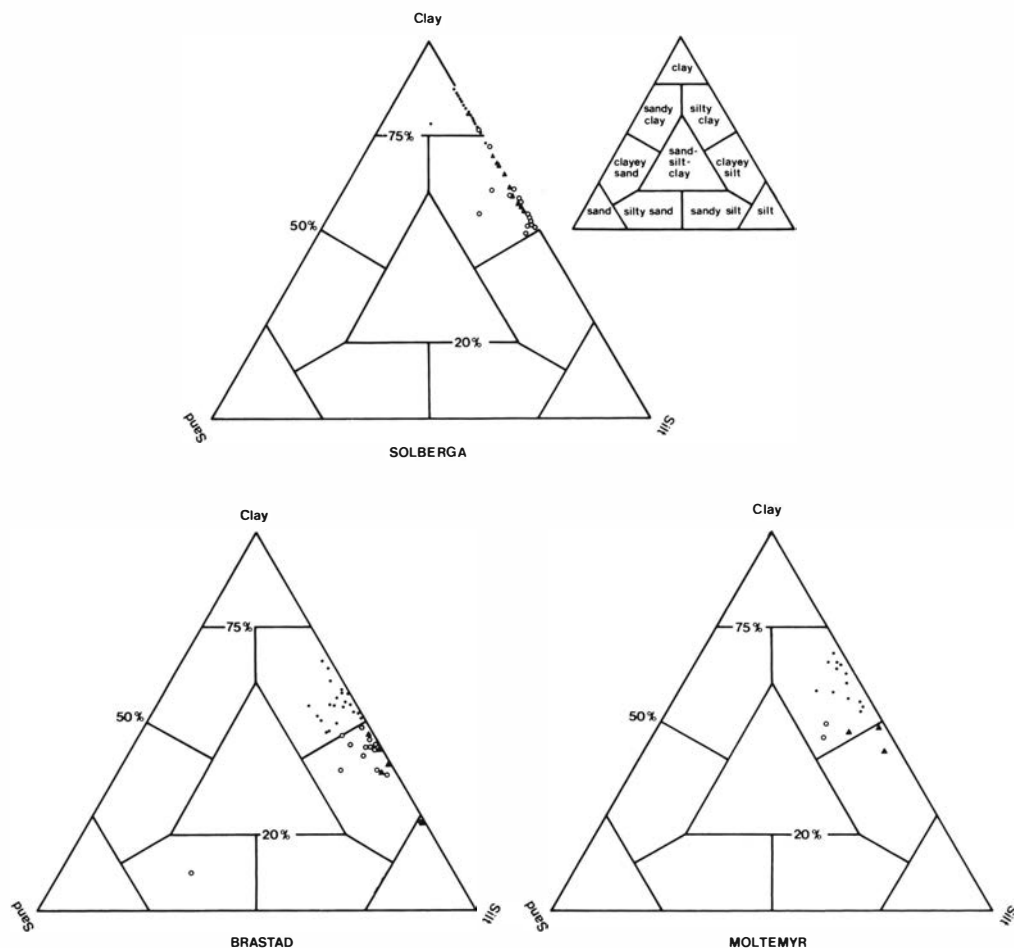


Fig. 7.4. Triangle diagrams of grain size from the Solberga, Moltemyr and Brastad cores.

The question arises, what can have caused the hydrographical conditions, which gave rise to the changed sedimentary pattern in Solberga? There is much evidence of intrusion of a water-mass with a heavy load of clay-size particles, *i.e.* the water-mass must have been transported long enough for the bulk of the coarser particle load to have settled and the current must have slackened so much, as to lose its erosive effect.

This points to the enormous discharge of meltwater, due to the intense retreat of the land ice during the Preboreal times. Approximately 500 000 km³ meltwater (see Chapter 2) and about 10 000 km³ freshwater from the Baltic Ice Lake (Strömberg 1977) were discharged into Skagerrak.

This huge quantity of water must have had a strong erosive capacity,

particularly on the first part of the approximately 250 km long drainage route. As the gradient of the mainland declined towards the coast the flow velocity of the discharged water decelerated, which caused deposition of the bottom load and the coarser material in the suspended load, followed by more fine-grained material as the velocity of the flow decreased. Only the most fine-grained material reached the coast and settled as the stream slackened and ceased.

The freshwater outflow into the marine environment causes the hydrographically mixed region thus formed (cf. *inter alios* Pritchard 1967, Bowden 1980) to act as a trap for fine-grained sedimentary material of freshwater origin. The clay-size particles flocculate in contact with salt water (Postma 1967) and settle more rapidly than when in peptized form. Clay-size particles may therefore predominate within, or in the bottom region adjoining a freshwater outflow into the marine environment, where particles measuring about 20 μm (ϕ 5.5) mainly settle (cf. Sundström 1970, Cato 1977, p. 67). This can also be seen in the Solberga core (Fig. 7:1) where the clay fraction predominates together with the coarse silt fraction (20–60 μm) above the zone discussed.

The peak in the sand fraction at Solberga probably represents the initial phase of drainage, but since the bottom transport is a much slower mode of transportation than the transport in suspension (cf. Haldorsen 1974, p. 30), the increase of the clay content occurs before the sand peak at this (during the time of deposition) further more offshore site. Higher up in the Solberga core the fine- and medium-silt fractions increase upwards when the clay content decreases and the grain-size distribution gradually returns to a more "normal", for this region, marine distribution at about 5 m depth. The lowest part of the core contains irregularities in the grain-size distribution which are typical of more or less varved glacial sediments (cf. the Tuve cores in Häger 1981).

The melt- and freshwater discharge followed two main courses; the Göta River Valley and the presumably most important one over the Uddevalla strait. The cores taken from Solberga and southwards (see below) represent the former and Moltemyr and Brastad in varying degrees the latter course.

Examination of the Brastad core revealed no clay-rich sequence as in the Solberga core. Instead there is a silt layer at 2.20–2.31 m depth, which separates clay sediments of a very different character above and below (see Chapter 6). This may indicate either a break in the sedimentation or exogenous disturbances such as slides, local erosion *etc.*

The interpretation of the Moltemyr core is far more difficult. The coarsening of the sediment from about 3 m upwards, followed by a decreased grain size at the top of the clastic part of the core is probably related to the shallowing due to the isostatic uplift and the isolation of the

site from the sea, respectively. Deeper down in the core the grain size decreases upwards at two levels, *i.e.* between 3.3 and 3.5 m and between 4.1 and 4.7 m. One of these variations may reflect the said discharge of meltwater during the Preboreal times or merely hydrographical changes of more local origin. Judging by the afore-mentioned decrease of the finer fractions, due to the shallowing of the site, it seems as though this change starts already at about 4 m depth. However, this change is interrupted by the occurrence of a peak in the sand fraction at 3.5 m depth which is directly followed by a 10% increase of the clay-, fine- and medium-silt fractions. The progress of this change resembles that found in the Solberga core rather than the change in the grain-size distribution at 4.1–4.7 m depth, which would imply that the change to a clay-rich sequence between 3.3 and 3.5 m more probably reflects the meltwater discharge in question. The very moderate increase of the finer fractions at this level in Moltemyr compared with e.g. Solberga may occur because Moltemyr is well protected by bed-rock hills, which consequently may have diminished the effect of the meltwater discharge.

CORRELATION WITH ADJACENT AREAS

The grain-size distribution of the described Solberga core is essentially the same as those observed in other deep corings in the Göteborg area (Fig. 7:5).

At Tuve, cores were obtained in connection with the geotechnical and geological investigations carried out after the landslide in 1977. The complete stratigraphy of the locality was clarified (Cato *et al.* 1981) from an undisturbed 26.5 m long core, taken outside the slide area. At a depth of about 8 m the silty clay sequence was interrupted by a 1 m thick zone containing several thin layers of silt (Häger 1981). This stratum is overlain by a 3 m thick layer characterized by a high clay content (75–80 %), a very low calcite content (Cato 1981a and b) and an extremely high incidence of planktonic freshwater diatoms (Miller 1981). The two zones were assumed by Cato *et al.* (1981) to have been formed as a consequence of the increased meltwater discharge due to the rapid ice retreat and the drainage of the Baltic Ice Lake during the Preboreal times. The initial phase of this discharge was represented by the silt layers. These zones seem to correspond to the zone 5–18.4 m at Solberga.

At Bäckebo (Sällfors 1975) the clay content in a 10 m long core from about 6.5 m downwards is about 30 % higher than in the upper part of the core. The depth of penetration of this zone of increased clay content into the 40 m thick sediments is not known. However, there are many indications

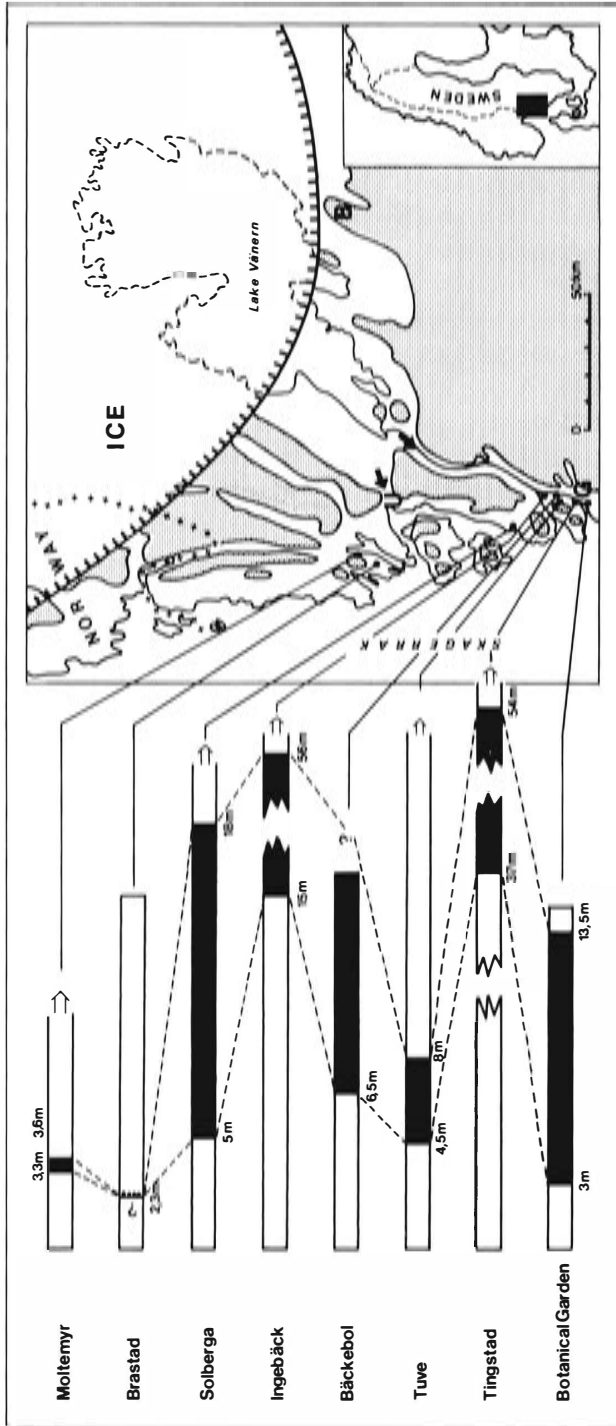


Fig. 7:5. The preliminary outlines of the extent of land (hatched areas) and ice during the opening of the Närke Strait and the presumptive main courses of the meltwater discharge to Skagerrak (black arrows). The cores show the extent, variation and position of the clay-bed originating from this drainage during the Preboreal times. B, L, U, and G denote Billingen, Lysekil, Uddevalla, and Göteborg.

that this clay-rich zone corresponds to the upper part of the Solberga zone 5–18.4 m, since the Pleistocene/Holocene boundary was found to be located at about 16 m depth (Klingberg 1977) or even deeper (see Chapter 14) in another core from Bäckebo.

The same increase of the clay content can also be seen between 54 and 56 m depth in a 70 m long core from Ingebäck (Tullström 1961) and between 51 and 54 m in a 93 m long core from Hisingen (Brotzen 1960, unpubl.).

In core B 873 from the Botanical Garden, Göteborg, (Mörner 1976) grain-size analysis was only performed on the upper 5 m. However, this part shows strong similarities with the upper part of the Solberga core. From about 3 m and down to the deepest analysis at 5 m depth in core B 873 the clay content is about 75–80 %. The water content of core B 873 is fairly constant from 3 m down to about 13 m, where it decreases by 50 %. It is likely that this change depends on a change in the grain-size distribution. If this assumption is correct the transition to the very fine clay sediment, documented in the upper part of the core, starts already at this level. Thus, the level of about 13 m depth in core B 873 corresponds to the 18.4 m level at Solberga.

In general no correlation between cores from different sites, based solely on the grain-size distribution, is possible, since the sedimentary conditions vary from place to place. However, similarities in the cores as above may be obtained. Whether or not these can be correlated, depends on whether an overall change in the sedimentary patterns due to the same hydrographical conditions occurred, and whether these patterns were strong enough to be reflected in the sediment, and bridge other processes causing changes of the sedimentary conditions at the different sites. Here these requirements seem to be fulfilled due to the enormous discharge of meltwater, which must have dramatically changed the hydrographical conditions along the former Skagerrak coast. But one can never be absolutely sure without studying other parameters.

SUMMARY AND CONCLUSION

It is thereby likely that the very fine-grained clay sequence seen in the Solberga core between 5 and 18.4 m depth also – as far as we know at present – appears with some variations in cores from the Göteborg region in the south up to the Lysekil area in the north (Fig. 7:5). Furthermore these considerable amounts of fine-grained sediments were transported to, and rapidly deposited in the Skagerrak as a consequence of the enormous discharge of meltwater from the rapidly retreating land ice during the Preboreal times. The rapid melting and retreat of the land ice was due to a

milder climate during this period. The transition into the upwards very clay-rich sequence (5–18.4 m) in Solberga at 18.4 m depth, and in other cores mentioned, may therefore indicate the improvement in the climate, and from a sedimentological point of view consequently corresponds to the transition from Pleistocene to Holocene. In Moltemyr this typical change in the grain-size composition may be seen at 3.5 m depth, while in Brastad it is lacking, probably because of a break or other exogenous disturbances in the sedimentation at 2.3 m depth.

With the exception of the uppermost 2.3 m in the Brastad core, these sites were found to represent stable depositional environments in the past.

According to Mörner (1976, p. 199) marine sediments of the Kattegatt Sea seem generally to record the change from the Younger Dryas to the Preboreal by a coarsening of the sediment; in his view the “Younger Dryas clay” is characterized by a very high clay content. It must be stressed that no such process was observed in this study; instead the opposite trend (cf. above) occurs along the Skagerrak coast.

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8. WATER CONTENT, BULK DENSITY AND ORGANIC CARBON

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METHODS

The readily oxidizable matter (organic carbon) was determined by the Walkley-Black method (Walkley and Black 1934), adopted and modified from Jackson (1962). To account for the organic carbon not readily oxidizable, the 1/0.76 factor was applied to the sediment analysis. The method excludes (up to 90–95 %) the elementary carbon present as graphite and charcoal (Walkley 1947). Proteins may also remain unoxidized (Olausson 1975). CaCO_3 has no influence on the method (Walkley 1947). The coefficient of variation for replicate analyses was determined as 3.8 % (Cato 1977).

The water content was determined as the difference in weight between a fixed quantity of wet sediment and the corresponding dry sediment which was obtained after drying at 105°C to constant weight. The content was expressed as a percentage of the weight of wet sediment. The coefficient of variation for replicate analyses was determined as 1.3 %.

The bulk density was determined by Niels Abrahamsen in connection with the magnetic sampling. Polystyrene beakers of constant volume were filled with sediment by pressing them into the undisturbed core. The samples were sealed and weighed immediately afterwards. The coefficient of variation for replicate analyses was determined as 1.2 %.

RESULTS

The results are plotted *versus* depth in the summary diagrams (see Chapter 20, Figs. 20:1a, 20:2a and 20:3a).

SOLBERGA

Organic carbon – The organic carbon content decreases progressively from about 1.7 % at the top of the core to about 0.8 % at about 4 m depth. Downwards the organic carbon content remains fairly constant to a depth of about 18.4 m where a slight increase can be observed, reaching a maximum at 19.3 m. Further down the organic carbon content varies around 0.8 % with a slight decrease at the bottom of the core. A minimum of 0.3 % occurs at 21.4 m depth, where the clay content reaches a maximum (see Chapter 7).

Bulk density and water content – The bulk density varies around 1.56 g/cc (water content 43.7 %) in the gyttja silty-clay, but decreases progressively downwards in the silty clay to a minimum of 1.45 g/cc (maximum of water content 52 %). At greater depth this change is followed by a short increase to about 1.52 g/cc (water content 47 %) at the transition to the homogeneous clay around 7 m. The bulk density and the water content then remain rather constant down to the sand peak at 17.5 m, where bulk density increases and water content decreases as the clay content sharply declines (cf. Chapter 7, Fig. 7:1). A maximum for bulk density (1.62 g/cc) and a slight minimum for water content (39 %) occur at the level (18.4 m) at which the clay content stops its downward decrease. The bulk density progressively increases downwards to about 1.7 g/cc while the water content decreases to about 30 % at the base of the core.

BRASTAD

Organic carbon – The organic carbon content is low (0.1–1 %) throughout the core and shows a very close relationship to the clay fraction. From the top of the core there is a continuous decrease downwards from 0.8 % to about 0.2 % at the bottom. A distinct minimum of 0.1 % appears in the silty layer at a depth of 2.20–2.31 m.

Bulk density and water content – The bulk density decreases from 1.9 g/cc to 1.57 g/cc while the water content increases from 20 % to 33 % from the top of the core down to a depth just above the silty layer (2.20–2.31 m).

In the silty layer, the bulk density shows a maximum peak (1.8 g/cc) and the water content a minimum peak (25 %). Below the peaks the parameters remain fairly constant (1.55 g/cc and 40 % respectively). From a depth of about 9.5 m the bulk density shows a continuous increase to 1.9 g/cc and the water content a gentle decrease to 25 % at the bottom of the core.

MOLTEMYR

Organic carbon – The organic carbon content is about 2.3 % at 2.5 m depth but drops suddenly to 0.8 % at 3 m. Another distinct decrease occurs at 3.5 m where the content falls from about 1 % to 0.5 %. Downwards the organic carbon content shows a gentle and continuous decrease to about 0.25 % at the base of the core.

Bulk density and water content – There is a more or less gradual increase of the bulk density (from 1.2 g/cc to 1.5 g/cc) with a corresponding decrease of the water content (from 88 % to 44 %) from the peat at the top of the core, down through the detritus gyttja into the gyttja silty-clay. Downwards the parameters remain fairly constant to about 3.3 to 3.5 m depth where a slight minimum and maximum occur for the bulk density and water content, respectively. At about 3.8 m depth the bulk density decreases sharply from 1.5 g/cc to 1.4 g/cc and hovers around this value down to about 4.5 m depth. The water content increases slowly to about 62 % at 4.5 m depth. At this level the water content decreases by about 20 % and the bulk density increases by 0.3 g/cc within less than 20 cm. Further down the parameters remain rather constant with a slow increase of the water content at the bottom of the core.

INTERPRETATION AND DISCUSSION

BULK DENSITY AND WATER CONTENT

The dense measurement of bulk density was used partly to differentiate lithology in considerable detail (cf. the less dense analyses of the grain-size distribution) partly to demonstrate broader variations in composition and consolidation of the sediments. The main features of the vertical distribution pattern in the cores for bulk density reflect the water content, affected by compaction, by grain-size distribution and to a smaller extent by the organic matter content.

As illustrated in Fig. 8:1, the bulk density varies inversely with the water and organic matter content of the sediment (cf. Cato 1977, p. 23). Organic matter has a density close to that of water (Revelle and Shepard 1939:265). As the diagram shows there is a wider dispersion of the data from the Brastad and Moltemyr cores compared with those from the Solberga core. Despite differences in the grain-size distribution the Brastad core shows a higher degree of consolidation.

In general, the bulk density of the cores increases and the water content decreases with increasing depth of burial. This is mainly due to the compaction of the sediment. However, variations occur as is to be expected, since the lithology is not consistent with depth. In the Solberga core the

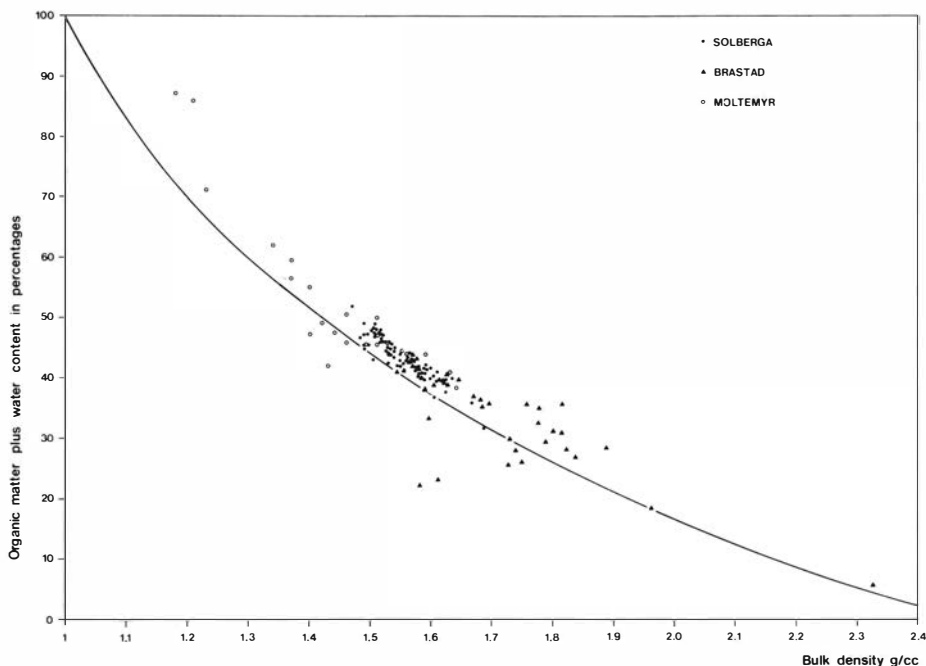


Fig. 8:1. Relationship between organic matter (organic carbon \times 1.724) plus water content and bulk density in the Solberga, Brastad and Moltmyr cores.

elevated bulk-density values and lowered water content in the upper 7 m of the core are directly related to the upwards gradually decreasing clay content. The low density values and higher water content between about 7 and 18 m reflects the very clay-rich sequence of the core (cf. Chapter 7, Fig. 7:1), with its higher porosity. The rapid downwards decrease of the clay content between 17.7 and 18.4 m depth is strongly reflected in an increase of the bulk density and a decrease of the water content. The interesting feature, however, is that the bulk density and the water content show decreased and increased values, respectively, at about 19 to 20 m depth, despite the absence of changes in the grain-size distribution. This can only result from the extremely high incidence of Foraminifera and Diatom specimens in the sediment at this level (see Chapters 14 and 16). These fossils have a spongy nature and consequently a strong water-retaining capacity, which is reflected by the bulk density and water content of the sediment. At greater depth the bulk density and water content are mainly a function of compaction.

The high bulk-density values and the upwards decreasing water content at the top of the Brastad core can not be due solely to the grain-size distribution. They also indicate exogeneous disturbances. The silty layer

between 2.20 and 2.31 m depth is clearly reflected by maximum and minimum peaks of the bulk density and water content, respectively. Further down the variations of these parameters are related partly to the grain-size distribution, partly to the increased compaction.

At about 13.3 m depth both the bulk density and water content indicate the occurrence of a silt layer, overlooked in the analyses of the grain-size distribution but seen in the visual examination of the core (see Chapter 6). This layer together with the variation of the bulk density in the clayey silt sequence (10.2–15 m depth) suggest that the bottom of the core may be varved – however, with a diffuse graded bedding not really visible during the examination of the core (Chapter 6).

The low bulk density and high water content in the upper part of the Moltemyr core reflect the uppermost high organic sediment, gyttja. At greater depth the parameters mainly reflect variations in the grain-size distribution. For example, the clay peak between 3.3 and 3.5 m and the 30 % clay decrease between 4.4 and 4.7 m (see Chapter 7) are clearly discernible from the distribution of these parameters *versus* depth. Further down the bulk density and water content weakly indicate the increased clay content, since they are mainly affected by the increased consolidation.

ORGANIC CARBON

The organic carbon content of the Solberga core is low (<1 %) and shows no variations *versus* depth, if the upper 4 m (1–2 % organic carbon) and the sequence between about 18 and 21 m (>1 % organic carbon) are excluded. The increased values within this lower zone may be due to a low sedimentation rate, *i.e.* the organic matter is less diluted with clastic particles than elsewhere in the core. The elevated values in the upper part of the core is a well-known phenomenon, due to the wave-washing and transportation of sediments from higher, emergent areas to areas still below the surface of the sea, *i.e.* postglacial sedimentation.

As a consequence of the amelioration of the climate during the Preboreal times the organic production increased (cf. *inter alios* Digerfeldt 1972, p. 87, Berglund and Malmer 1971). It is interesting that the organic carbon content does not increase in the clay-rich sequence between 7 and 17.7 m, which is here assumed to be of the Preboreal age. This indicates an increased dilution of organic matter in this sequence of the Solberga core, due to an accelerated sedimentation rate of clastic sediments poor in organic matter. The latter in turn may point to a sediment sequence of mainly allochthonous origin.

At Brastad the organic carbon content is less than 1 %. Below about 3 m it shows a close relationship to the grain-size distribution. Above this level

stronger variations occur with a sharp minimum in the silt layer between 2.20 and 2.31 m. The elevated values in the upper 2 m can be related to postglacial sedimentation (see above).

In the Moltemyr core, too, organic carbon content is less than 1 %, if the upper 3 m is excluded (peat and gyttja). It shows a close relationship to the grain-size distribution below, but not above 3 m depth. The gradual increase of the organic carbon above this level is probably caused by the progressively increased protection of the site from the sea just before its isolation. The increased organic carbon content between 3.2 and 3.5 m depth is related to the increased clay content (see Chapter 7). This implies that the sedimentation rate did not change as much as at Solberga during this phase of deposition.

SUMMARY AND CONCLUSION

The measurement of bulk density and water content *versus* depth was partly used to differentiate the lithology in considerable detail. With the exceptions given below, the results could be related to changes in grain-size distribution and to the natural consolidation of the sediments.

In general, the bulk density increased and the water content decreased with increasing depth of burial. The clay-rich sequences between 7 and 18.4 m at Solberga, between 3.3 and 3.5 m, 3.8 and 4.5 m at Moltemyr, and the silt layer at 2.2–2.3 m depth at Brastad are clearly reflected by these parameters. On the other hand the bulk density and the water-content values between 19 and 20 m in Solberga and around 1.5 m depth in Brastad show anomalies. The former is assumed to reflect the high incidence of foraminifers and diatoms at this level (see Chapters 14 and 16), while the latter is probably an effect of exogenous disturbances of the sediment.

The organic carbon content in general falls below 1 %, but in the uppermost part of the Solberga and Moltemyr cores rises to about 2 %. At Solberga this can be related to postglacial sedimentation, while at Moltemyr the gradual isolation from the sea may be of greater importance. The low organic carbon content between 7 and 17.7 m at Solberga is presumably a consequence of an increased sedimentation rate of clastic sediments of allochthonous origin.

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9. CLAY MINERALS AND CHEMISTRY

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INTRODUCTION

Clay mineral ratios were used in the earlier study of the Pleistocene/Holocene boundary, as reported by Georgala and Jacobsson (in Mörner 1976, Chapter 8). The work was based on X-ray diffraction. From the peak height of selected reflections from kaolinite, chlorite and mica the ratios of these minerals were calculated and plotted *versus* depth. Reproductions of the X-ray curves were presented in the O.R. 1973 as Figs. 1 and 2, but were omitted in Mörner 1976. The work involved laborious pretreatment of the samples and only eight were studied from a core length of about 12 m. Georgala and Jacobsson concluded that the clay mineral ratios could be of use in cases where sedimentation had occurred in salt water.

In the present study it was not possible to carry out a similar detailed study because of the number of samples involved. Rather than reduce the number of samples by selection, we tried to find parameters which could give us information without undue effort. The identification is based on X-ray diffraction (XRD) also in this study. Illite, chlorite, quartz, and feldspars are minerals present in all samples, the relative amounts being influenced by the particle-size distribution. Kaolinite is the mineral which may illustrate variations in the parent material. In the XRD curves, however, the 001–002 basal reflections from kaolinite nearly coincide with the 002–004 reflections of chlorite. The type of chlorite occurring in the samples studied has its 004 reflection at $25.2^\circ 2\theta$ while the 002 kaolinite reflection appears at $24.9^\circ 2\theta$ (CuK α -radiation). Where no kaolinite is present the chlorite peak is comparatively narrow.

With increasing kaolinite the peak broadens. Accordingly we used the width of the peak at half height as a measure of the kaolinite content. Smectite is another mineral which might provide information about source material. The smectite is best evaluated from a 17\AA peak from a glycolated specimen. The sedimented material as a whole does not consist of well crystallized minerals, easy to identify, but includes more or less amorphous material, partly weathering products, partly aggregated silica skeletons, which can be traced by a raised background in the low angle region up to

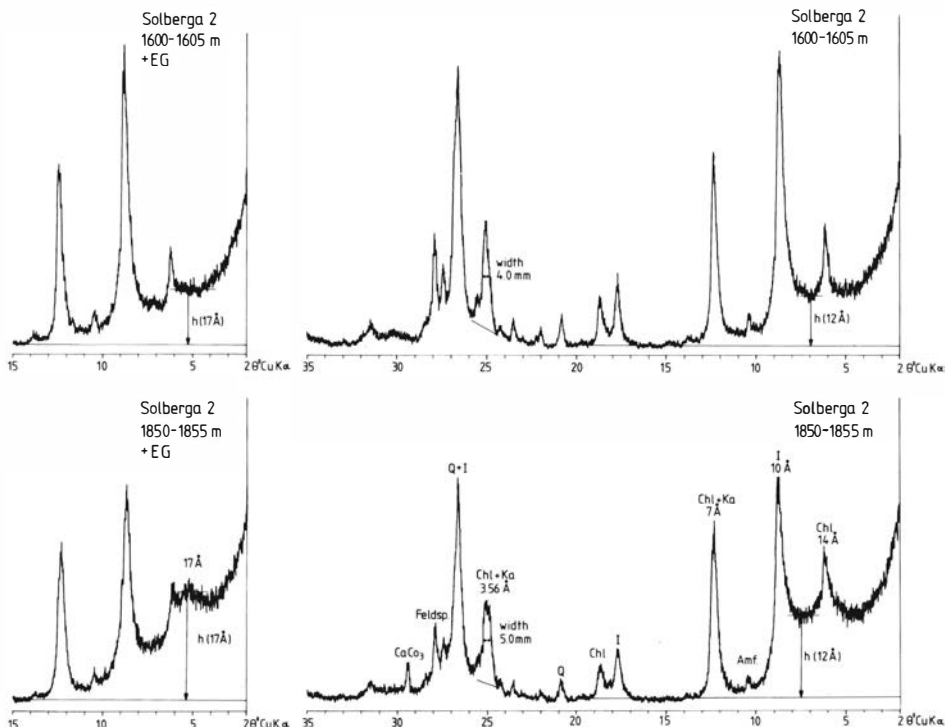


Fig. 9:1. XRD-curves of oriented samples of the clay fraction. $\text{CuK}\alpha$ -radiation, goniometer speed $1^\circ 2\theta/\text{min}$, paper speed 10 mm/min.

Right, air-dried specimen, left, glycolated specimen.

Above: typical XRD-curve above the 18 m level.

Below: typical XRD-curve below the 18 m level.

Chl = chlorite, I = illite, Amf = amphibole, Ka = kaolinite, Q = quartz, Feldsp. = feldspars, CaCO_3 = calcite.

about 10\AA (the 001-illite peak). They are here classified as mixed layer material, and the height at 12\AA above a constructed background conveys an idea of the amount present. The parameters used may be seen in Fig. 9:1, where curves from two different levels are reproduced. We feel justified in using the above parameters, because of the similarity in the preparation of the specimens, and because the samples from the first core to be studied, Solberga, showed a monotonous character for over 16 m whereafter changes suddenly became evident.

SAMPLE PREPARATION

The samples were moist on arrival. Without drying, 5 g of each sample were dispersed in 200 ml of distilled water and disintegrated with the help of

ultrasonic vibration and manual stirring. Some of the samples coagulated because of the presence of salt. The supernatant solution was decanted and a new portion of distilled water added. After settling, a portion (15 ml) was withdrawn, calculated to contain particles $<2 \mu\text{m}$, and filtered through a membrane filter (Millipore, size 47 mm diam., $0.45 \mu\text{m}$ pore size). The clay cake on the filter was transferred to a glass slide (Drever 1973), dried in air and XRD curves were made. The specimen was then placed in an ethylene glycol (EG) vapour bath at 60°C , and left there at least over night. New XRD curves were taken of the EG-specimens.

CHEMICAL ANALYSIS

It was considered of interest to know whether variations in the chemical composition, *i.e.* preferably the trace elements, of the sediments could give information on the source material. A "direct" survey of the freeze-dried powdered material was made by X-ray fluorescence. The errors can be great by this method but, because of the similarity of the samples and the fact that the analytical work was performed on one occasion, incline to believe that the values are comparable. From the data, CaO and S, and the relationship Rb/Sr and K/Rb were extracted and plotted *versus* depth.

The cores from Brastad and Solberga were both studied in this way. The results may be seen in Figs. 9:2 and 9:3, while the analytical data are listed in Tables 9:1 and 9:2.

CORES STUDIED

- Solberga – 35 samples were selected for the XRD-work and 41 samples for the chemical determinations.
- Brastad – From this core 22 samples were selected for the XRD work and the chemical determinations.
- Moltemyr – From this core too 22 samples were selected. XRD work only.
- Vägen – A preliminary survey, only, was made including 10 samples.

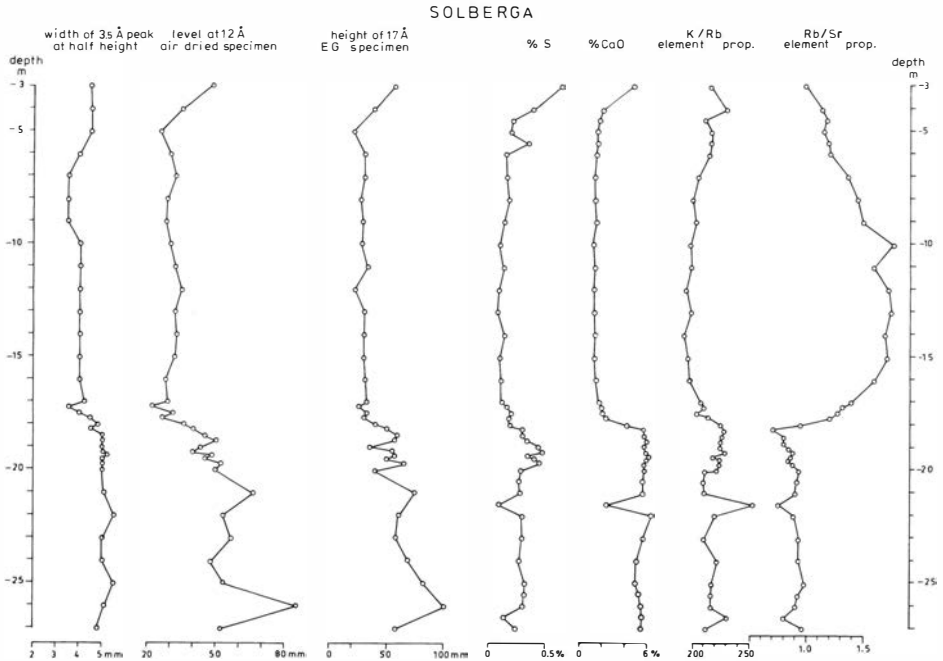


Fig. 9:2. Results from the Solberga core.

RESULTS

Solberga— The results from the chemical analysis are listed in Table 9:1. The XRD work is compiled in Fig. 9:2, which also includes % S, % CaO and the elementary proportions of K/Rb and Rb/Sr.

At about 18–17 m a change occurs in the sedimentary material. From here upwards the sediment is very monotonous, we have no calcite in the fine fraction, very low frequency of smectite components and a relatively lower content of kaolinite than is found below this level. From between 17 and 18 m downwards the sediments have a different character. They hold kaolinite, fine-grained calcite, smectite and weathered material of poorly crystallized phyllosilicates. There is also a higher sulphur content, and at 18 m gypsum is present.

The CaO-curve shows a marked change between 18 and 17.7 m depending on a change in the calcite content. The deviation of the CaO-curve at the level 21.50–21.55 m, reflected also in the other chemical components, has been checked by X-ray diffraction of a nonfractionated sample at this level and of the samples above and below. The anomalous sample shows a lower clay content and higher contents of quartz and

TABLE 9:1. SOLBERGA. Chemical analyses of freeze dried samples, element ratio of Rb/Sr and K/Rb.

IDENT	depth m	Na ₂ O %	MgO %	Al ₂ O ₃ %	SiO ₂ %	P ₂ O ₅ %	K ₂ O %	CaO %	TiO ₂ %	MnO %	Fe ₂ O ₃ % tot	S %	Rb ppm	Sr ppm	Rb/Sr	K/Rb
S 1	3.00	2.10	3.61	18.01	57.7	.17	4.32	4.57	.77	.08	7.29	.62	183	188	0.97	214
S 2	4.00	2.51	3.43	18.78	57.4	.18	4.57	2.05	.70	.09	7.21	.37	183	163	1.12	227
S 2B	4.50	3.31	3.38	18.48	60.3	.19	4.83	1.74	.73	.10	7.24	.20	209	180	1.16	209
S 3	5.00	2.99	3.37	18.28	59.9	.19	4.75	1.54	.71	.10	7.22	.18	200	175	1.14	215
S 3B	5.50	3.02	3.41	18.21	58.9	.18	4.72	1.50	.69	.09	7.58	.33	200	169	1.18	214
S 4	6.00	2.93	3.30	17.96	56.9	.18	4.59	1.43	.68	.09	7.22	.15	195	164	1.19	214
S 5	7.00	2.96	3.41	19.18	57.3	.19	4.76	1.35	.66	.09	7.93	.15	212	157	1.35	203
S 6	8.00	2.97	3.53	19.52	57.2	.19	4.83	1.36	.69	.10	8.39	.16	221	154	1.44	198
S 7	9.00	2.95	3.59	19.69	58.5	.21	5.03	1.39	.70	.10	8.12	.13	226	153	1.48	202
S 8	10.00	2.72	3.87	20.67	56.8	.20	5.28	1.21	.72	.10	8.74	.09	243	138	1.76	197
S 9	11.00	2.72	3.63	19.98	56.9	.19	5.06	1.30	.68	.10	8.39	.12	232	147	1.58	197
S 10	12.00	2.78	3.71	20.37	57.7	.20	5.20	1.18	.71	.09	8.31	.09	244	143	1.71	193
S 11	13.00	2.66	3.76	20.43	57.3	.19	5.20	1.24	.73	.10	8.71	.06	238	137	1.74	198
S 12	14.00	2.67	3.74	20.13	57.2	.20	5.19	1.34	.76	.10	8.94	.13	246	146	1.68	191
S 13	15.00	2.67	3.83	20.20	56.6	.20	5.21	1.32	.73	.11	9.13	.08	243	143	1.70	195
S 14	16.00	2.78	3.74	20.10	57.0	.20	5.14	1.43	.75	.11	8.80	.10	236	149	1.58	197
S 15	17.00	2.80	3.51	19.13	57.8	.20	5.03	1.69	.73	.10	7.86	.11	220	158	1.39	207
S 16	17.25	2.82	3.48	19.18	59.0	.20	4.96	1.94	.74	.11	7.91	.14	217	166	1.31	208
S 17	17.50	2.90	3.43	18.95	59.3	.20	4.91	2.06	.72	.10	7.76	.18	218	172	1.27	204
S 18	17.75	2.88	3.32	18.90	59.7	.20	4.86	2.26	.72	.10	7.33	.17	208	173	1.20	212
S 19	18.00	2.45	3.23	17.21	56.8	.18	4.32	4.11	.73	.09	6.75	.19	175	186	0.94	224
S 20	18.25	2.26	3.23	16.45	55.6	.18	4.02	5.57	.74	.09	6.62	.29	161	229	0.70	226
S 21	18.50	2.10	3.22	16.42	56.3	.17	3.95	5.64	.74	.09	6.53	.29	159	200	0.80	225
S 22	18.75	2.01	3.17	15.96	54.8	.17	3.85	5.85	.75	.09	6.54	.32	156	196	0.80	224
S 23	19.00	2.00	3.22	16.45	54.7	.17	3.85	5.57	.74	.10	6.84	.42	157	187	0.84	223
S 24	19.25	2.01	3.36	16.69	55.6	.17	3.90	5.85	.76	.10	7.13	.46	156	179	0.87	227
S 25	19.45	1.92	3.43	16.84	56.9	.18	4.00	6.12	.79	.10	6.98	.33	167	195	0.86	217
S 26	19.55	1.97	3.30	16.25	56.2	.17	3.85	5.81	.76	.10	6.91	.39	157	186	0.84	223
S 27	19.75	1.97	3.33	16.29	56.7	.17	3.93	5.69	.77	.11	7.06	.43	160	184	0.87	222
S 28	20.00	2.01	3.37	16.72	57.9	.18	4.05	5.70	.79	.09	7.03	.27	174	187	0.93	211
S 28B	20.50	2.06	3.36	16.93	56.9	.19	4.15	5.61	.79	.11	7.37	.25	180	197	0.91	209
S 29	21.00	2.21	3.44	17.19	57.4	.20	4.22	5.53	.79	.11	7.56	.27	183	203	0.90	210
S 29B	21.50	3.04	2.54	16.27	64.2	.21	4.46	2.27	.69	.10	5.19	.08	160	214	0.75	252
S 30	22.00	1.80	3.37	16.92	54.8	.18	4.05	6.19	.80	.09	7.41	.29	169	192	0.88	218
S 31	23.00	1.79	3.38	17.34	56.8	.21	4.16	5.56	.80	.11	7.54	.29	179	194	0.92	210
S 32	24.00	1.86	3.33	17.26	56.8	.20	4.14	5.02	.77	.11	7.48	.26	170	183	0.93	221
S 33	25.00	1.68	3.37	17.64	56.8	.19	4.26	4.85	.78	.09	7.50	.31	178	181	0.98	217
S 33B	25.50	1.66	3.36	17.11	55.5	.19	4.11	5.15	.78	.09	7.23	.31	172	187	0.92	216
S 34	26.00	1.64	3.39	17.27	56.8	.19	4.18	5.40	.78	.09	7.26	.29	175	194	0.90	216
S 34B	26.50	1.62	3.33	17.34	56.2	.18	4.18	5.49	.75	.09	6.52	.13	165	207	0.80	229
S 35	27.00	1.72	3.48	18.37	57.2	.18	4.57	5.26	.81	.10	7.45	.23	196	205	0.96	211

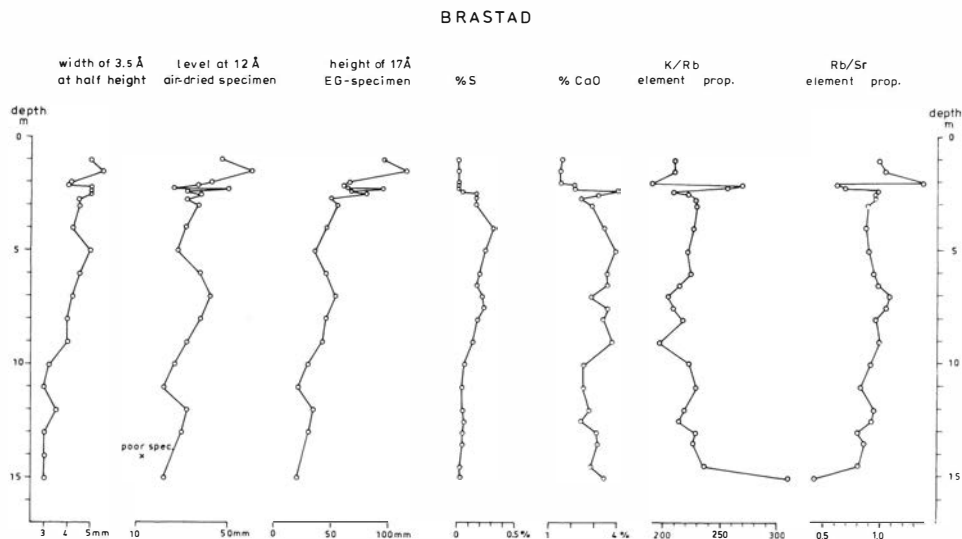


Fig. 9:3. Results from the Brastad core.

feldspar than the surrounding samples. The proportion of potassium feldspar to plagioclase is higher in the anomalous than in the surrounding samples where it is quite low. Table 9:1 indicates that K_2O has a peak at the level in question. The K/Rb relation also shows a deviation which may be traced to the potassium feldspar. It may be mentioned that just above this layer, low in clay minerals, a clay peak has been registered at 21.40–21.45 m.

The relationship K/Rb for different minerals was studied by *inter alia* Reynolds (1963) who found that K/Rb in feldspars tends to be higher than K/Rb in micas. The implication for Solberga would be a higher mica content from about 18 m upwards, and/or an altogether different origin of the parent material.

In the profile the change in the Rb/Sr proportion follows the change in the CaO-content, Sr being closely related in chemistry to Ca. A high Ca concentration is accompanied by high Sr and in consequence a low Rb/Sr proportion.

Brastad – This core shows a different development from the Solberga one. From 15 m upwards there is an increase in both the kaolinite content and the smectite material, and above 2.5 m the layers seem to be disturbed. An increase in the smectitic layers can be observed, but may be due to secondary weathering.

TABLE 9.2. BRASTAD. Chemical analyses of freeze dried samples, element ratio of Rb/Sr and K/Rb.

IDENT	depth m	Na ₂ O %	MgO %	Al ₂ O ₃ %	SiO ₂ %	P ₂ O ₅ %	K ₂ O %	CaO %	TiO ₂ %	MnO %	Fe ₂ O ₃ tot %	S %	Rb ppm	Sr ppm	Rb/Sr	K/Rb
B 1	100-105	2.09	2.83	17.23	62.1	.18	4.28	1.60	.78	.08	7.00	.01	185	188	0.98	210
B 2	150-155	1.89	3.01	17.69	61.8	.20	4.35	1.52	.78	.07	7.05	.01	188	181	1.04	210
B 3	200-205	1.99	3.25	18.31	60.8	.20	4.72	1.53	.77	.09	8.69	.01	226	164	1.38	190
B 4	215-220	2.66	2.01	14.97	66.8	.22	4.18	2.09	.60	.08	4.27	.01	141	227	0.62	269
B 5	225-230	2.76	2.16	15.95	66.8	.22	4.47	2.12	.69	.08	4.84	.01	158	230	0.69	256
B 7	240-245	1.87	3.38	18.06	60.2	.19	4.39	3.99	.80	.10	7.32	.04	191	194	0.98	209
B 8	250-255	1.90	3.28	18.29	61.3	.19	4.39	3.20	.79	.12	6.84	.16	180	188	0.96	221
B 9	275-280	1.97	3.27	18.11	62.8	.19	4.36	2.42	.76	.10	6.27	.16	177	184	0.96	224
B 10	300-305	1.97	3.30	17.91	62.8	.19	4.30	2.87	.76	.09	6.15	.16	170	191	0.89	229
B 11	400-405	2.27	3.47	17.80	61.0	.19	4.47	3.41	.76	.10	6.85	.31	179	206	0.87	227
B 12	500-505	1.94	3.47	17.90	59.4	.19	4.47	3.99	.77	.10	6.94	.24	184	205	0.90	221
B 13	600-605	1.97	3.46	17.45	58.1	.18	4.46	3.52	.77	.10	6.91	.19	180	192	0.94	224
B 13B	650-655	2.02	3.56	18.59	60.0	.19	4.63	3.41	.79	.10	7.00	.17	196	198	0.99	214
B 14	700-705	1.92	3.69	18.51	59.2	.19	4.78	3.52	.83	.10	7.54	.21	213	197	1.08	204
B 14B	750-755	1.86	3.71	19.05	58.5	.19	4.71	3.75	.81	.10	7.57	.23	205	195	1.05	208
B 15	800-805	2.23	3.61	17.52	58.9	.18	4.57	2.86	.80	.11	7.18	.18	191	198	0.96	217
B 16	900-905	2.11	3.79	18.01	59.5	.18	4.71	3.57	.83	.11	5.44	.14	205	208	0.99	196
B 17	1000-1005	2.47	3.71	18.79	60.2	.18	4.54	2.54	.79	.13	6.91	.06	185	202	0.92	222
B 18	1100	2.54	3.60	18.06	61.8	.18	4.45	2.55	.77	.12	6.22	.04	176	212	0.83	229
B 19	1200	2.39	3.88	18.33	60.0	.18	4.64	2.80	.82	.14	7.11	.05	192	202	0.95	219
B 19B	1250	2.59	3.75	18.19	60.9	.19	4.59	2.44	.80	.13	6.74	.06	195	213	0.92	214
B 20	1300	2.42	3.50	18.27	61.3	.18	4.45	3.08	.75	.13	6.25	.05	176	221	0.80	229
B 20B	1350	2.34	3.81	17.30	59.1	.18	4.46	3.12	.77	.14	6.56	.05	179	210	0.85	226
B 21	1450	2.44	3.54	17.15	61.5	.18	4.44	2.89	.76	.13	6.13	.03	171	213	0.85	236
B 22	1503-1509	2.98	1.92	14.22	69.7	.16	3.52	3.47	.46	.07	3.19	.03	104	247	0.42	311

Moltemyr – The samples along this core all show very similar XRD patterns and no distinct change like that found at Solberga can be observed. From 3.30 m downwards, however, the contributions of kaolinite to the 3.5 Å peak are quite clear and may indicate a change corresponding to the Solberga one at 18 m (see Chapter 20, Fig. 2a). In addition there is a slight increase in the smectite component, although more marked, in the samples from the 3.40 m levels downwards. It is very difficult to define a boundary as the material seems to be very consistent throughout the core, and some variations may even depend on variations in the preparation of the XRD-mounts. Variations in the rate of sedimentation seem more likely than an altogether different origin of the material. No chemical analysis has been made of this core.

The results from Vågen are preliminary and will not be discussed in detail in this report.

CONCLUSION AND DISCUSSION

At Solberga all the results indicate a change in the sedimentation conditions close to a depth of 18 m. Below this level the sedimentation was relatively slow. The parent material was rich in weathering products and is similar to deposits now present in Quaternary clays in Skåne and Denmark. Calcite is present and may derive from chalkey material. Above 18 m the sediment is monotonous up to the top of the core. No calcite is present in the clay fraction and weathered material is scarce apart from the very top. Illite, chlorite, quartz, and feldspars are the chief components, minerals normally found in Quaternary clays in central Sweden. The change seems to have occurred, when large quantities of meltwater brought material from northern and eastern Sweden to the south-western region.

It may be of interest to compare the CaO-curve (chiefly representing CaCO_3) at Solberga with the results from core B873 (Mörner 1976, p. 255) and Tuve (Cato 1981). The low CaO-content between 4 and 18 m at Solberga may be correlated with the section in core B873 between 3 and 13.5 m which shows a low calcite content apart from a few isolated peaks. At 13.5 m there is a sudden increase in calcite similar to the finding at Solberga at about 18.5 m. At Tuve the section between 4.5 and 7.5 m is low in calcite and may correspond to the above-mentioned section in core B873 and the interval 4–18 m at Solberga.

As regards the mineralogy a direct comparison of the results reported by Georgala and Jacobsson (1976) is difficult because of the few samples studied and the different techniques used in presenting the findings. Nevertheless thanks to Georgala, I had the opportunity to see reproductions

of the X-ray curves from the report quoted as O.R. 1973: Figs. 1 and 2. These curves clearly show that in core B873 the sample 113 at 13.9 m is similar to samples from the lower part of the Solberga core, *i.e.* below 18.5 m, the background level at 12\AA is high, and both smectite and interstratified minerals are present. The sample 105, in core B873 close to 12.8 m, is clearly of the type above 17 m at Solberga, low in background level at 12\AA and poor in smectite minerals. Judging by the diagram Fig. 8:3 in Georgala and Jacobsson (1976) there is an increase in kaolinite between the two samples mentioned (113 and 105), corresponding to the findings in the Solberga core between 18 and 17 m. The two upper samples of core B873 (*viz.* Nos 1 and 15 above 2.5 m) again show an increase in the 12\AA background level and the smectite content, as also found at Solberga above 5 m, which in the present case was interpreted as due to secondary weathering.

It may be concluded from the comparison of results that the change in mineralogy reported between levels 13.9 and 12.8 m in core B873 corresponds to the change at Solberga between 18 and 17 m.

The Brastad core is more difficult to interpret. The fluctuations at the top may well be due to secondary weathering or to displacement of the sediments.

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10. STABLE ISOTOPES

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INTERPRETATION OF $^{18}\text{O}/^{16}\text{O}$ DATA

The $^{18}\text{O}/^{16}\text{O}$ ratio using foraminifers in marine carbonates depends on the isotopic ratio of ambient sea water and the temperature. This is apparent from the equation

$$T = 16.5 - 4.3 (\delta_c - \delta_w) + 0.14 (\delta_c - \delta_w)^2$$

where T is the temperature, δ_c the isotopic ratio of the sample (calcite), and δ_w the isotopic ratio of the water in which the fossil (calcite) was formed (Emiliani 1955). The δ_w normally varies between +1 (high pressure areas)

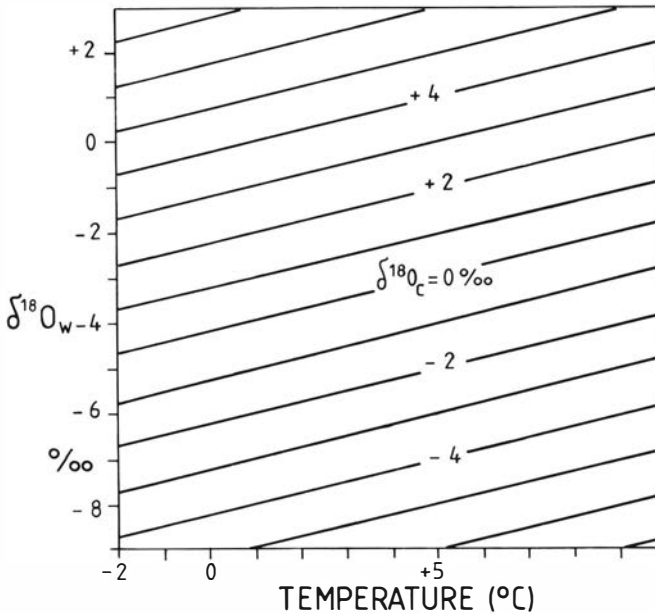


Fig. 10:1. A. Graphic relation between temperature and the $^{18}\text{O}/^{16}\text{O}$ ratio according to Emiliani (1955). δ_c is the isotopic ratio of the sample (calcite), and δ_w the isotopic ratio of the water in which the fossil was formed.

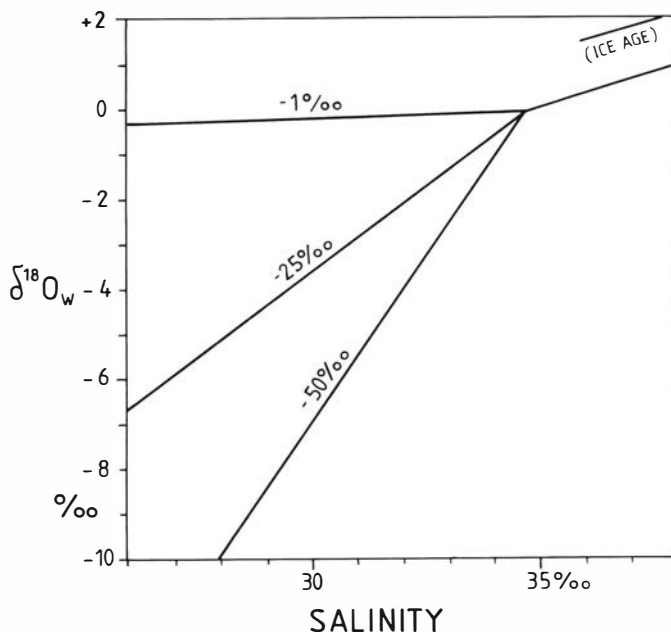


Fig. 10:1. B. The relation between salinity and the δ^{18} of sea water mixed with equatorial rain water ($\delta^{18} = -1$ per mil), with meltwater such as that from the Scandinavian ice sheet (-25 per mil) and with very light meltwater (e.g. meltwater from central Antarctic).

and -1 per mil (where precipitation exceeds evaporation) but decreases below -1 where river supply and, particularly, meltwater contributions are appreciable. The δ^{18} of ice sheets is very low (-30 to -55 per mil) and meltwater injection thus exerts a strong influence on the δ_c of foraminifers. Due to the waxing and waning of ice sheets and their gradual δ_{ice} changes, the δ_c generally has a peak-to-valley amplitude of about 1.5 per mil (see further Olausson 1981). A temperature increase also gives more negative δ_c values, as does a meltwater addition.

In the above equation δ^{18}_w is necessary in order to calculate T (temperature). By knowing the δ^{18}_w the salinity of ancient water can be estimated. In this context the δ^{18}_w derives from sea water mixed with meltwater from the disintegrating Scandinavian ice sheet. Below this ice sheet calcium carbonate was precipitated on rocks (see e.g. Samuelsson 1964). This carbonate could give us an approximate δ^{18} value of the meltwater. Therefore, a few such samples have been analyzed. The samples were kindly placed at my disposal by Sven-Åke Larsson, Geological Survey of Sweden. The following results (in per mil and relative to PDB) were obtained:

	$\delta^{13}\text{O}_c$	$\delta^{18}\text{O}_c$
Västra Frölunda (11°55'E; 57°40'N)	-3.7	-18.8
—''—	-4.4	-19.1
Torslanda (11°46'E; 57°43'N)	-4.3	-17.3
—''—	-4.0	-19.1
Hovenäset (11°17'E; 58°22'N)	-3.9	-21.6
—''—	-3.8	-21.4
Sotenkanalen (11°16'E; 58°22'N)	-3.5	-18.8

These data indicate that in central Bohuslän, the δ^{18} of the water below the ice was about -25 per mil, and about -23 per mil in the Göteborg area. The δ^{18} values of the carbonate support the theory that it was precipitated below an ice sheet, and the δ^{13} values suggest that the water was primarily non-marine. Consequently, $\delta^{18}_w = -25$ can be used as a (minimum) value for the meltwater injections in western Sweden, which is discussed further below. The conversion from δ_w to salinity appears in Fig. 10:1.

MELTWATER SPIKES

The additional ice stored in the ice sheets during the Weichselian was of the order of $50 \cdot 10^6 \text{km}^3$. During deglaciation this water was returned either more or less gradually during the warm temperate phases or more abruptly when large ice lakes were drained. This meltwater spread on top of the sea water, retarding the mixing processes of the ocean so that a salinity stratification and, in some instances (e.g. in the Eastern Mediterranean), even a stagnation developed (Olausson 1961, 1965, 1969 and in press, Worthington 1968, Berger *et al.* 1977). These meltwater discharges are responsible for the δ^{18} signals named meltwater spikes. The light sea-surface layer also gave rise to a lower δ_w in precipitation, as suggested by the decline of δ_c in Swiss lakes during the Alleröd (see Eicher *et al.* 1981, Fig. 2) The large isochronous drop in δ_{ice} from -35 to -40 per mil in the Camp Century core could also be a result of the same event if Fisher's time-scale (1979) is used.

One of the largest ice-margin lakes was the Baltic Ice Lake, 1 500 km in length, which adjoined the south-eastern margin of the Scandinavian ice sheet. When this ice sheet receded from Fennoscandian terminal moraines the lake surface was lowered 26–28 m and some 10^4km^3 of meltwater was suddenly discharged into the Skagerrak. The drainage presumably occurred 10 163 years B.P. (Donner and Eronen 1981). During the Preboreal meltwater from the disintegrating Scandinavian ice sheet ($\sim 5 \cdot 10^5 \text{km}^3$) was also discharged into the Skagerrak. This volume is equal to a 1.5 m thick layer over the oceans, or a 12 m thick "lid" on the North Atlantic.

BRASTAD

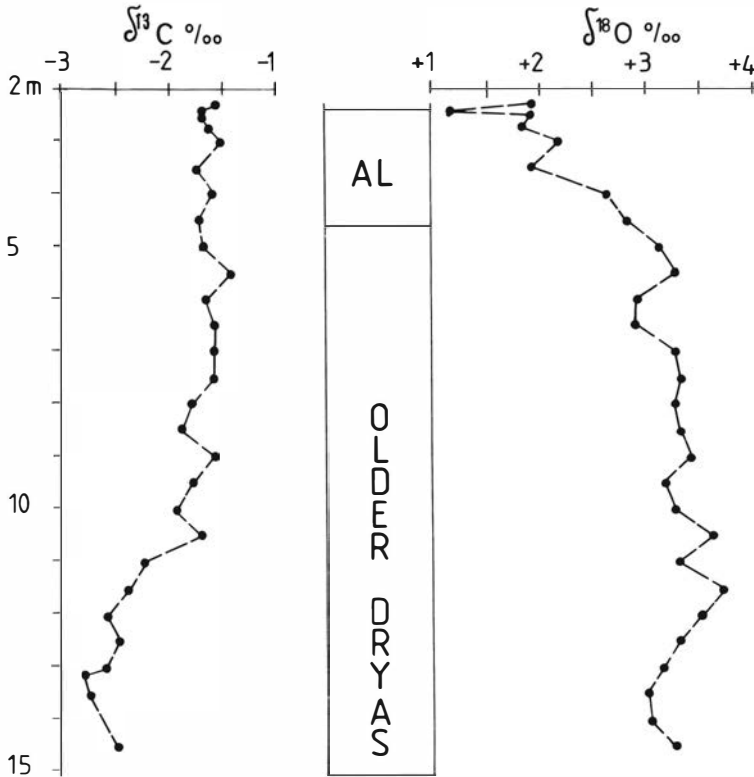


Fig. 10:2. Carbon and oxygen records relative to PDB in the Brastad core (58°23.4'N; 11°31.2'E). AL = Alleröd chronozone.

ISOTOPE ANALYSIS

Isotope analysis was performed on the benthic Foraminifera *Elphidium excavatum* from four sediment cores (Figs. 10:2–5). This Foraminifera is an indicator of the bottom-water conditions. No plankton organisms in sufficient number were available to give information regarding the surface-water conditions. The microscopical preparation was carried out by Karen Luise Knudsen (the Brastad, Moltemyr and Solberga cores) and L-M Fält (the Tuve core), the chemical treatment by Rosa Svensson, and the mass-spectrometer work by Owe Gustafsson. All data are given relative to PDB.

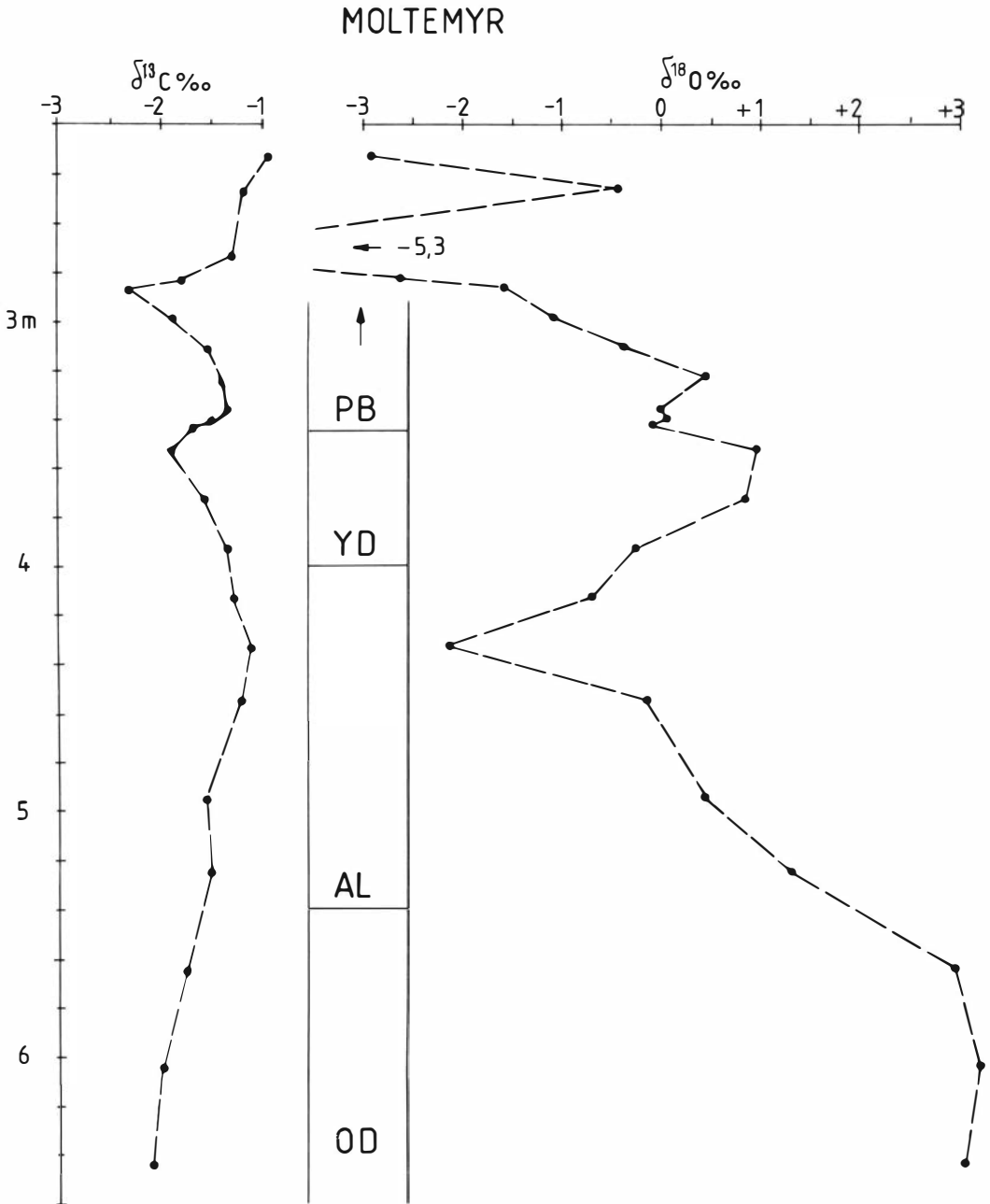


Fig. 10:3. Carbon and oxygen records relative to PDB in the Moltemyr core (58°26.5'N: 11°32.4'E). OD = Older Dryas, AL = Allerød, YD = Younger Dryas, and PB = Preboreal.

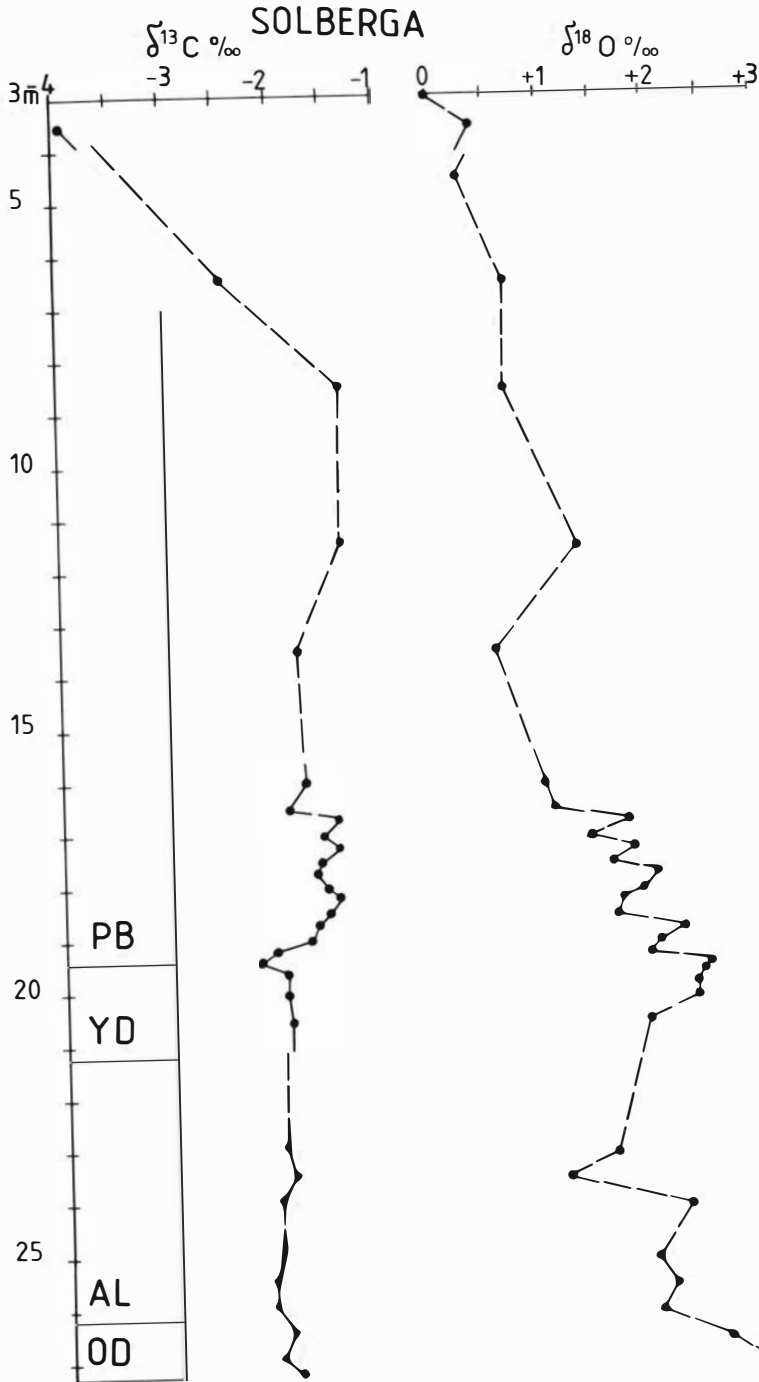


Fig. 10:4. Carbon and oxygen records relative to PDB in the Solberga core ($57^{\circ}57'N$; $11^{\circ}47.4'E$). OD = Older Dryas, AL = Alleröd, YD = Younger Dryas, and PB = Preboreal.

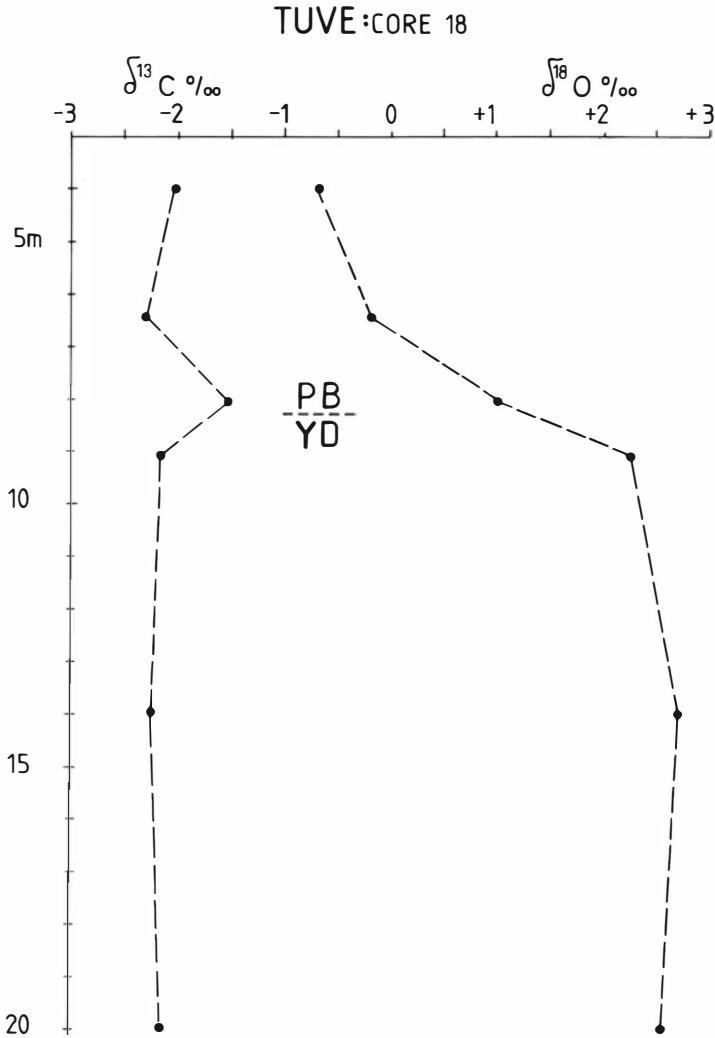


Fig. 10:5. Carbon and oxygen isotope records relative to PDB in the Tuve core ($57^{\circ}45'N$; $11^{\circ}56'E$). YD = Younger Dryas and PB = Preboreal.

OLDER DRYAS

The $\delta^{18}C$ in the Older Dryas sections approaches +3 per mil in all three cores (Fig. 10:6). This means a δ_w somewhere between -1 and -2 per mil (and uniform bottom-water conditions). The glacial δ_c of benthic foraminifers from the Atlantic is around +5 per mil (Shackleton 1977) which indicates a 2 per mil lighter bottom water in the inner Skagerrak than in the Weichselian Atlantic and about 3 per mil lower salinity if the excess water was of glacial origin with a $\delta^{18}O = -25$ per mil.

ALLERÖD

The $\delta^{18}\text{O}_c$ declines in the early Alleröd substage and diminishes by 5 per mil to -2 o/oo in the Moltemyr core, and 2 per mil, down to $+1$ o/oo, in the Brastad and Solberga cores. This is the first real meltwater injection observed in these cores (the supposed Böllig interstadial at ~ 14 m in the Brastad core revealed only a 0.25 o/oo lowering in δ_c). One possible explanation is that the deglaciation during the Bölling was comparatively slow in Bohuslän (cf. Mörner 1969) so that the ice front during the Alleröd could have been rather close to Moltemyr (the Berghem terminal moraine) or, at least, that a meltwater outlet was relatively near. – The δ_c drop in the Moltemyr core would correspond to a salinity reduction in the bottom water by some 6 per mil.

YOUNGER DRYAS

The meltwater content decreased in the bottom water during the Younger Dryas. The increased δ_c in the Moltemyr core was $+1$ and in both the Solberga and the Tuve core $+2.5$ per mil.

THE PLEISTOCENE/HOLOCENE BOUNDARY
AND THE PREBOREAL

There is again a decrease in the $\delta^{18}\text{O}_c$ at the presumptive Pleistocene/Holocene boundary. During the Preboreal it drops 6 per mil in the Moltemyr core, down to -5.3 o/oo followed by an increase. In the Solberga core the drop is less than half of that in the Moltemyr core from $+1.5$ to -1 per mil, and in the Tuve core the δ_c decreases from about $+2$ to -0.7 o/oo. – The salinity of the bottom water in the Moltemyr region could have decreased to near $3/4$ of that which prevailed during the Younger Dryas. A much smaller salinity decrease occurred in the Göteborg region.

The water depth at the onset of the Holocene was about 50 m at Solberga, around 30 m at Moltemyr, Brastad and Tuve and around 10 m at the Botanical Garden, Göteborg, (Miller, Chapter 16). We have no direct information as to the δ_w of the surface water and how well the water was mixed or stratified. However, the hydrographic conditions in present estuaries (see e.g. Bowden 1980, pp. 40–41) suggest that a salt wedge estuary existed in the Uddevalla–Dalbo area and in the Göta River almost throughout the period following deglaciation. The main outlet was through the Uddevalla Sound. When the outflow was high the salt wedge was more

or less ejected from the estuary, and the water flowing through the sound was only meltwater. Due to the higher discharge through the Sound at Uddevalla, the flow created stronger erosive conditions in central than in southern Bohuslän. Outside, in the easternmost Skagerrak, part of the meltwater mixed with the bottom water; twice as much in the Moltemyr area as in the calmer and less mixed waters in the Göteborg region.

This interpretation of the ancient hydrography allows better understanding of the formation of the gigantic shell beds in Uddevalla at that time (the Bräcke shell bank is the largest Quaternary shell bank in the world). Further, the hiatus in Brastad could be due to a strong reaction current. Only in well protected areas, such as Moltemyr, (and nearby Sämstjärn; see Fries 1951, p. 171) could sedimentation continue through the period when the connection with the Baltic existed.

¹³C

There is an increase in the $\delta^{13}\text{C}$ of *Elphidium excavatum* in the Brastad core, from the minimum in the 'Bölling' section up to 7.5 m (from -3 to -1.5 ‰). Above this level the $\delta^{13}\text{C}$ is rather constant. In the adjacent Moltemyr core the same trend can be found (from -2 to -1 ‰). The variation is larger in its Holocene section, which suggests a limnic influence.

The $\delta^{13}\text{C}$ in the Solberga section starts from -2 ‰, becomes irregular in the Preboreal, but remains around -1.5 ‰ up through the clay section. The terrestrial-limnic influence is obvious in the uppermost 6-7 m.

CONCLUSION

The best indications of a global change from glacial conditions to an interglacial are meltwater spikes. There are two large ones in our data: in the Alleröd and in the Preboreal chronozones. The intervening, cooler Younger Dryas substage, assumed to be 800 years in length, has not been identified in the southern hemisphere. Furthermore, such a short interval can hardly be recognized in deep-sea cores with their generally low resolution (± 2000 years; see Berger, Chapter 22). Therefore, the isotopic meltwater anomaly in deep-sea cores is, at present, recognized only as a single, continuous phase.

In the Bohuslän part of the expanded Skagerrak area the meltwater supply was stronger in the Preboreal than in the Alleröd substage. The Baltic Ice Lake and the subsequent deglaciation of Scandinavia should have contributed enormously during the Preboreal substage. This meltwater supply should also be recognized in the deep-ocean sediment as an isotopic signal,

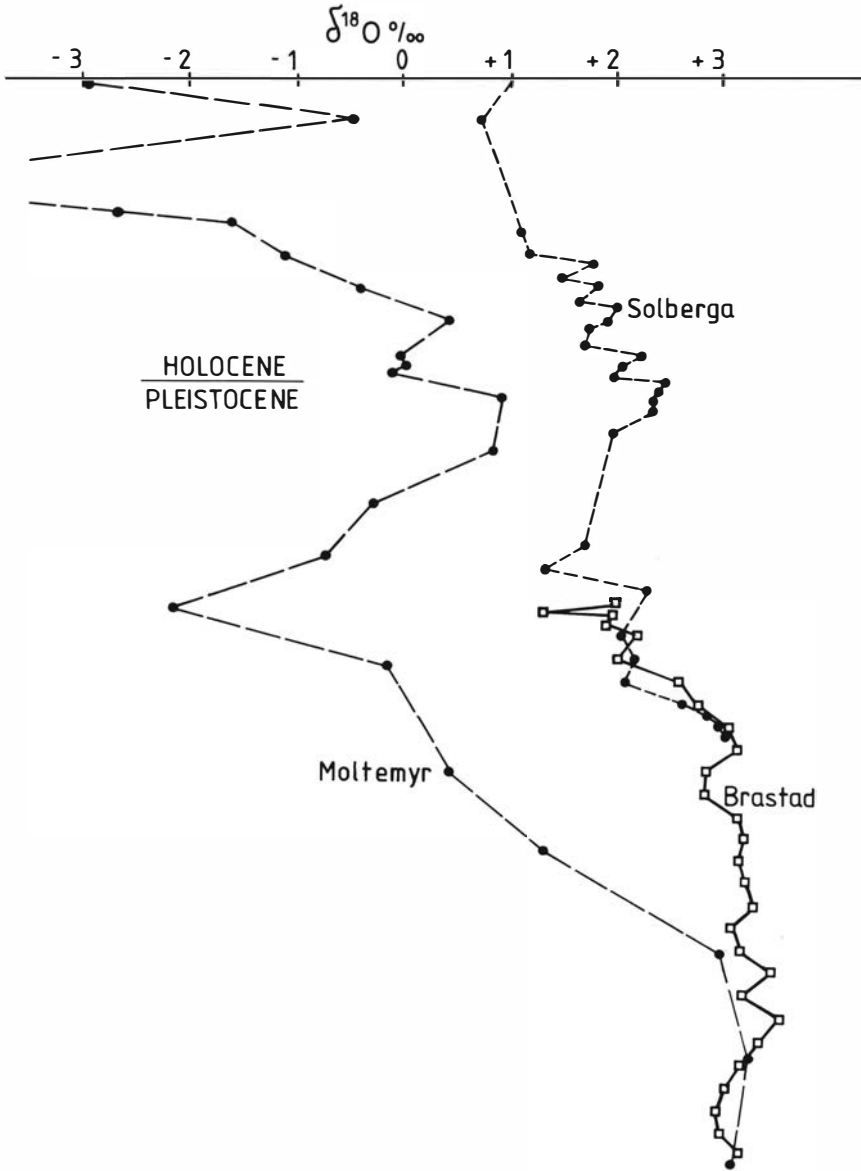


Fig. 10:6. Chronostratigraphical correlation of the oxygen records given in Figs. 10:3-5.

enlarged by the meltwater addition through other outlets of disintegrating ice sheets and drainages of peripheral lakes. As shown in Figs. 10:3-4, the meltwater spikes are obvious in both the Moltemyr and Solberga cores. The δ^{18} changes are, however, stronger in the former area than in southern Bohuslän.

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11. MAGNETOSTRATIGRAPHY

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INTRODUCTION

Virtually all sediments carry a remanent magnetization (RM), the direction and intensity of which is a function of the geological history of the sediment in question. The magnetic properties are complex functions of mineralogy, grain size, biological activities, diagenesis, lithological disturbances and variations of the geomagnetic field during and after deposition.

The purpose of the present work is to present the magnetic signals stored in three continuous sediment cores from Solberga, Brastad and Moltemyr, north of Gothenburg, and to deduce some palaeomagnetic and magnetostratigraphical results from these records.

SAMPLING TECHNIQUES

SOLBERGA AND BRASTAD

Azimuthally oriented vertical cores were obtained in the field with the help of a 66 mm Piston Foil Corer (see Chapter 4), the north direction being carefully indicated by means of small plastic plugs ($\pm 2^\circ$) in each core section. In the laboratory radiographs were made, and the declination and horizontal intensity preliminarily measured on the core sections mounted in plastic liners on a Digico vertical spinner magnetometer (Molyneux 1971).

The palaeomagnetic subsampling was performed together with the lithological description and joint sampling of the whole core for the stratigraphical, lithological and palaeontological studies. Cylindrical 1" x 1" polystyrene beakers were pressed into the cleaned, undisturbed sediment orthogonal to the core axis, and with common azimuthal orientation. The magnetic sampling interval was usually 10 cm, except around the suspected Pleistocene/Holocene transition, and around declination anomalies in the preliminary magnetic record, where the sampling interval was condensed to 3–5 cm.

The palaeomagnetic specimens were sealed with a lid and weighed immediately afterwards to give the bulk density (wet), the volume being

constant. This bulk density proved to be a rapid and easily determined, useful indicator of lithological changes, which in combination with the preliminary magnetic intensity record served to focus the attention on the suspected Pleistocene/Holocene boundary, enabling a denser sampling around this depth for various other purposes already at this early stage of the joint investigations.

MOLTEMYR

At Moltemyr a somewhat different procedure was followed, as a magnetic pilot study was first made on a 1 m long piston core section (2.5 to 3.5 m depth), and later on a 14 m long by 37 mm thick piston foil core (Moltemyr 1981) was sampled and palaeomagnetically investigated in detail.

MAGNETIC TECHNIQUES

Besides the whole core vertical spinner measurements of the natural remanent magnetization (NRM) which were essentially used as a guide for the magnetic subsampling, the subsequent measurements of the remanent magnetizations (RM) of the oriented specimens were also made on the Digico spinner magnetometer. The spin time was adjusted to allow an accuracy in direction of $\pm 2^\circ$ for intensities $> 1\mu\text{G}$ ($\cdot 10^{-3}$ A/m).

After measurement of the NRM intensity J_o , the stability of the remanent magnetization was tested by alternating field demagnetizations in zeroed earth field ($\pm 10\gamma$). Most specimens were subjected to stepwise demagnetizations with peak alternating fields of 100 and 300 Oe, and every fifth specimen was further demagnetized in fields of 500, 900, and 1500 Oe peak.

Finally, the reversible bulk susceptibility k of all specimens was measured in a 1 Oe (1 kHz) susceptibility bridge with a noise level of $3 \cdot 10^{-7}$ G/Oe ($4\pi \cdot 3 \cdot 10^{-7}$ SI), and the modified Koenigsberger ratio $Q = J_o/k$ computed.

MAGNETIC MEASUREMENTS ON SOLBERGA CORE

INTENSITY

The intensity J_o of the NRM is shown in Figs. 11:1b and 11:2a, the general range being between 0.8 and 10 μG ($\cdot 10^{-3}$ A/m). On the whole the intensity varies broadly from a maximum at 26 m to a minimum at 12 m and a maximum again at 6 m.

Through most of the core the intensity varies fairly smoothly, apart from the depth intervals 17 m to 13.2 m and 7 m to 5 m, where the scatter is notably higher. This probably reflects a higher variability in the grain size or

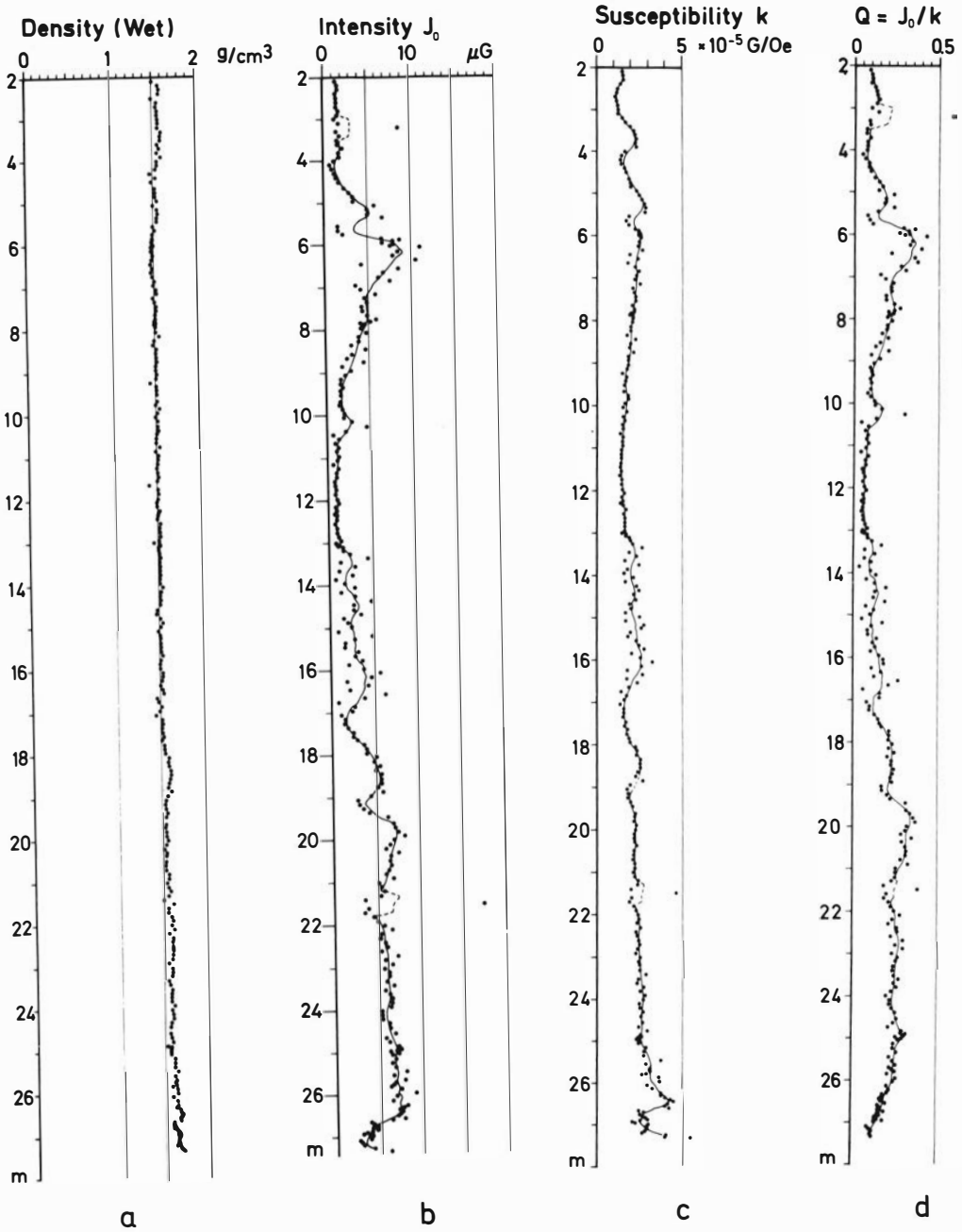


Fig. 11:1. Density, NRM intensity J_0 , susceptibility k and modified Koenigsberger ratio $Q = J_0/k$ of the Solberga core. Continuous curves are 5-point moving averages; depth in metres.

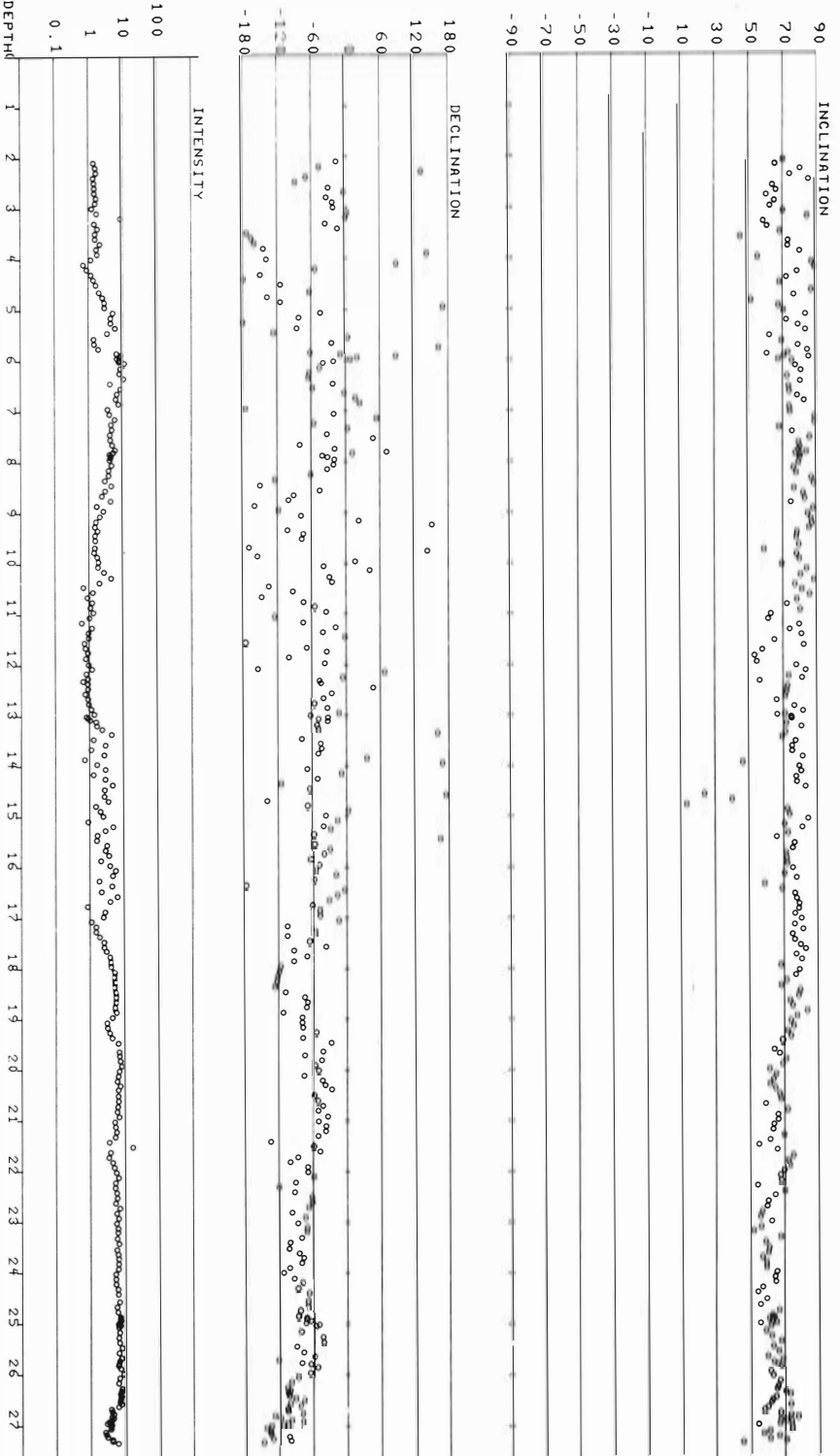


Fig. 11:2a-c. Intensity (log scale), declination and inclination of the Solberga core. Individual measurements; curves are 5-point moving averages. Swings in the declination and inclination are labelled D1 through D8 and I1 through I13, respectively. a. Solberga, NRM.

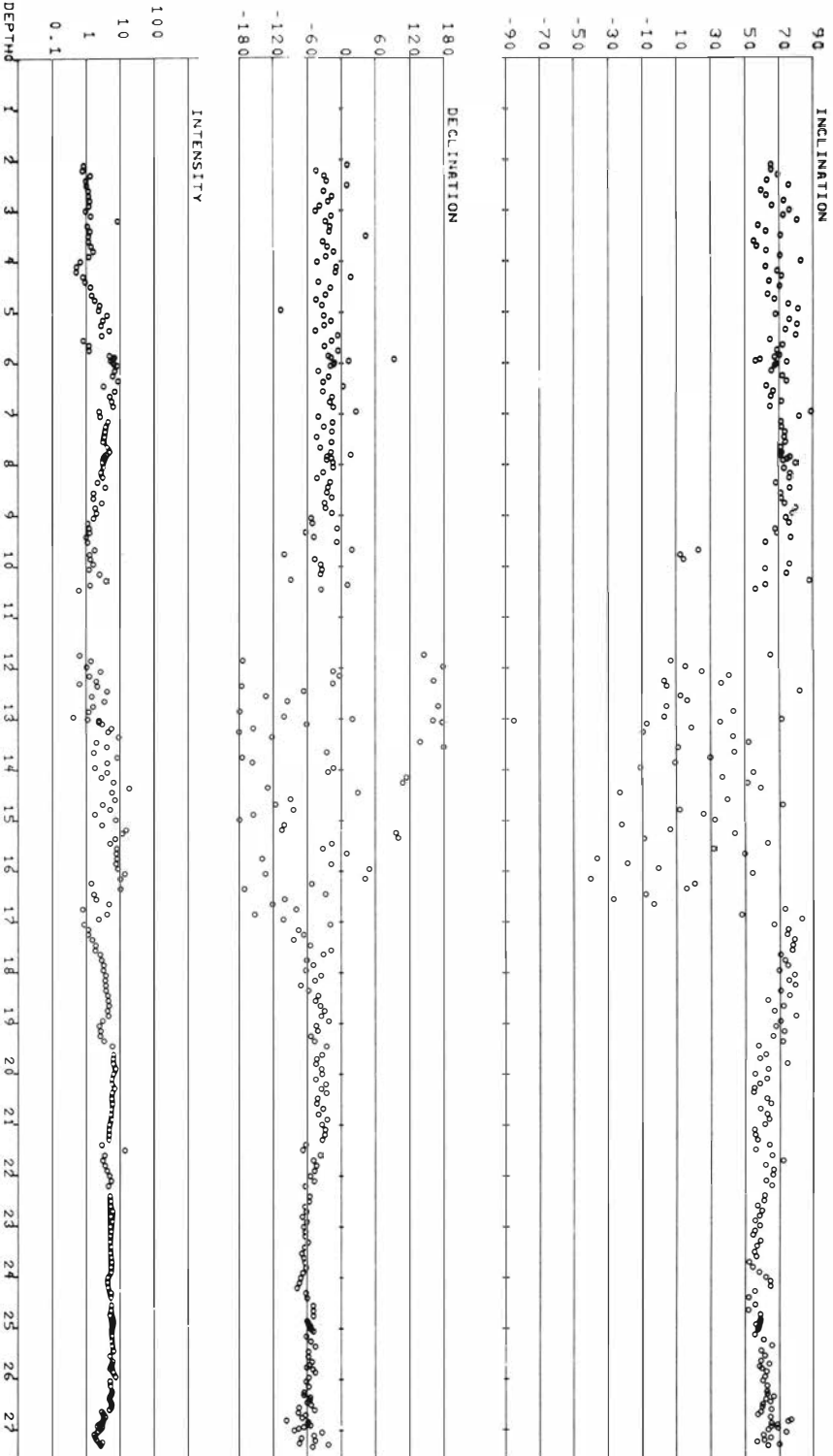


Fig. 11:2b. Solberga, F = 100 Oe.

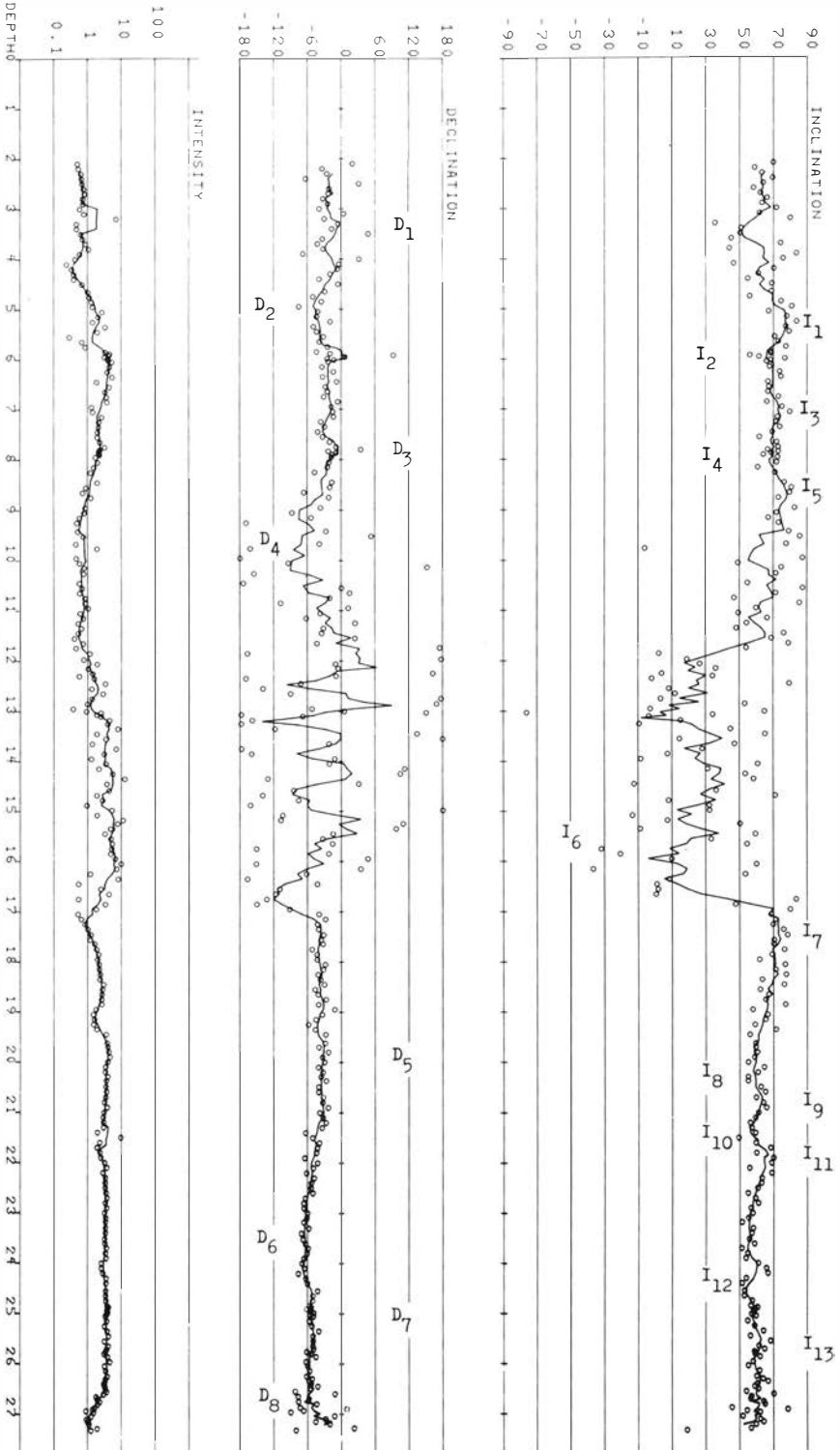


Fig. 11.2c. Solberga, F = 300 Oe.

content of the ferromagnetic minerals, and hence indicates a variation in depositional and environmental conditions, such as e.g. grain-size distribution, bioturbation, slumping, water depth, turbulence, salinity, and/or temperature. This is further discussed below.

The low intensity values $<5 \mu\text{G}$ at the bottom up to 26.6 m are probably caused by the higher sand content in the clay. Between 26.6 m and 19.45 m the intensity is relatively smooth and constant (between 5 and 8 μG), except for a local minimum at 21.4–21.7 m with one isolated high value. At 19.4–19.0 m the intensity drops significantly, and above another well defined offset at 18.95 m a very smooth decrease until 17.0 m is found, probably indicative of some systematic change in lithology and/or environment.

Between about 17 and 9 m the intensity is systematically low, at first rather scattered with a mean level about 3 μG , but above 13.2 m with constant values around 1 μG up to 10.4 m. Above a local peak at 10.2 m the values gradually increase up to a (somewhat scattered) peak of 8 μG at 6 m depth. Above a local minimum between 5.8 and 5.5 m the intensity finally decreases and stabilizes around 1–2 μG at the top.

SUSCEPTIBILITY

The reversible susceptibility k varies between 10 and 50 $\mu\text{G}/\text{Oe}$ ($\cdot 4\pi\text{SI}$), and is obviously strongly correlated with the intensity, as the susceptibility record (Fig. 11:1c) is in many respects a mirror image of the intensity record. This is the case too with regard to the scatter between 17.0 and 13.2 m and to the position of peaks and gradually broad changes. However, the susceptibility variation is smoother, the range of variation relatively smaller, and the peaks generally less pronounced, apart from those at 26.5 m and 3.8 m, which are barely noticeable on the intensity record.

It thus appears that on the whole we may assume that the integrated contribution of the individual ferromagnetic particles to the NRM intensity and the reversible low field susceptibility are approximately proportional; hence the compositional variations should tend to be cancelled when forming the Q-ratio, the magneto-sedimentary properties being roughly constant (except for the 'diluted' interval, as discussed below).

Q-RATIO

The modified Koenigsberger ratio $Q = J_o/k$ shown in Fig. 11:1d varies in general between 0.05 and 0.4. Between 27 m and 6 m about 3/4 of a fairly regular sinusoidal cycle appears to be present, followed by a sharp decrease in the Q-ratio above 6 m. Taking the broad sinusoidal minimum around 13 m as 0.06, and the broad maximum around 22 as 0.30, this corresponds to a variation between 33% and 167% of the broad mean value of $Q = 0.18$.

Provided that the suggestion concerning the individual ferromagnetic particles above is correct, this wide variation in the Q-ratio is likely to mirror the geomagnetic field intensity variations at the site during the deposition of the sediment, the NRM intensity being proportional to the inducing field. Correlations with sequences of equal ages and non-variant lithology may thus be possible. The relative variation is slightly higher than the average global intensity variations of the geomagnetic field (between about 50% and 150%) for the last *c.* 9 000 years inferred from palaeointensity studies on archaeomagnetic materials (Bucha 1970, Kovacheva 1980, Shaw 1979).

DIRECTIONS OF REMANENT MAGNETIZATION

The intensity of the NRM has already been commented upon in relation to the susceptibility and Q-values of Fig. 11:1 (linear scales). In Fig. 11:2a the NRM intensity is replotted on a logarithmic scale together with the (true) declination and inclination, while Figs. 11:2b and 11:2c show the intensity, declination and inclination after partial demagnetizations in zeroed earth field with alternating peak fields of 100 and 300 Oe, respectively.

The NRM declination (Fig. 11:2a) is fairly well defined with moderate scatter between 27 m and 17 m depth, whereas above this level the declinations are more discrete, although a systematic pattern is still visible. The local mean of the declination is systematically westerly, with an overall mean around 60° west.

The NRM inclination generally varies between 50 and 90° with a few low values around 15 m, the overall mean value being close to the central axial dipole inclination of 71° at the site. A broad sinusoidal variation is apparently present, with maximum at 27 m, minimum at 23–25 m, and generally high values above 19 m.

Turning to the partially demagnetized values, at 100 and 300 Oe in Figs. 11:2b and 11:2c, the importance of magnetic cleaning is clearly demonstrated, as both records have significantly changed: The cleaned declination records generally show less scatter than the uncleaned NRM values, and hence are likely to give a better estimate of the geomagnetic declination pattern. We still observe a higher scatter in declination between 17 and 9 m (as well as in intensity between 17 and 13 m).

Between 27 and 17 m two cycles in the declination are seen (D_8 , D_7 , D_6 , D_5 in Fig. 11:2c) with amplitudes of 10 to 15°, and between 12 and 3 m another double cycle (D_4 , D_3 , D_2 , D_1) with amplitudes between 15 and 20° may be present. These amplitudes are of the same magnitude as that of present day secular variation as known from historical and archaeomagnetic records, as well as from post-glacial lake sediments in England (Creer *et al.*

1972) and Poland (Creer *et al.* 1979) and late-glacial sediments in Denmark (Abrahamsen and Knudsen 1979, Abrahamsen and Readman 1980).

The cleaned inclination records with $F = 100$ Oe (Fig. 11:2b) and $F = 300$ Oe (Fig. 11:2c) show a systematic secular variation pattern between 27 and 17 m (I_{13} – I_7), and between 9 and 2 m (I_5 – I_1) with amplitudes of between 4 and 7°. Between 17 and 12 m, however, the inclination values have been significantly lowered by the cleaning process (I_6), the majority of values now falling between -30 and $+50^\circ$, although the scatter has increased. The increased scatter may be due to some kind of disturbance, followed by a postdepositional partial remagnetization in the present steeply inclined field direction as caused by the increasing freshwater flux discussed below.

At the same level, the declination is very scattered too, variations up to $\pm 180^\circ$, and the intensity and the Q-ratio are low. The age of this scattered low-inclination interval is somewhat younger than 10 000 years B.P. See further discussion below.

MAGNETIC MEASUREMENTS ON BRASTAD CORE

INTENSITY

The NRM intensity J_0 is shown in Fig. 11:3b on a linear and in Fig. 11:4a on a logarithmic scale. Between 15 and 8 m the intensity reaches a relatively high level, between 20 and 40 μG , with a sharp drop at 8 m to a level around 5 μG between 8 and 3 m. From 3 to 2.3 m the intensity decreases to around 1 to 2 μG and remains low except for a sharp peak at 2.3 m, which coincides with a lithological hiatus also present in the density record (Fig. 11:3a).

SUSCEPTIBILITY

The susceptibility (Fig. 11:3c) varies more smoothly from high values at the bottom about 100 $\mu\text{G}/\text{Oe}$ to a level of 30 to 40 $\mu\text{G}/\text{Oe}$ between 8 and 3 m. Above 3 m the susceptibility approaches 15 $\mu\text{G}/\text{Oe}$, except for a peak at the hiatus at 2.3 m. Both major trends and minor anomalies in the susceptibility record are clearly discernible in the density record of Fig. 11:3a, too.

Q-RATIO

The Q-ratio increases fairly smoothly from 0.2–0.3 at the bottom to about 0.6 at 8.5 m, with a sudden drop above 8 m to a level of between 0.1 and 0.2. Moreover in Q there is a peak at the hiatus at 2.3 m.

Both the intensity and the Q-ratio records suggest rather significant lithological (and hence environmental) changes at 8 m, 3 m, and 2 m, whence any conclusions about the palaeointensity would be problematic. The density and susceptibility records show a smoother variation around 8 m. All parameters clearly indicate the hiatus at 2.3 m.

DIRECTIONS OF REMANENT MAGNETIZATION

The directions (declination and inclination) of the NRM are shown in Fig. 11:4a, while Figs. 11:4b and 11:4c illustrate the same parameters after partial demagnetizations in zeroed earth field with alternating peak fields of 100 and 300 Oe, respectively; in Fig. 11:4c a 5-point moving average has been superposed on the data.

The declination of the primary data is rather scattered, whereas in the cleaned data the scatter has diminished considerably. In Fig. 11:4c about half a cycle of a broad-scale, secular variation is seen, the declination being around 60°E at the bottom (d_7), decreasing to about 60°W at 5 m depth (d_2), and increasing to around 0° at the hiatus at 2.3 m. At the top of the core, the declination again varies rapidly to about 60°E (d_1). The latter trend towards the east above the hiatus (*i.e.* of postglacial age) may be correlated with an equivalent eastward change, recorded in some Ancyclus-Yoldia sedimentary cores from the Baltic Sea east of Bornholm (Abrahamsen, in prep.).

The NRM inclination data mostly vary between 60° and 80°, while the cleaned data are lowered slightly to between 60° and 70° in most cases, the overall mean being 5° to 10° below the axial dipole inclination of 71°. In the cleaned data about 5–6 short period cycles with amplitudes of 4° to 8° appear ($i_{11}-i_1$) superposed on a broad cycle with maximum at 14 m, minimum around 10 m, maximum around 6 m and minimum at 3 m.

MAGNETIC MEASUREMENTS ON MOLTEMYR CORE

INTENSITY

The NRM intensity J_0 is shown in Fig. 11:5b on a linear, and in Fig. 11:6a on a logarithmic scale. Below 15 m depth the intensity is relatively high (13 to 22 μ G). Between 15.0 and 14.7 m the intensity decreases to about 5 μ G. Between 14.7 and 7.1 m it remains fairly stable with values typically between 5 and 8 μ G (depths between 14.7 and 9.7 m), the mean level gradually increasing to around 10 μ G (9.7 to 7.1 m) and with local peaks around 11, 9.6, 9.2, 8.6, and 7.9 m. After a sharp drop at 7.1 m to 4 μ G, the intensity gradually decreases to about 2 μ G at 5.1 m. Between 5.1 and 4.3 m a rapid oscillation (0.3 to 12 μ G) is seen, and above 4.3 m the level finally stabilizes around 1 to 2 μ G.

SUSCEPTIBILITY

The susceptibility k (Fig. 11:5c) shows essentially the same trends as the intensity. Three levels with high (~ 50 μ G/Oe), intermediate (~ 30 μ G/Oe) and low (~ 10 μ G/Oe) average values are found below 15 m, between 15 and

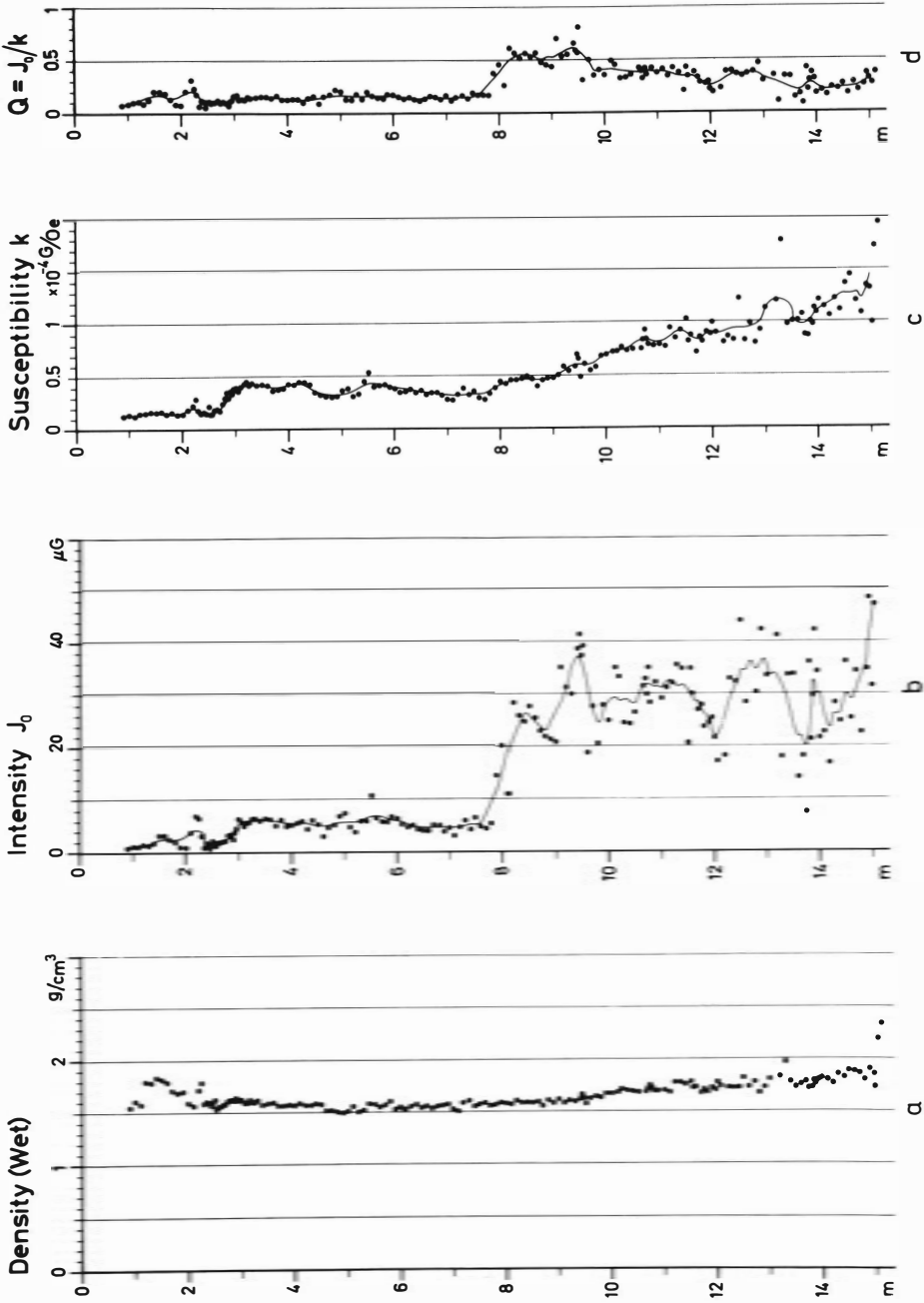


Fig. 11:3. Density, NRM intensity J_0 , susceptibility k and modified Koenigsberger ratio $Q = J_0/k$ of the Brastad core. Continuous curves are 5-point moving averages; depth in metres.

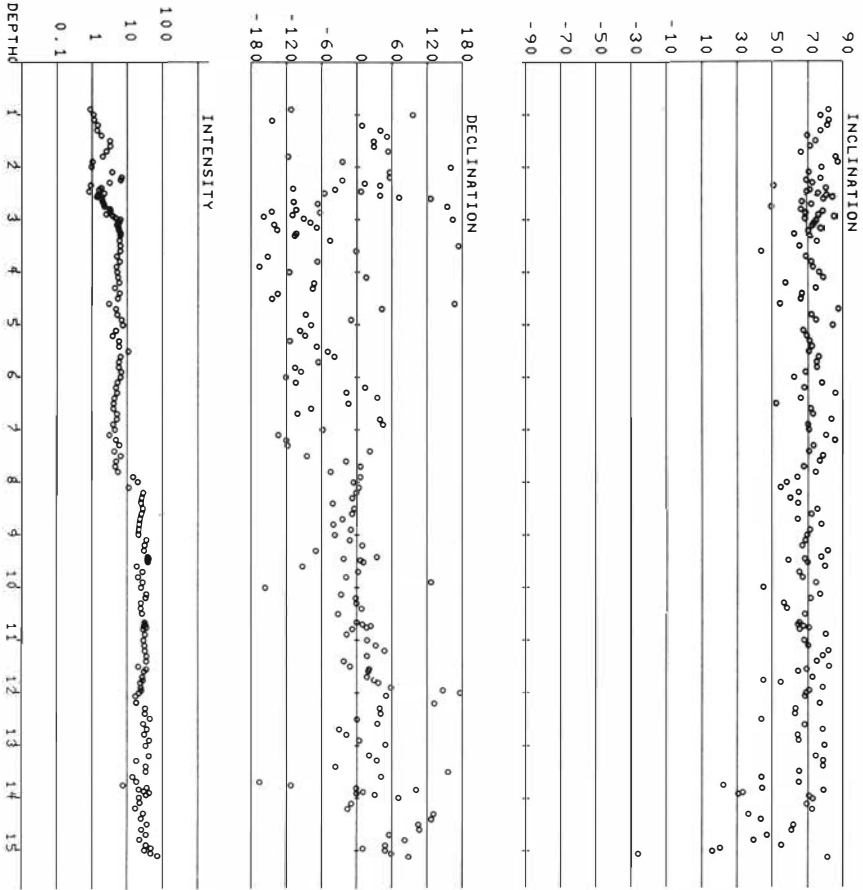


Fig. 11:4a-c. Intensity (log scale), declination and inclination of the Brastad core. Individual measurements; curves are 5-point moving averages. Swings in the declination and inclination are labelled d1 through d7 and il through i11, respectively. a. Brastad, NRM.

6.3 and above 4.3 m, respectively, while more or less pronounced local peaks are seen at 15.2, 13.7, 10.8, 9.7, 9.2, 8.0 to 7.2, 5.5, and 5.0 to 4.3 m, respectively. The three levels and most of the local peaks are easily recognizable and closely correlated with the density record, as described elsewhere (Chapter 8). Hence at least part of the density variations are likely to be caused by variations in the dominating magnetic minerals.

Q-RATIO

The record of the Q-ratio (Fig. 11:5d) shows a smooth variation with values around 0.3 at the bottom, a level around 0.17 between 14.7 and 9.7 m, a higher level around 0.25 between 9.7 and 7.8 m and a low level around 0.1 between 7.0 and 3.2 m. Very pronounced peaks are found at 9.2 ($Q=0.7$)

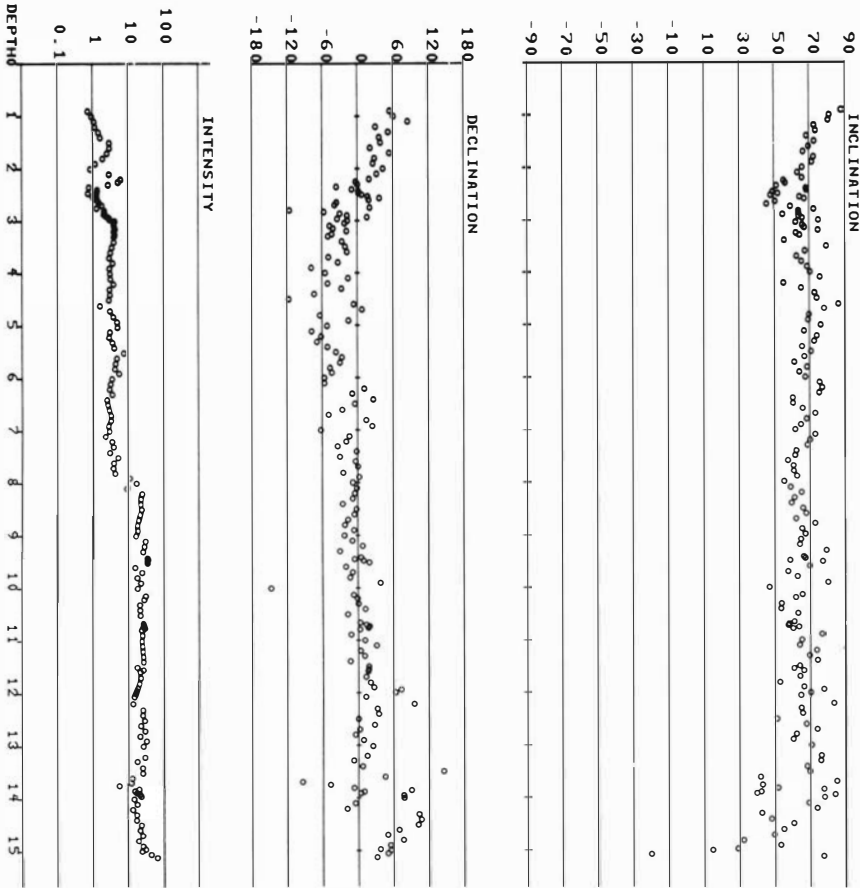


Fig. 11:4b. Brastad, $F = 100$ Oe.

and 2.2 m, and minor peaks are seen at 11, 8.6, 8.0, 7.1, and 4.65 m ($Q=0.23$), the latter being a rapid oscillation with a minimum of .026 at 4.40 m. At this level the grain-size distribution indicates a shift in lithology from clayey silt to silty clay (see Chapter 7).

DIRECTIONS OF REMANENT MAGNETIZATION

The NRM intensity (logarithmic scale), declination and inclination records are illustrated in Fig. 11:6a, while Figs. 11:6b and 11:6c show the same parameters after partial demagnetizations in alternating peak fields of 100 and 300 Oe respectively. In Fig. 11:6c the curve is a 5-point moving average. Pilot demagnetizations indicate median destructive fields typically between

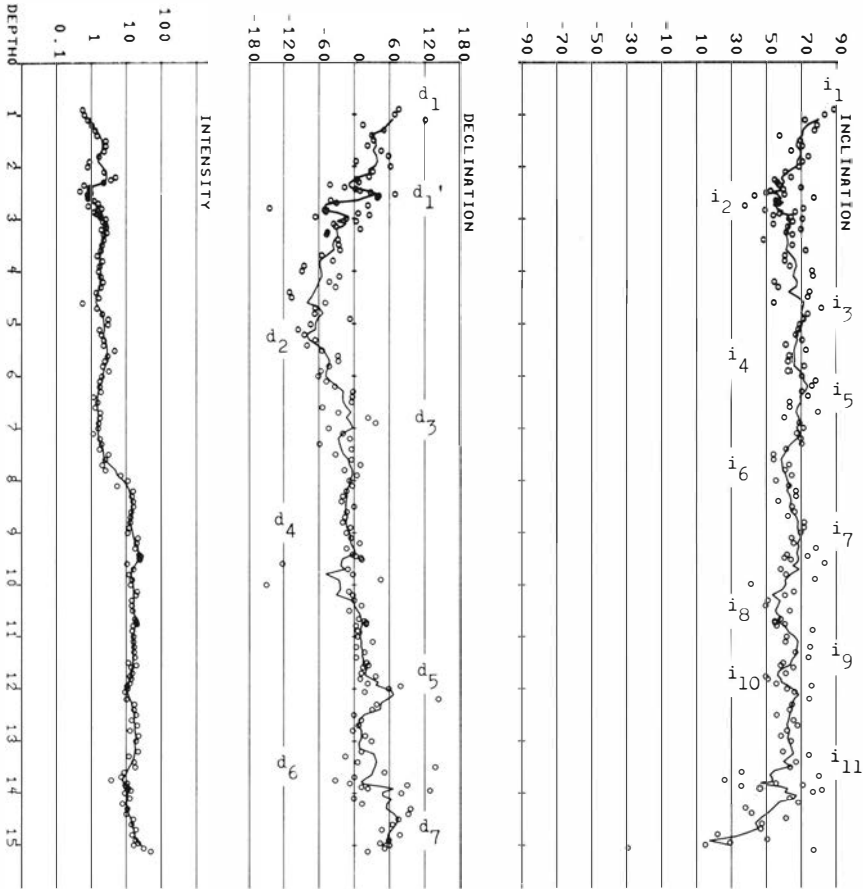


Fig. 11:4c. Brastad, $F = 300$ Oe.

200 and 300 Oe. The declination records show only minor changes during the magnetic cleaning in contrast to the Solberga and Brastad cores.

The declination record of the Moltemyr core appears to be somewhat dubious below 8.2 m, as systematic offsets between 90 and 180° seem to be present at 8.2, 9.5 and 12 m. These levels coincide with some of the sections, into which the core was cut before transportation and subsampling in the laboratory, as indicated in Fig. 11:6a. Furthermore as the inclinations do not change sign the shifts in declination cannot be due to reversals, and errors in the azimuthal orientation are the most likely explanations of the offsets. In the declination record, the original measurements are given by circles, while crosses indicate a 180° correction in search of better continuity.

The inclination records show a systematic increase from about 70° at 15 m to 85° at 10 m, with minor short wave oscillations superposed. Above 10 m

the mean inclination is 50 to 60°, except at the top. Because of the higher scatter, the interval between 10 and 3 m of the inclination record appears to be less reliable. It may be recalled, that highly scattered and low inclination values were found also in the cleaned records of the Solberga core between 17 and 12 m.

DISCUSSION

SOLBERGA

Most of the lithological, stratigraphical and palaeontological parameters studied by the working group suggest the existence of a boundary around the 19 m level in the Solberga core.

Focussing especially on the 19 m level in the Solberga core, a change is indicated in the wet density at 18.95 m, a jump occurs in the NRM intensity at 18.95 and 19.35 m, a smooth increase in susceptibility begins at 19.0 m (and a jump at 18.85 m), and there is a jump in Q at 18.95 and 19.35 m, with a significant change in level above 19.35 m. A directional change is seen in the NRM declination record at 17.95 and 18.50 m but not in the cleaned records. The inclination shows a smooth variation below 17 m with a gradual increase between 20 and 17 m, indicating that at least up to this level, a postdepositional disturbance of the sediment is unlikely to have occurred.

The combined magnetic information thus supports the idea that a significant transition, presumably induced by climatic variations causing a change in environment, lithology and hence magnetic properties, may be present around the 19 m level.

The directionally very scattered interval between 17 and 12 m is interesting from a geomagnetic point of view, as it may indicate an excursion of the geomagnetic field. However, no well documented excursions of the geomagnetic field in Holocene time are yet known, and the directional scatter could most simply be explained as due to some kind of postdepositional disturbance such as sliding, slumping, bioturbation, or compaction.

As described elsewhere in this volume (Chapters 3, 7, 10, and 16), there are several signs in the Solberga core around 18–19 m depth of a change in the environment from saline to more brackish water conditions. This may be related to the climatic amelioration at the Pleistocene/Holocene transition, with an increase in the meltwater flux and with the drainage of the Baltic Ice Lake.

The increased flux of sediment-carrying freshwater into the marine waters is likely to increase the deposition rates, as the accompanying clay particles flocculate in the saline waters. Indeed, the clay percentage increases at 18 m depth from 50–55% to 80–85% while the silt percentage is reduced (Chapter

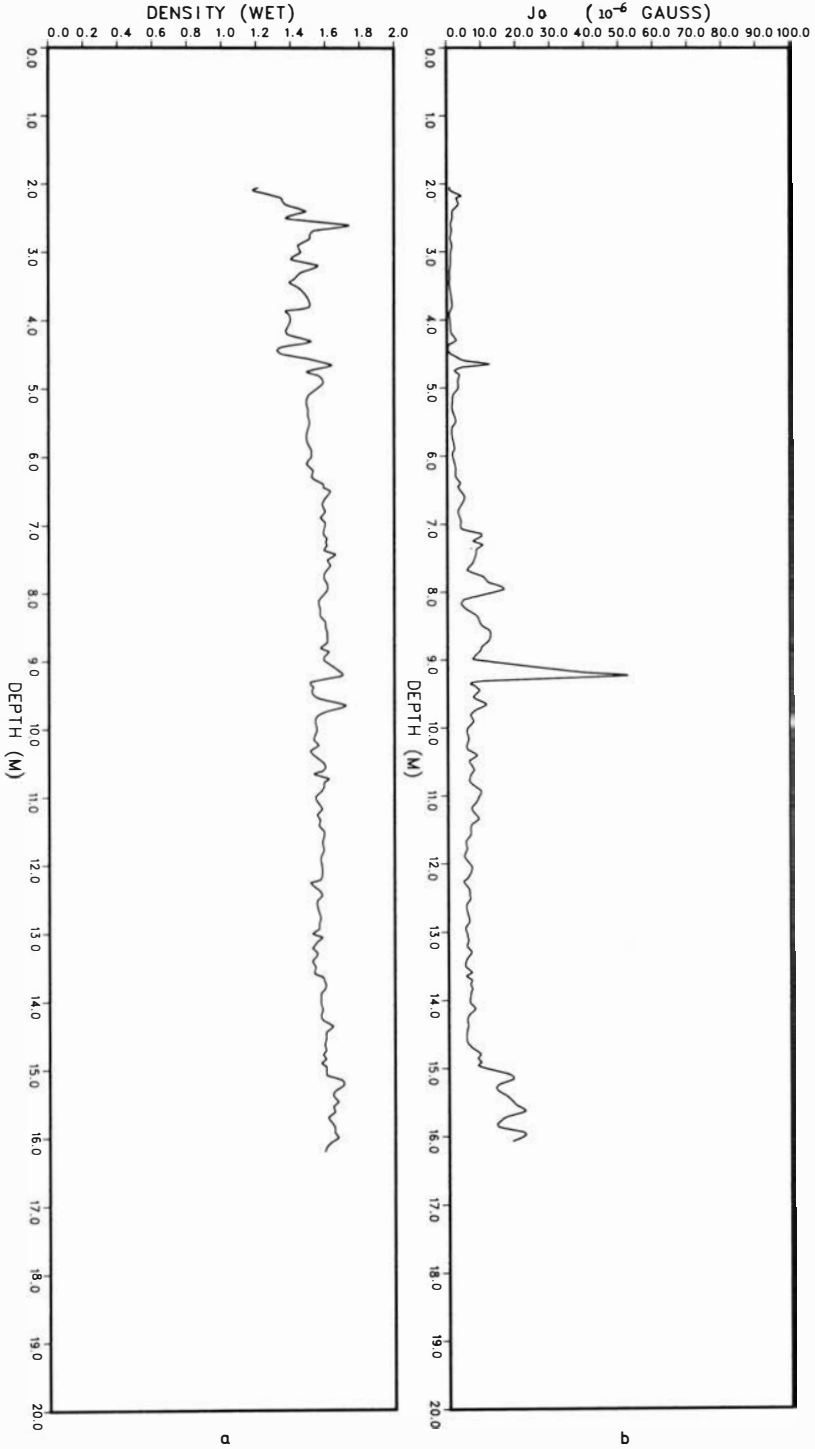
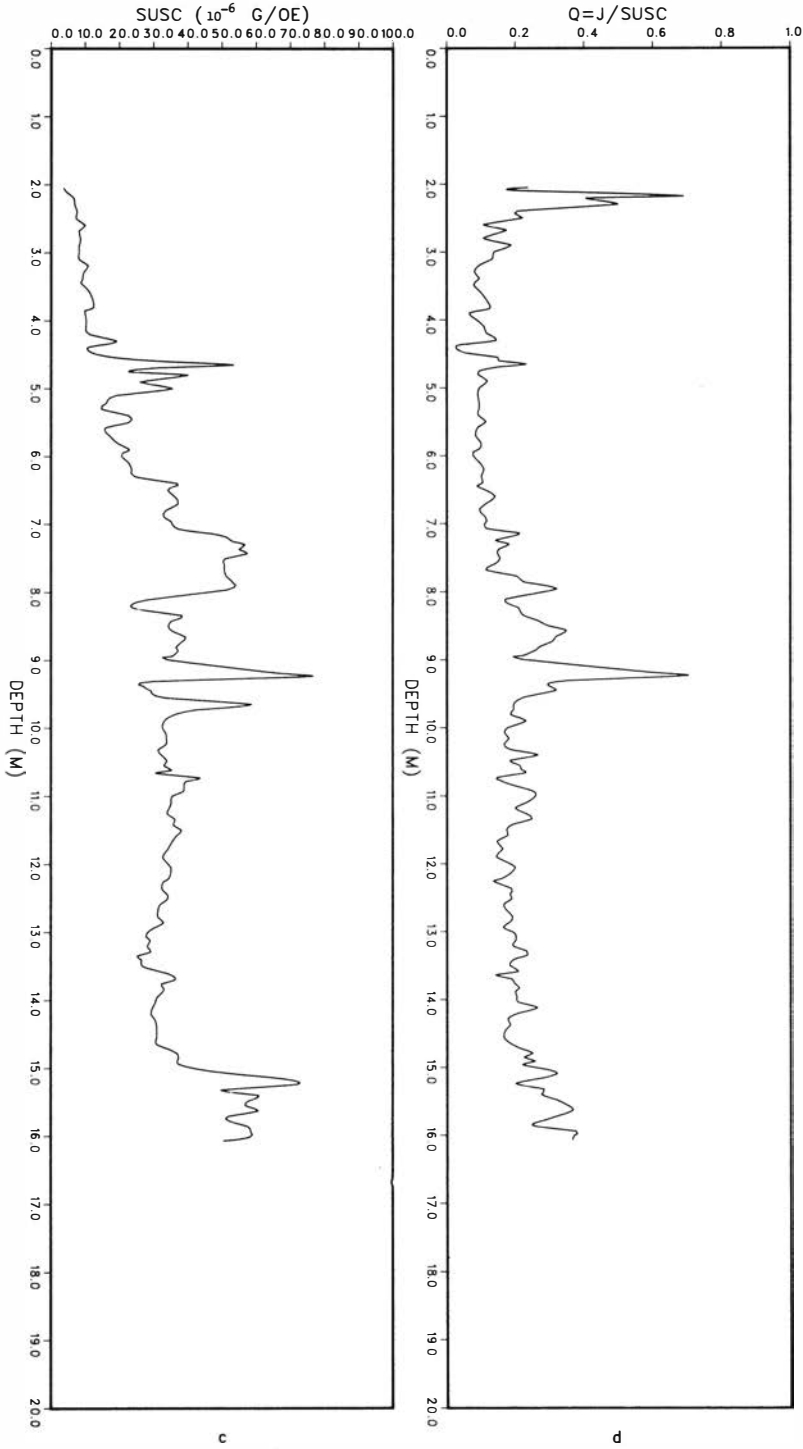


Fig. 11:5a-d. Density, NRM intensity J_0 , susceptibility k and modified Koenigsberger ratio



Q = J₀/k of the Moltemyr core. Depth in metres.

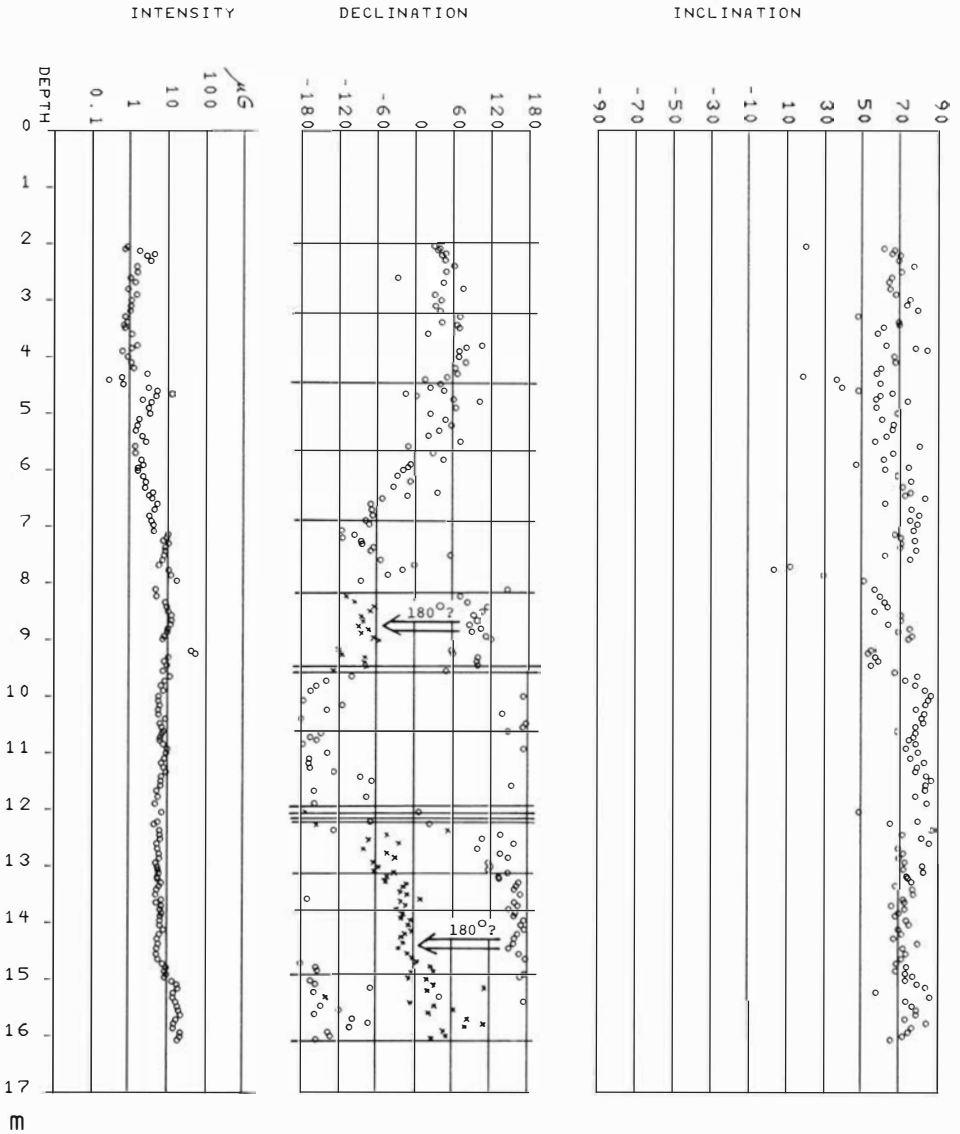


Fig. 11:6a-c. Intensity (log scale), declination and inclination of the Moltemyr core. Horizontal lines in the declination record indicate the core sections. Original data are indicated by small circles, while crosses indicate a possible (hypothetical) shift in azimuth of 180° . The curves are 5-point moving averages. a. Moltemyr, NRM.

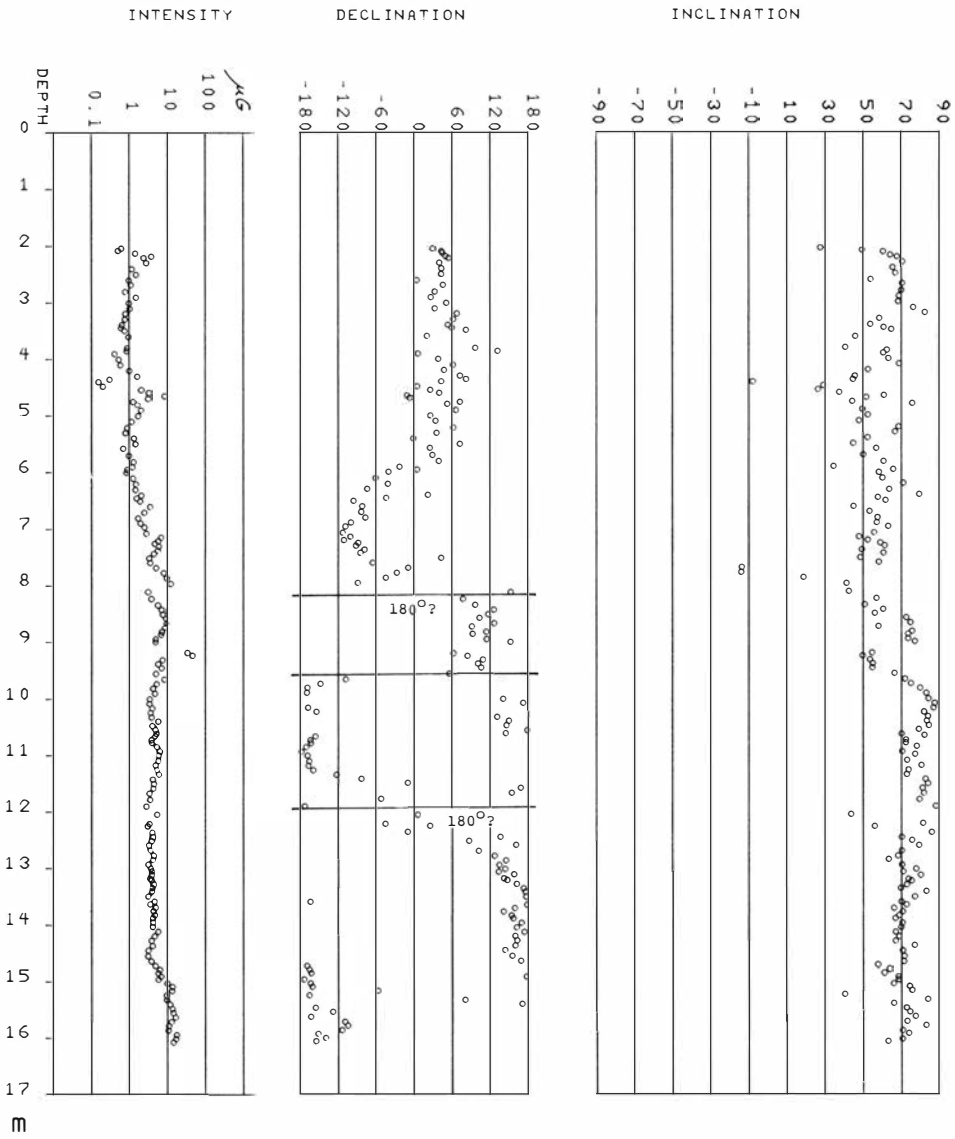


Fig. 11:6b. Moltemyr, $F = 100$ Oe.

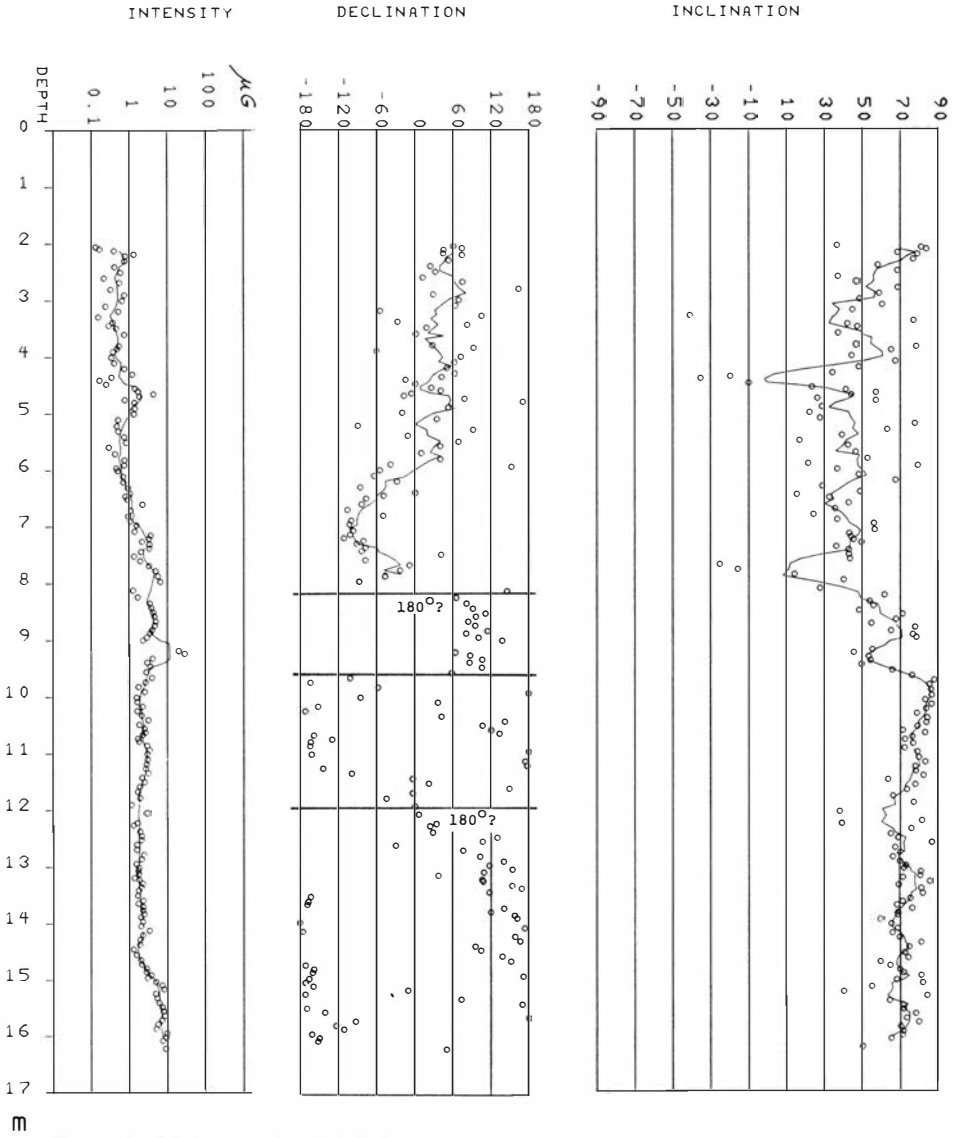


Fig. 11:6c. Moltemyr, F = 300 Oe.

7) and the numbers of fossils (Chapters 13, 14, 16, and 17) decrease, indicating a "dilution effect" of the clay by the increased rate of deposition.

Suppose that the majority of the carriers of remanence are detrital magnetites of silt fraction size (2–60 μm). The "dilution effect" of the increase in the clay percentage would then cause a reduction of the NRM intensity. The average intensity between 26.6 and 18 m depth is $6.2 \pm 1.1 \mu\text{G}$, and between 17 and 12 m (the scattered interval of inclination) $2.3 \pm 0.2 \mu\text{G}$, the ratio of mean intensities thus suggesting a "dilution factor" of $2\frac{1}{2}$ –3. The reason why this dilution is less perceptible in the susceptibility record must be that a significant contribution to the susceptibility stems from the paramagnetic minerals in the clay fraction $< 2 \mu\text{m}$.

Thus the rate of deposition is presumably far from constant in the Solberga core, the time scale probably being enlarged by a factor of 2–3 between 17 and 12 m depth as compared with the lower parts of the core. Between 12 and 6 m the intensity gradually increases, the clay percentage decreases, and the diatoms are still dominated by freshwater species (Chapter 16). This interval may represent a recovery phase with more tranquil sedimentological conditions compared with the increased rate of deposition from the meltwater discharge due to the Preboreal rapid ice retreat.

The unusually high directional scatter between 17 and 12 m is likely to be related to a change in the grain-size distribution. Low inclination values could thus be caused by postdepositional compaction of the flocculated clay particles after acquirement of the depositional NRM. A still younger postcompactional viscous magnetization would give the ordinary inclination values of the NRM found, in which case partial magnetic cleaning would reveal the more scattered low inclinations. The intensity of the remanent magnetizations is usually reduced by partial demagnetizations, as is also generally found in the Solberga core, except in the interval 12–17 m, where the intensity in most cases increases at $F = 100 \text{ Oe}$ and then decreases at $F = 300 \text{ Oe}$. This indicates that a significant part of the NRM in this interval is indeed of viscous origin in accordance with the mechanism suggested above.

Thus, on comparison of the cleaned and uncleaned records, a directionally dominant viscous magnetization is found, as the cleaned directions scatter and deviate drastically from the ordinary geomagnetic field direction at the site ($D = 0^\circ$, $I = +71^\circ$), whereas the NRM direction is close to it.

The possibility of disturbance (slumping and bioturbation) is contradicted by the discovery of only minor signs of possible disturbances in the radiographs, and in the carefully described, photographed and sampled cores. Furthermore compaction, bioturbation and slumping are unlikely to cause a systematic change in declination, since the ambient field tends to induce the ordinary direction during any disturbance in the sediment.

Nevertheless, the cleaned records as summarized in the histograms of Fig. 11:7 demonstrate a significant bias in both D and I away from the axial dipole direction, which is difficult to explain. The cleaned records may therefore depict a diffuse signal of geomagnetic origin. The apparent distance of the corresponding virtual geomagnetic pole would be about 90 degrees from the site, and the virtual colatitude about 60 degrees.

Pending an independent proof of the reality of such an "excursion" shortly after 10 000 years B.P., however, we prefer to ascribe it to an unexplained disturbance of the sediment, rather than due to a (local?) excursion of the geomagnetic field.

BRASTAD

In the Brastad core, a hiatus is obviously present at 2.31 m. Furthermore, the very pronounced change in remanent intensity, susceptibility, and Q-ratio at 7.8 m in the Brastad core, which is not found in the Solberga core (although deposited in about the same Lateglacial environment) suggests that the lower half of the former is older than the bottom of the latter, which after subtraction of the reservoir age was radiocarbon dated (Chapter 19) to $11\ 020 \pm 340$ years B.P. (26 to 26.5 m level) and $11\ 520 \pm_{380}^{440}$ years B.P. (26.5 to 27 m level), respectively. The two cores may tentatively be correlated by the swings in declination d_2 to d_1' at 5 m and *c.* 3 m in the Brastad core, and D8 (or D6) and D5 at 26–27 m (or 23–24 m) and 19–21 m in the Solberga core.

The "Gothenburg Excursion" of the geomagnetic field, which is suggested to end at $12\ 350 \pm 50$ years B.P. (Mörner 1976) is too early to appear in the Solberga core with an age at the bottom of $11\ 200 \pm 400$ years B.P.

The Brastad core, however, is likely to reach further back in time as discussed above. Below 13.5 m the declinations and the inclinations are very scattered, and at the very bottom of the core, four specimens with low inclinations and ordinary declinations are indeed found (Figs. 11:4a–d). Above 14.8 m the core is dominated by clay (36–66%) and silt (32–76%), but at the base the grain size is very much coarser, with 10% sand and 2% gravel at 14.90–14.95 m level and 38% sand and 21% gravel at 15.03–15.09 m (Chapter 7). A significant inclination error (Griffiths *et al.* 1960, McElhinny 1973) may then be expected here, and the low inclinations found may be ascribed to the coarse grain size rather than the geomagnetic field. During magnetic cleaning the scatter is not significantly altered in the bottom metre, indicating that viscous components do not influence the scattered directions. The directional scatter must therefore be due to orientational scatter in the sediment rather than a differential response to viscous overprints in the ambient field. This prompts the conclusion that a

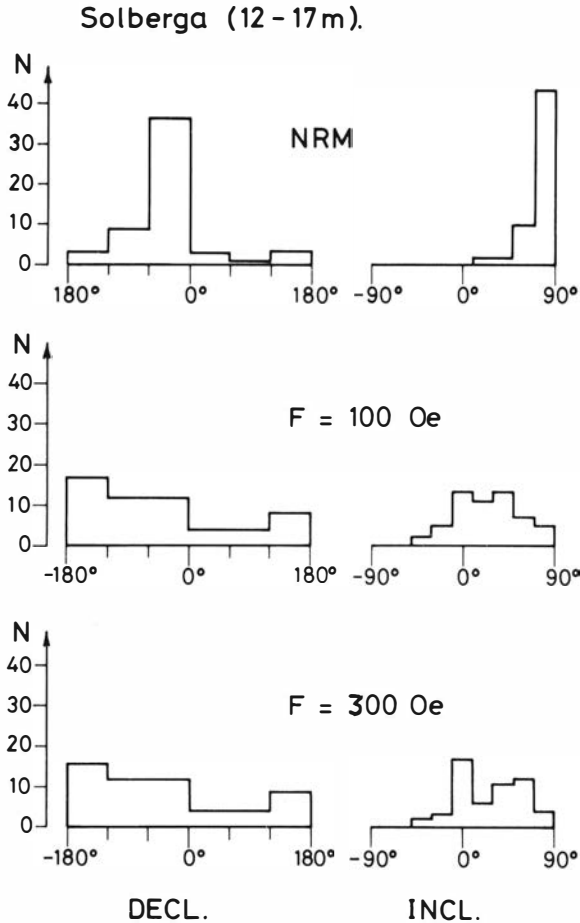


Fig. 11:7. Histograms of declination and inclination of 57 specimens of the scattered interval 12 to 17 m of the Solberga core. During demagnetization, the mean declination changes from *c.* 30° W to *c.* 150° W, and the inclination values are split into a bimodal distribution with peaks at *c.* +50° and 0°. The cleaned directions may indicate either a geomagnetic excursion or a postdepositional disturbance. See text for further discussion.

geomagnetic excursion is probably *not* seen at the bottom of the Brastad core.

An equal shift in intensity, susceptibility and Q-ratio, as seen at 7.8 m in the Brastad core, was found at 11 m in the Lateglacial cliffs of Younger Yoldia Clay at Nörre Lyngby in North Jutland (Abrahamsen and Readman 1980, Fig. 6). At Nörre Lyngby this level was deposited at about 14 000 years B.P. The two levels are unlikely to be of exactly the same age, as the ice recession and the isostatic adjustments at Brastad were out of phase and probably somewhat younger than those of Nörre Lyngby. This is supported

by the lack of correlation between the secular variation pattern at Brastad and the well developed pattern in the top part of the Nörre Lyngby profile. Although somewhat different in age, the magnetically equivalent shifts at both localities may suggest that sedimentological/environmental changes were equivalent. Lithostratigraphically the Nörre Lyngby profile may, therefore, be considered to be an "open section equivalent" of the Brastad core, more easily accessible to further studies.

MOLTEMYR

The directional variations in the Moltemyr core (Fig. 11:6c) were not labeled, as the declination and inclination records are considered less reliable. Based on similarities in the Moltemyr records of J, k and Q as compared with those of the nearby Brastad core (about 5 km away), it may however be suggested, that the 4.5 m level in Moltemyr is lithologically correlated with the 2.4 m level in Brastad, and 15 m in Moltemyr corresponds to 8 m in Brastad. Because of the greater distance to Solberga and the probable variance in environment, no magneto-lithological correlations with this site were attempted.

CORRELATIONS

A possible correlation with magnetic secular variation patterns in European lake sediments of Lateglacial age may be found in Lac de Joux near Lake Geneva, about 1 400 km SSW of the present sites. The magnetic record of a 5 m core from Lac de Joux (Creer *et al.* 1980) shows a distinct pattern of inclination maxima and minima, with interpolated "magnetic" ages as follows: ϱ (minimum \sim 14 000 years B.P.), π (maximum \sim 13 400 years B.P.), ξ (min. \sim 12 800 years B.P.), ν (max. \sim 9 800 years B.P.), μ (min. \sim 8 300 years B.P.), and λ (max. \sim 7 200 years B.P.), while the declination record shows easterly and westerly extremes marked P (westerly \sim 14 000 years B.P.), N (easterly \sim 13 400 years B.P.), M (W \sim 12 900 years B.P.), L (E \sim 12 400 years B.P.), K (W \sim 12 000 years B.P.), J (E \sim 10 800 years B.P.?), I (W \sim 10 200 years B.P.), H (E \sim 9 000 years B.P.), and G (W \sim 8 200 years B.P.).

The rate of deposition at Solberga and Brastad was an order of magnitude higher than that at Lac de Joux, so we may expect to see details in Solberga and Brastad which are not present in the cores of Lac de Joux. Bearing this in mind, as well as the geographical distance, and also the scatter in the absolute ages, it may cautiously be suggested that I_5 to I_7 at Solberga may correlate with ν (\sim 9 800 years B.P.) at Lac de Joux, D_2 or D_4 with G (\sim 8 200 years B.P.), D_3 to D_5 with H (\sim 9 000 years B.P.), D_6 with I (\sim 10 200

years B.P.), D₇ with J (~ 10 800 years B.P.), and D₈ with K (~ 12 000 years B.P.).

The general westward change in declination of the Brastad core between d₇ (15 m), or d₅ (12 m), and d₂ (5 m) with intervening minor deflections at d₃ and d₄, or d₃, d₄, d₅ and d₆ may correlate with the equivalent trend at Lac de Joux between N (~ 13 400 years B.P.) and K (~ 12 000 years B.P.) or I (~ 10 200 years B.P.) with the intervening minor deflections of M and L, or M, L, K, and J, respectively. In contrast to the declination, the simple Lateglacial inclination pattern of Lac de Joux apparently has no simple equivalents in the Lateglacial part of the Brastad core with 4 short-term inclination cycles.

Indeed, short-term secular variations with periods of a few hundred years duration are known from both historical and archaeomagnetic records, and recently, short periods between 522 and 670 years in inclination and between 290 and 372 years in declination have been suggested to be present in highly scattered palaeomagnetic records of Holocene lake sediments in northern Poland (Tucholka 1980). In Peary Land (northern Greenland) too, rapid variations in the inclination were found in marine sediments *c.* 8 000 years B.P. (Abrahamsen 1980). The rapid minor variations in the Solberga and Brastad cores may demonstrate that such short periods were present in Lateglacial time also.

SUMMARY

Three azimuthally oriented piston-foil cores of clay and silty clay from Solberga, Brastad and Moltemyr in south-western Sweden have been palaeomagnetically investigated with the purpose of investigating the transition from Pleistocene to Holocene time as part of a joint project (IGCP 128) in search for a holotype for this boundary or transition.

Susceptibility, density, Q-ratios and natural remanent magnetizations were measured on 666 specimens, as well as cleaned values after partial demagnetizations in peak fields of 100, 300, 500, 800 and 1500 Oe. Characteristic levels of k, Q and J were found, which indicate lithological variations, and local magneto-lithological correlations between the Brastad and Moltemyr cores are suggested.

The remanent directions are generally stable, and a detailed directional record was obtained, suggesting rather short-periodic geomagnetic secular variations in Lateglacial time. Parts of the Solberga core variations are tentatively correlated with those from Lac de Joux in Switzerland. During the progressive alternating field demagnetizations, an interval of the Holocene part of the Solberga and Moltemyr cores show decreasing

inclinations probably due to viscous magnetic overprints, which may indicate *either* unusual magneto-sedimentological properties related to an increase in deposition rate because of flocculation of clay particles caused by the increased freshwater flux of the amelioration period into the marine environment, *or* a hitherto unrecognized Postglacial (local?) geomagnetic low-inclination excursion, occurring shortly after 10 000 years B.P. The geomagnetic Gothenburg excursion, dated to end around 12 350 years B.P., is not seen in these records, although the Brastad and Moltemyr cores probably reach further back.

ACKNOWLEDGEMENTS

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12. MOLLUSCS AND OTHER MEGAFOSSILS

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INTRODUCTION

Molluscs are an excellent tool in the stratigraphical evaluation of outcrops and cleared sections where they can be sampled in reasonable quantities, but not in thin cores where they, as other megafossils, are only casually and incompletely represented. Molluscs are so rare in the investigated cores that they should only be used with caution for biostratigraphical purposes in the present study.

The samples investigated represent half slices of the core. Most of them are 10 cm, some are 20 cm and some are less than 10 cm thick. The dry weight of the samples varies from 20 g to 90 g.

Out of 76 examined samples of the Solberga core, only 43 contained fragments or valves of molluscs. The valves are rare and the fragments are usually small. Of 45 examined samples of the Brastad core, 26 contained valves or fragments of molluscs. On the other hand, only 2 of the examined samples of the Moltemyr core were completely barren, but many mollusc fragments of this core were reworked.

It has been possible to group the occurring species into four zoogeographical units (Fig. 12:1), viz., *High-Arctic*: these are mainly limited to the present day High-Arctic region; *Arctic-Boreal*: Arctic species which may also occur in the Boreal region; *Boreal-Arctic*: Boreal species which may also occur in the Arctic region; *Boreal*: species which are limited to the Boreal region, or which are Boreal-Lusitanian in their distribution (for definition of these terms see Antevs 1928, p. 482, Hessland 1943, p. 273, Feyling-Hanssen 1955, p. 25). The most commonly occurring species of molluscs are the Arctic-Boreal *Nucula tenuis* (Montagu), *Nuculana minuta* (Müller), *Nuculana pernula* (Müller), *Yoldiella lenticula* (Møller), the Arctic *Yoldia hyperborea* (Lovén), and the High-Arctic *Portlandia arctica* (Gray). Arctic-Boreal in their main distribution are also *Macoma calcarea* (Gmelin), *Hiatella arctica* (Linné) and *Mya truncata* Linné, whereas *Mytilus edulis* Linné is Boreal-Arctic to Lusitanian. Its main habitat is the Boreal region, but it may occur in Low-Arctic waters. Boreal molluscs are *Nucula*



Fig. 12:1. Zoogeographical regions. Redrawn from Feyling-Hanssen 1955.

nitida Sowerby, *Abra nitida* Müller, *Montacuta bidentata* Montagu, and *Hydrobia stagnalis* Baster. Of the most common cirripedes *Balanus crenatus* Bruguiere and *Balanus balanus* (Linné) occur today in Arctic and Boreal regions, whereas *Balanus balanoides* (Linné) is Boreal-Arctic (Brøgger 1901, Odhner 1915, Jensen 1905, Soot-Ryen 1932, Jensen and Spärck 1934, Thorson 1934, Feyling-Hanssen 1955, Ziegelmeier 1957, Ockelmann 1958, Petrov 1966, Simonarson 1977).

SOLBERGA

Zonation – This core is divided into three parts (Fig. 12:2), an upper part, zone A, down to 4.70 m below surface, with Boreal-Lusitanian shallow-water molluscs, a middle part, zone B, from 4.70 m to 17.15 m, practically without molluscs and a lower part consisting of zones C, D and E, from 17.15 m to the end of the core, with Boreal-Arctic to High-Arctic mollusc species.

Zone C, from 17.15 m to 19.30 m, is characterized by *Abra longicallis* Scacchi, *Nuculana minuta* and *Macoma calcarea*; zone D, from 19.30 m to

SOLBERGA			
DEPTH	SAMPLE NO.	MOLLUSC ZONES	SPONGE SPICULES BRYOZOAN ECHINOID SPINES OPHIURID PARTS BALANUS CREMATUS ANGULUS FABULA ABRA NITIDA NUCULA NITIDA SCROBICULARIA PLANA VENUS FASCIATA ? MONTACUTA BIDENTATA ABRA LONGICALLIS NUCULANA MINUTA MYTILUS EDULIS CLINOCARDIUM ? MYA TRUNCATA YOLDIELLA FRIGIDA YOLDIELLA LENTICULA NATICA SP. YOLDIELLA FRATERNA MACOMA CALCAREA NUCULANA PERNULA HIATIELLA ARCTICA PORTLANDIA ARCTICA NUCULA TENNIS
E	2.50 - 2.55	A	X X
3	3.00 - 3.05		X X X
3.50 - 3.55	4.00 - 4.05		X X X
4	4.50 - 4.55		X
5	5.00 - 5.05	B	X
5.50 - 5.55	5.90 - 5.95		•
5.95 - 6.00	6.00 - 6.05		•
6	6.50 - 6.55		•
7	7.00 - 7.05		•
7.50 - 7.55	7.80 - 7.85		•
8	7.85 - 7.90		•
8.00 - 8.05	8.50 - 8.55		•
9	9.00 - 9.05		•
9.45 - 9.50	9.50 - 9.55		•
10	10.00 - 10.05		•
10.50 - 10.55	11.00 - 11.05		•
11	11.50 - 11.55		•
12	12.00 - 12.05		•
12.50 - 12.55	13.00 - 13.05		•
13	13.50 - 13.55		•
13.80 - 13.85	14.00 - 14.05		•
14	14.50 - 14.55	•	
15	15.00 - 15.05	•	
15.50 - 15.55	16.00 - 16.05	•	
16	16.50 - 16.55	•	
16.75 - 16.80	17.00 - 17.05	•	
17	17.00 - 17.05	•	

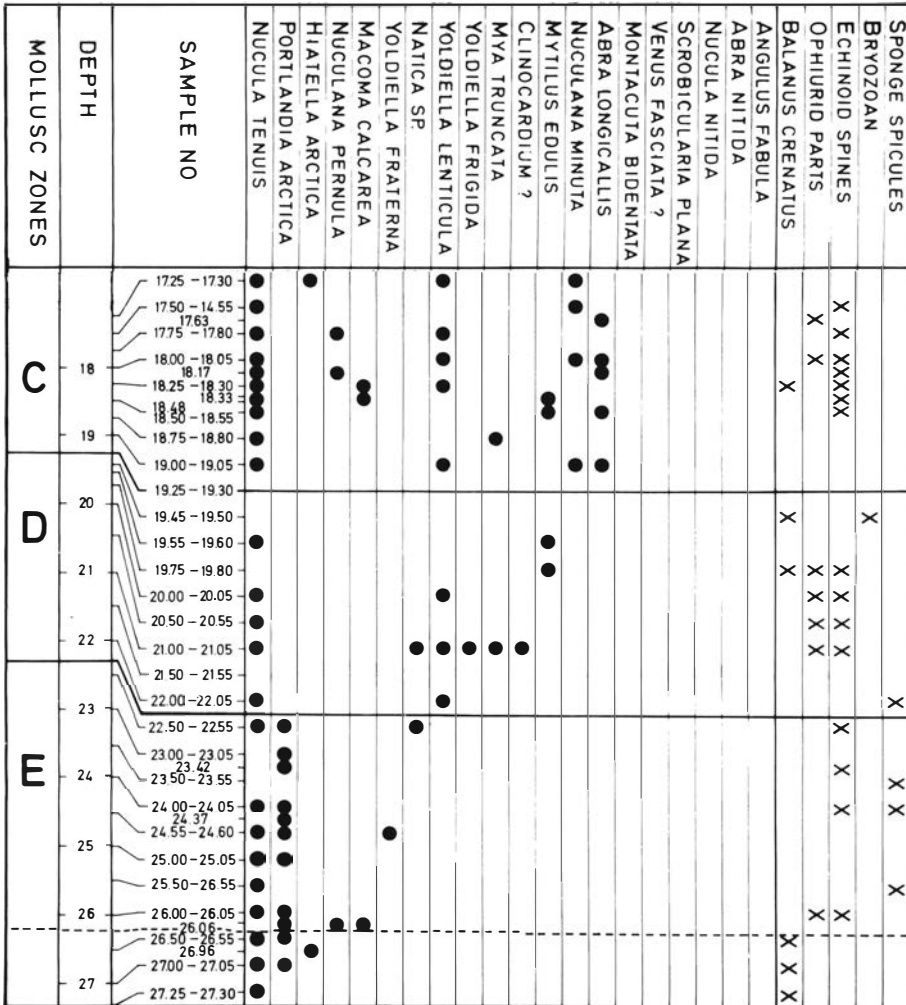


Fig. 12:2. Distribution of megafossils in the Solberga core. Zonation to the left.

22.30 m, is characterized by the appearance of *Yoldiella frigida* (Torell), *Mya truncata* and *Clinocardium ciliatum* (Fabricius); and zone E, from 22.30 m down, is characterized by *Portlandia arctica*.

In the lowest part of zone E, *Portlandia arctica* is quite frequent. There were six umbonal fragments and many others in sample 26.50–26.55 m and nine umbonal fragments and many others in sample 26.24 m. The barnacle *Balanus crenatus* is also present in the lowest quarter of zone E. Thus the lowest part of zone E could equally well have been distinguished as a separate zone.

Palaeoecology – Favourable marine-ecological conditions are mirrored by the species of zone A. In present day waters the zone A species are distributed in coast-near areas from western Norway to the Mediterranean. They live on or in muddy or sandy sea floors, mostly in shallow water. In the Solberga core they represent a Postglacial, Holocene, part of the sediment sequence. Most of these species are recorded from other Postglacial deposits on the Swedish West Coast (Antevs 1928, Asklund 1936, Hessland 1943).

Conditions have been unsuitable for molluscs during sedimentation of zone B.

Zone C reflects Arctic, but ameliorated, conditions. Most of the species of this zone occur in even High-Arctic waters of the present day, but they extend their habitat into the Boreal and some of them even into the Lusitanian zoogeographical region. *Nuculana minuta* does not occur in the High-Arctic region of the present day and *Abra longicallis* is registered as a Boreal species by Brøgger (1901) and as Boreal-Lusitanian by Antevs (1928). In the Quaternary deposits of the Oslofjord area its first appearance is in the Younger Arca Clay which was deposited during retreat of the inland ice front to the moraines in the northern part of the city of Oslo, the Aker substage. Antevs (1928) reports this species only from the Postglacial “Last uplift” at Heestrand, north of Lysekil.

Zone D is populated only by species which today extend their habitat into the High-Arctic region. *Abra longicallis* and *Nuculana minuta* are absent. A few fragments of *Mytilus edulis* are present in the upper part of the zone.

Zone E is characterized by the High-Arctic *Portlandia arctica*. At present *Portlandia arctica* prefers loose mud-bottom of shallow (10–50 m), sediment-loaded water. A retreating ice front and turbid water may have provided favourable conditions for this species. The foraminifers indicates that there was a high sedimentation rate in the upper three quarters of zone E (~ zone 5 of the Foraminifera zonation).

During sedimentation of the lowest part of zone E, where *Portlandia arctica* is frequent, an ice front might have been fairly close to the Solberga core site.

BRASTAD

Zonation – This core has been divided into seven zones (Fig. 12:3). An upper zone Q1, extending from the surface to 2.31 m contains no molluscs. A dubious fiber, which might have belonged to *Mytilus edulis* occurred at 2 m. Zone Q2, from 2.31 m to 4.75 m, has scattered *Mytilus edulis*. Zone Q3,

ZONATION	DEPTH cm	B						
		MYTILUS EDULIS	NUCULANA MINUTA	MACOMA CALCAREA	NUCULA TENUIS	YOLDIELLA LENTICULA	PORTLANDIA ARCTICA	YOLDIELLA FRATERNA
Q 1	100 - 105							
	200 - 205				?			
	225 - 231							
Q 2	231 - 235						●	
	240 - 245						●	
	400 - 405							?
Q 3	500 - 505	●	●	●	?			
	550 - 555	●	●					
Q 4	600 - 605					●	●	
	650 - 655							●
Q 5	700 - 705					●	●	●
	750 - 755			●	●	●	●	●
	800 - 805					●	●	
Q 6	850 - 855	●	?					
	900 - 905		●					
	950 - 955		●					
	1000 - 1005	●	●	●				
	1100 - 1105		●	●				
1150 - 1155					●			
Q 7	1200 - 1205							
	1350 - 1355					●		
	1450 - 1455					●		
	1509 - 1515							

Fig. 12:3. Mollusc distribution in the Brastad core. Zonation to the left.

from 4.75 m to 5.70 m, carries *Portlandia arctica* and scattered *Yoldiella lenticula*. Zone Q4, from 5.70 m to 6.70 m, has scattered *Nuculana minuta*, *Mytilus edulis* and *Macoma calcarea*. Zone Q5, from 6.70 m to 8.30 m, shows a firm representation of *Nucula tenuis*, *Yoldiella lenticula*, *Nuculana minuta*, and *Macoma calcarea*. *Mytilus edulis* occurred in the lower part of Q4 and in the upper part of Q5. Zone Q6, from 8.30 m to 11.80 m, is characterized by *Yoldiella lenticula* and by the presence of *Portlandia arctica*. Zone Q7, from 11.80 m down, is almost barren of molluscs. Three umbonal fragments and other fragments of *Portlandia arctica* occurred at 13.50 m, and two valves of *Yoldiella fraterna* (Verrill and Bush) at 14.50 m.

Palaeoecology – No firm conclusions can be made about the environmental conditions during deposition of the zone Q1 sediments. Scattered fragments of *Mytilus edulis* in zone Q2 may indicate ameliorated conditions. The firm representation of *Portlandia arctica* in zone Q3 reflects High-Arctic conditions.

Zones Q4 and Q5 appear to have been deposited during somewhat ameliorated conditions as inferred by *Mytilus edulis* and *Nuculana minuta* and partly also by *Macoma calcarea* which is present in a small form not usually found in present day High-Arctic regions.

Zone Q6 indicates High-Arctic conditions. This may also apply to zone Q7, but there are too few molluscs for palaeoecological conclusions.

MOLTEMYR

Zonation and palaeoecology – Five units are distinguished in the 6.50 m long Moltemyr core (Fig. 12:4).

Zone V, comprising the uppermost sample, 222–230 cm below surface, contains plant remains, a few tiny fragments of *Mytilus edulis* and a small gastropod fragment. Very little can be deduced from these remains, the water was probably very shallow and the salinity very low.

Zone W, comprising the samples between 232 cm and 277 cm below surface, is characterized by some shells and fragments of the small gastropod *Hydrobia stagnalis*, by quite abundant fragments of *Mytilus edulis* and compartments and operculae of the cirripede *Balanus balanoides* in all samples except 250–258 cm, which is barren.

These remains indicate that sedimentation occurred in shallow water of low salinity, and that temperature conditions were close to those of the present day. *Balanus balanoides*, when attached to rocks, stones or other types of substratum, is linked to the tide-water zone, usually between low-water mark and mid-tide level. In the present sediment the species occurs as

Hydrobia stagnalis is absent. The fragments are few and many of them worn. *Mytilus edulis* is only represented by tiny fragments. One sample (331–339) contains no fossils, and the lowest sample (344–349) is almost barren. Many of the shell fragments in this unit may have been redeposited.

The sediment of this zone was probably deposited in slightly deeper and somewhat more saline water than that of the overlying zone. The poor representation of *Mytilus edulis* may be explained by a somewhat greater depth; or such species may have been worn away during transport.

Zone Y, comprising the samples from 350 cm to 540 cm below the surface, is the most fossiliferous part of the core. The zone is characterized by consistent occurrence of echinoid spines and plates, most probably of *Strongylocentrotus droebachiensis* (Müller).

The comparatively high diversity – there is a total of 17 species within the zone – may indicate higher salinity than in the overlying zones. The occurrence, particularly in the lower part of the zone (below 450 cm), of some Arctic and Arctic-Boreal species, viz., *Nucula tenuis*, *Astarte elliptica* (Brown), *Nuculana pernula*, *Yoldia hyperborea*, and *Chlamys islandica* (Müller), indicates lower water temperature than in the overlying zones. It seems, however, that a temporary shift towards higher temperature occurred in the middle part of the zone where the Arctic and Arctic-Boreal species mentioned above are absent and *Balanus balanoides* and *Mytilus edulis* become frequent (sample 410–420 cm). *Littorina littorea* (Linné) occurs in sample 430–440 cm. The upper samples of the zone are again poorer in megafossils. The depth seems to have been slightly greater than in zone X, but many of the fragments are worn and may have been reworked.

Zone Z, comprising the samples from 560 cm to 650 cm, is characterized by *Portlandia arctica* and *Nucula tenuis*, and by the absence of many of the species of the overlying zone. Sample 560–580 cm forms a transition between High-Arctic conditions below to Arctic-Boreal conditions above. The water-depth during deposition of zone Z was greater than during any of the other zones, probably more than 20 m.

CORRELATION

The occurrence and distribution of mollusc shells and fragments in samples from the three cores treated suggest that the conspicuous boundary between zones Z and Y of Moltemyr correlates with the boundary between zones E and D of the mollusc zonation of the Solberga core (22.30 m below surface) and probably with the 4.75 m level below surface of the Brastad core. The other units of the cores are not easily correlated on the basis of their

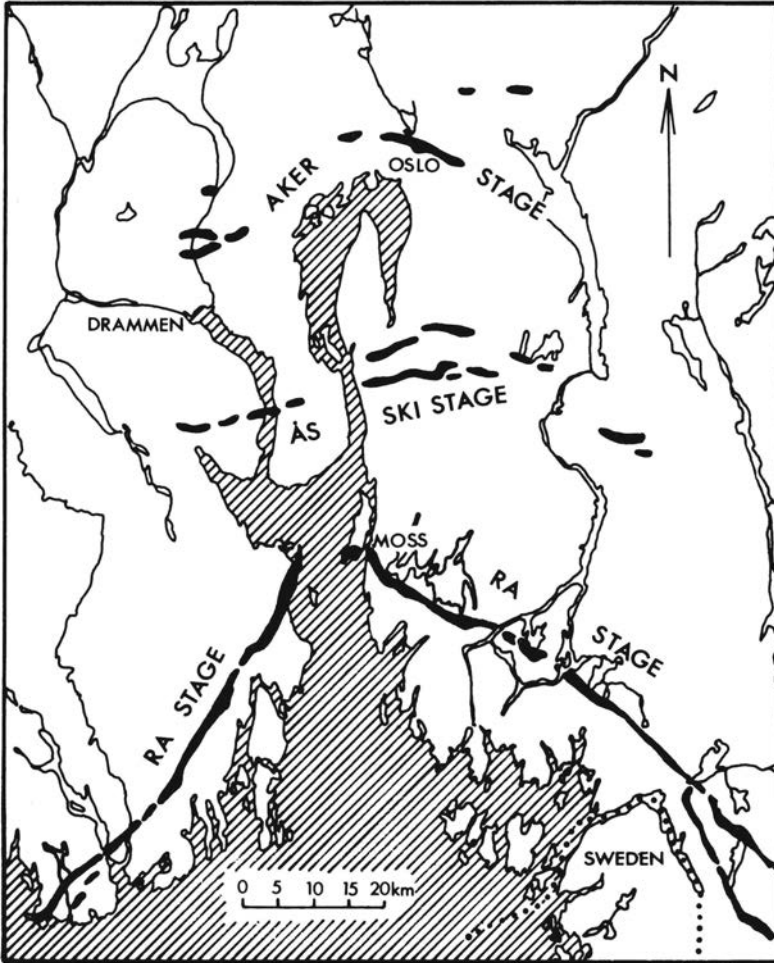


Fig. 12:5. Ice marginal formations in the Oslofjord area of Norway.

megafossil content, except that zone A of Solberga and zone V and W of Moltemyr represent Holocene deposits.

THE PLEISTOCENE/HOLOCENE BOUNDARY

The Scandinavian inland ice retreated from the area of investigation about 12 700 years before present (Berglund 1979). The marine deposits of our cores are, therefore, probably younger than this. The sedimentation may have continued in any one locality as long as the sea covered that site. The

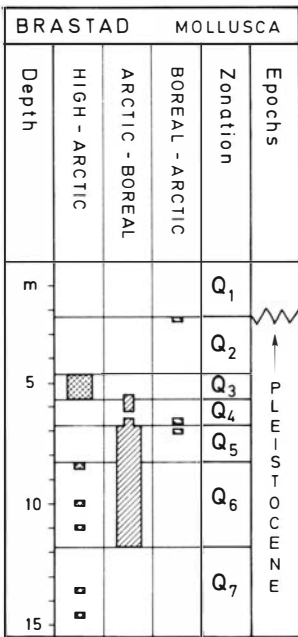


Fig. 12:6. Palaeoecology of the Brastad core.

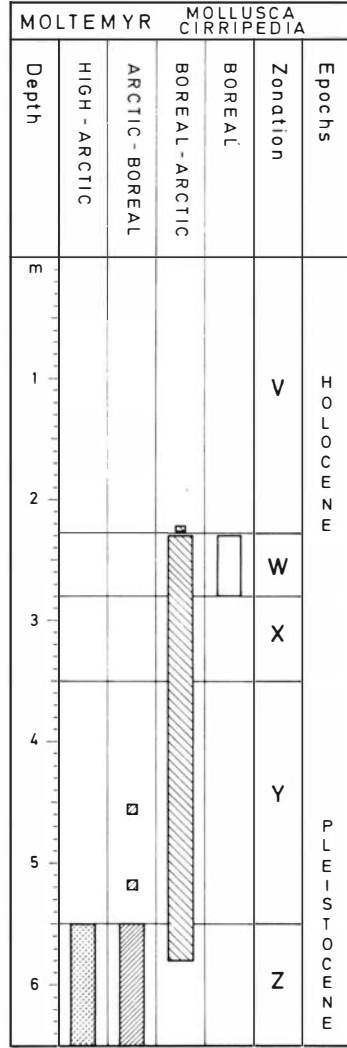


Fig. 12:7. Palaeoecology of the Moltemyr core.

lowest-lying core sites should thus contain the youngest marine deposits in their upper parts.

The lowest parts of the cores may contain sediments which are approximately 12 000 to 10 000 years old – those parts contain *Portlandia arctica*.

The High-Arctic mollusc species *Portlandia arctica* has previously been recorded from *glacial* clays of western Sweden (*i.a.*, Antevs 1928, Asklund 1936, Hessland 1943). In the Oslofjord area of Norway it characterizes the Yoldia Clay of the mollusc stratigraphy of Brøgger (1901). That clay was

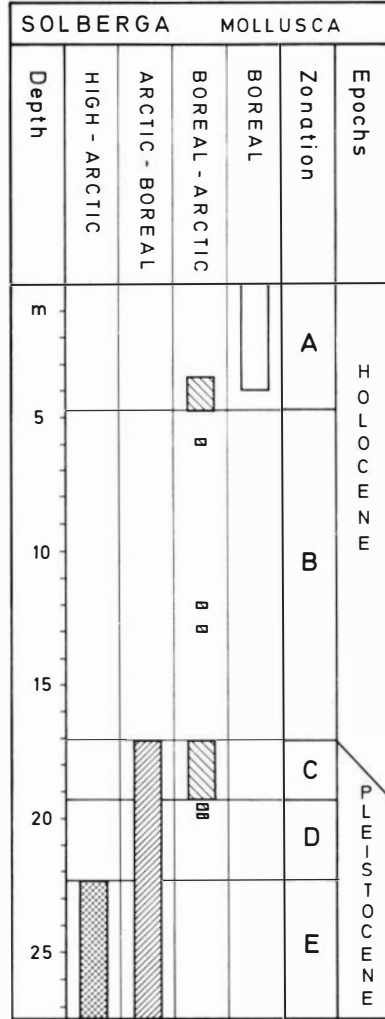


Fig. 12:8. Palaeoecology and the Pleistocene/Holocene boundary in the Solberga core.

deposited mainly outside (*i.e.*, south of) the conspicuous ice-marginal formation, the Ra ridge, of the Oslofjord area (Fig. 12:5). Deposits with *Portlandia arctica* in the Oslofjord area have radiocarbon ages between 11 200 and 9 950 years B.P., and the Ra ridge itself is considered to be a Younger Dryas formation (Holtedahl 1960, 1974, Feyling-Hanssen 1963, 1964). Andersen (1975) summarized occurrences and dates of the *Portlandia arctica* fauna in all Norwegian deposits and found that they are of Younger Dryas age or older. He writes (p. 54): "Evidently, P.a. lived near the ice fronts also during older glacial phases, but it seems to have disappeared from our coasts shortly after the Ra event, probably due to a warming of the sea".

In 1979 Sørensen reinterpreted radiocarbon dates of the Oslofjord area and found that the Ra ridge, or ridges, was formed in early Younger Dryas, and that it was still Younger Dryas when the inland ice margin halted at the marginal formations of Aas-Ski, midway between the Ra and the Aker stage of Oslo. This would imply that *Portlandia arctica* disappeared from the Oslofjord area before the end of Younger Dryas, that is, somewhat before 10 000 years B.P.

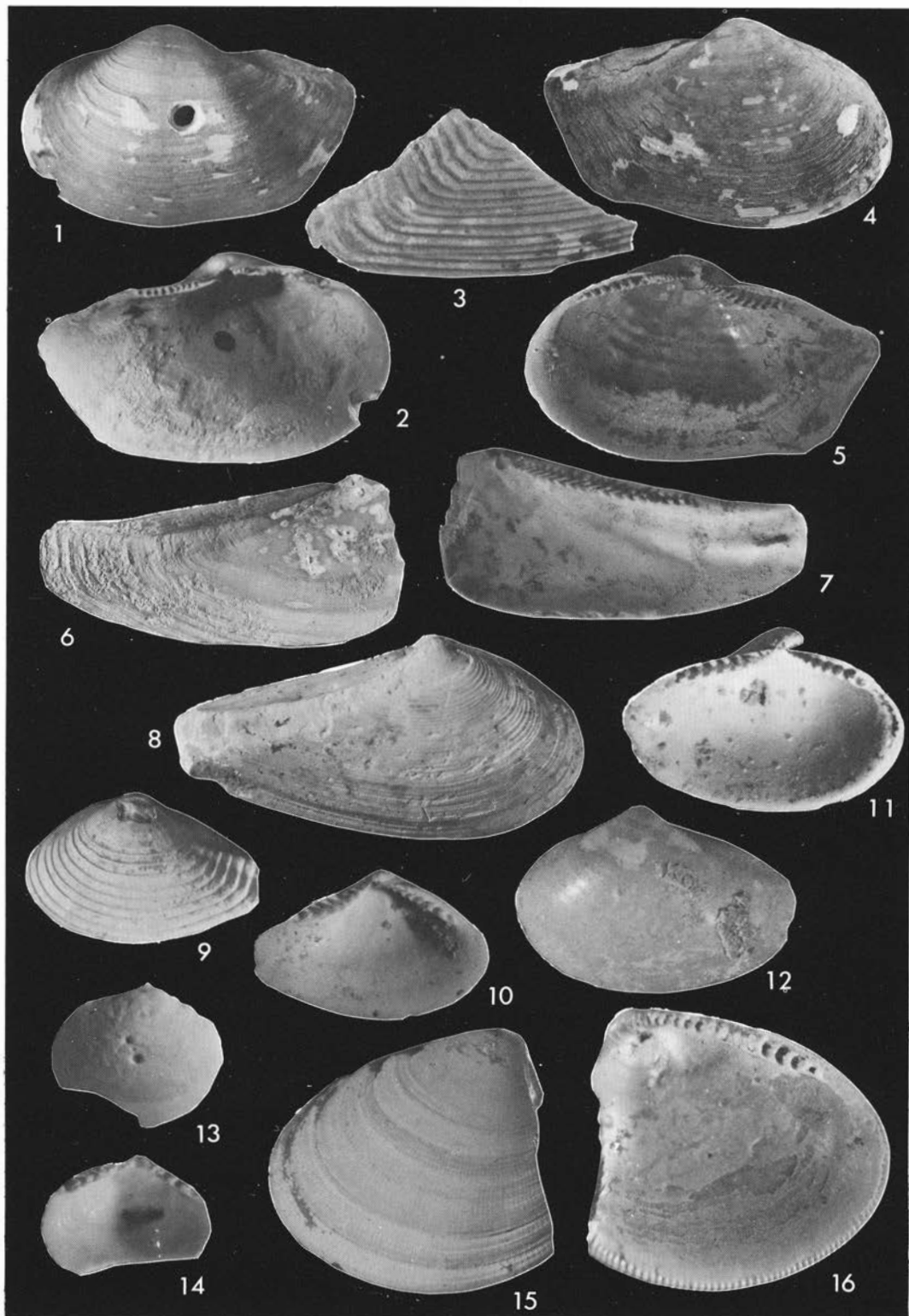
Portlandia arctica characterizes the molluscan zone E of the Solberga core, zone Z of the Moltemyr core and occurs up to 4.7 m below surface in the Brastad core (*i.e.*, up through Q3 at Brastad). The Pleistocene/Holocene boundary should be sought at the top of these occurrences or somewhat higher up in the cores.

The Brastad core contains very few mollusc fragments above zone Q3, and a boundary may be placed at or above 4.7 m (Fig. 12:6). The mollusc occurrences of this core cannot contribute further to the boundary location.

The Moltemyr core shows a quite distinct megafossil boundary between zones Z and Y at 5.5 m below surface (Fig. 12:7). The Pleistocene/Holocene boundary may be located there or higher up. No *clear* succession of climatic development is mirrored by the megafossils above zone Z. Arctic-Boreal

PLATE 12:1

- Figs. 1, 2. *Portlandia arctica* (Gray). Left valve from 5.65 m depth, Brastad core. x 2.
 Fig. 3. *Nuculana minuta* (Müller). Fragment of right valve from 7.00 m, Brastad core. x 3.
 Figs. 4, 5. *Portlandia arctica* (Gray). Right valve from 24.37 m, Solberga core. x 2.
 Figs. 6, 7. *Nuculana pernula* (Müller). Fragment of posterior end of a right valve from 18.17 m, Solberga core. x 4.
 Fig. 8. *Nuculana pernula* (Müller). Right valve from 17.75 m, Solberga core. x 4.
 Figs. 9, 10. *Nuculana minuta* (Müller). Left valve from 19.00 m, Solberga core. x 4.
 Figs. 11, 12. *Yoldiella lenticula* (Møller). Left valve from 19.00 m, Solberga core. x 12.
 Figs. 13, 14. *Yoldiella fraterna* (Verrill and Bush). Specimen from 14.50 m, Brastad core. x 21.
 Figs. 15, 16. *Nucula nitida* Sowerby. Left valve from 3.00 m, Solberga core. x 4.



species continue, very sparsely, up to 4.5 m, but Boreal-Arctic species are also found in the upper part of zone Z, and there are indications of reworking.

The Solberga core displays an upward succession of increasingly ameliorated mollusc-stratigraphical units, from High-Arctic (zone E) to Arctic-Boreal (zone D), Arctic-Boreal and Boreal-Arctic (zone C) followed by a mollusc free section (zone B), to the pure Boreal zone A at the top (Fig. 12:8). Pure Arctic conditions end with zone E. The Pleistocene/Holocene boundary, reflecting the transition from the Younger Dryas to the Preboreal, may be found at the transition E/D or within zone D or close to, but hardly above, the transition D/C.

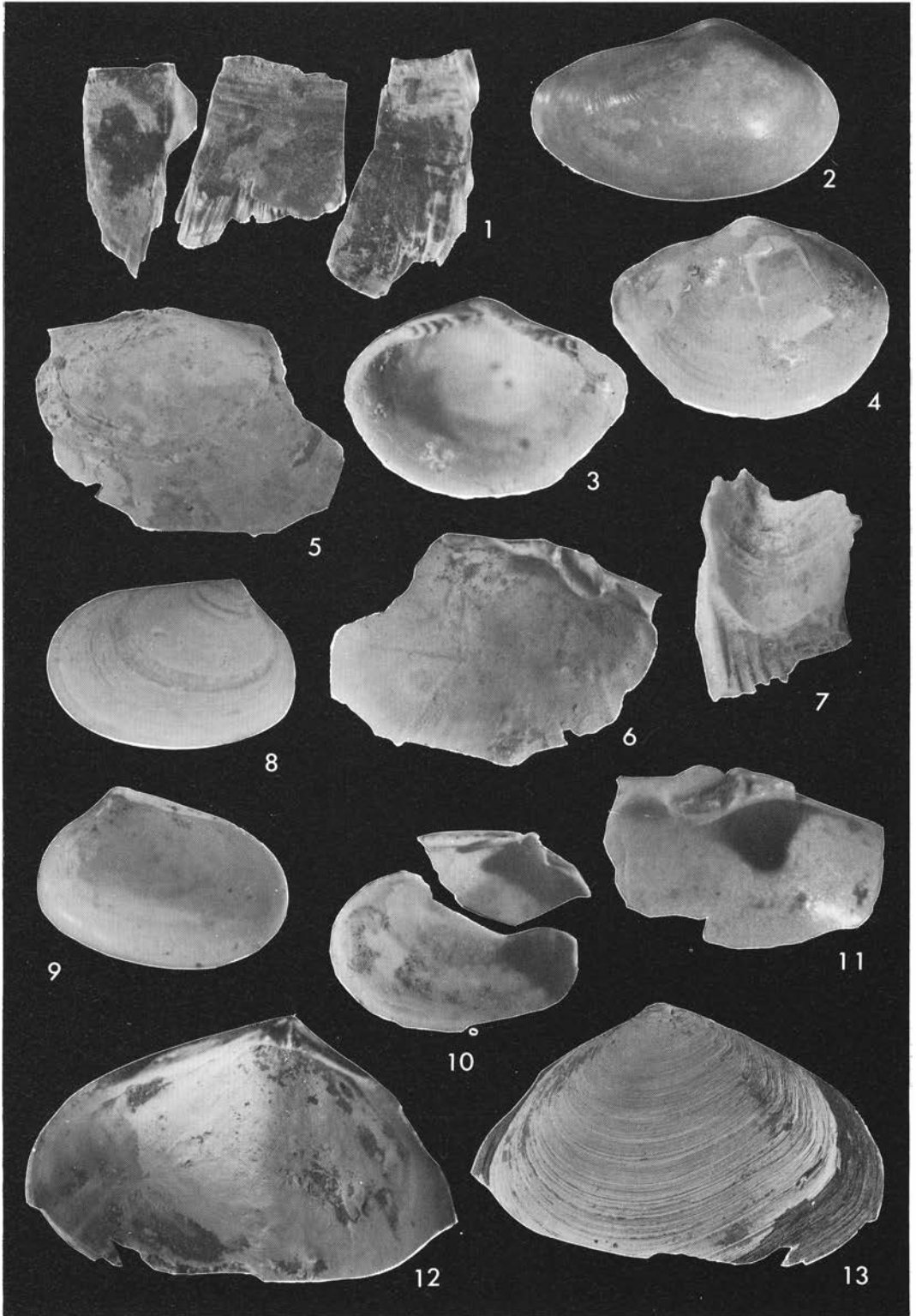
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PLATE 12:2

- Fig. 1. *Mytilus edulis* Linné. Fragments from 6.50 m. Brastad core. x 8.
- Fig. 2. *Yoldiella lenticula* (Møller). Complete specimen from 19.25 m, Solberga core. x 12.
- Figs. 3, 4. *Yoldiella frigida* (Torell). Right valve from 21.02 m, Solberga core. x 16.
- Figs. 5, 6. *Abra longicallis* Scacchi. Fragment of right valve from 18.48 m, Solberga core. x 8.
- Fig. 7. *Balanus crenatus* Bruguiere. Compartment from 6.52 m, Brastad core. x 8.
- Figs. 8, 9. *Montacuta bidentata* Montagu. Left valve from 2.52 m, Solberga core. x 14.
- Fig. 10. *Montacuta bidentata* Montagu. Broken right valve from 2.52 m, Solberga core. x 14.
- Fig. 11. *Abra nitida* Müller. Fragment of left valve from 3.02 m, Solberga core. x 30.
- Figs. 12, 13. *Macoma calcarea* (Gmelin). Left valve from 7.32 m, Brastad core. x 2.



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13. OSTRACODS

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INTRODUCTION

Material was kindly provided by Karen Luise Knudsen from samples prepared in Aarhus Universitet for foraminiferal study, thus numbers of ostracods and foraminifers are directly comparable as they are complete assemblages from the same samples. As ostracods, unlike foraminifers, cannot be successfully concentrated by flotation methods the specimens were picked by hand from light and heavy flotation fractions following removal of the foraminifers. Ostracods were common: Brastad core – 37 samples studied of which 7 were barren, Solberga core – 65 samples studied of which 16 were barren. In the case of the Moltemyr core time did not permit examination of the same samples for both foraminifers and ostracods. In this latter core 30 samples were studied of which 9 were barren.

THE OSTRACODA

Living ostracods inhabit all aquatic environments, in the benthos and as marine zooplankton. In the present material only benthic forms occurred and no freshwater/non-marine species were found. The distribution patterns and ecological preferences of many of the species are well known (see Appendix) as they are extant and have been recorded, for example, by G.O. Sars (1865, 1922–1928) off Norway, by O. Elofson (1941) off southwestern Sweden and by A. Rosenfeld (1977, 1979) from the Baltic Sea. It is, however, surprising that many species have uncertain modern records, a problem compounded by reworking of fossil material into Recent assemblages. In many older records (e.g. Brady 1868, Brady and Norman 1889) it is impossible to tell if the specimens were alive at the time of collection or only isolated valves and carapaces which may have been reworked. Certain species are known living only from high-latitude waters (*Rabilimis mirabilis*, *Baffinicythere emarginata*, etc.) or as fossils from apparently cold-water deposits (*Cytheropteron biconvexa*, *C. montrosiense*, *Roundstonia globulifera*, etc.). Other species have a wide arctic and boreal distribution at the present day and are common in most assemblages (*Acanthocythereis*

dunelmensis, *Elofsonella concinna*, *Heterocyprideis sorbyana*, *Eucytheridea bradii*, *E. punctillata*, *Palmenella limicola*, etc.). Similarly, certain species do not occur in modern high-latitude waters but are characteristic of the southern Norwegian, Baltic and Celtic/Britannic areas (*Leptocythere* species, *Cytheromorpha* species, certain *Semicytherura* and *Loxoconcha* species, etc.). Some ten of the species found are common in brackish waters, but only *Xestoleberis nitida* is essentially restricted to brackish conditions (15–30‰). Many of the marine forms are to some extent euryhaline (cf. Rosenfeld 1977 on Baltic Sea distributions).

The core study has been particularly valuable as it has provided a *stratigraphical* record of ostracods in the late Pleistocene and Holocene and this aspect of the work will be described fully elsewhere. The material contained two new species of *Cytheropteron* (*C. brastadensis*, *C. elofsoni*) and specimens assigned to '*Cytherura*' *complanata* Brady, Crosskey & Robertson, a species unrecorded since its original description in 1874.

BRASTAD

Assemblages from Brastad (Fig. 13:1) core contain 37 species of which 13 belong to the genus *Cytheropteron*, a taxon common in Quaternary Boreal and Arctic faunas (see Whatley and Masson 1979).

At the bottom of the sequence poor assemblages reflect cold, shallow-water essentially arctic conditions, but from 13.00 m below surface a more temperate, Boreal element is present and density/diversity increase. From 11.50 m conditions apparently deteriorated, culminating in a poor cold, shallow-water assemblage at 10.50 m. Between 10.50 and 6.50 m assemblages increase in size and diversity with some temperate/southerly species present, generally indicative of open-marine boreal-arctic conditions. From this point the number of specimens in the assemblages declines and temperate species disappear, the Arctic element in the fauna fluctuates while the widespread Boreal-Arctic species remain a more-or-less constant element. This suggests a gradual cooling of the waters, perhaps associated with some change in water-circulation patterns, however, the change is not dramatic and maximum diversity occurs at 3.50 m (just before maximum foraminiferal diversity) despite decreasing numbers of specimens. Above 3.50 m there is a rapid decline in diversity and density and above 2.30 m only a few specimens occur suggesting cold, shallow-water conditions. It is curious that the highest percentage of Boreal foraminifers should occur at 2.75 m when the ostracod assemblages have already declined.

The proportion of extinct to extant species and the assemblage compositions suggest that much of the section of the Brastad core below 2.30 m

BRASTAD

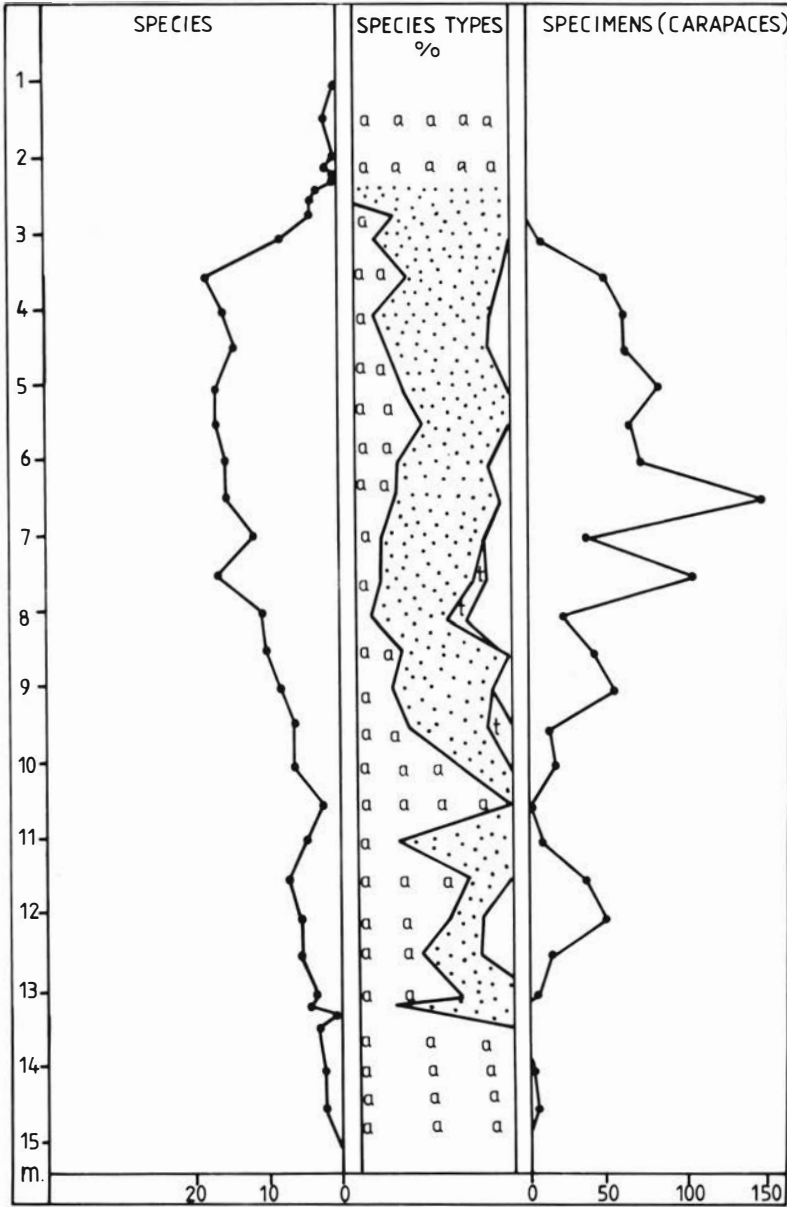


Fig. 13:1. Brastad core density and diversity plots and assemblage analyses. Note diversity refers to total number of species present. a = Arctic/cold water species, dotted area = wide spread Arctic and Boreal species, t = temperate/southerly species, blank = indeterminate and miscellaneous juveniles.

reflects a relatively temperate episode during the late Weichselian. The sharp break at 2.30 m, seen also in the sediments, *etc.*, indicates a non-sequence possibly associated with a meltwater or ice event and the few ostracods found in the top part of the section may well be reworked.

SOLBERGA

Assemblages from Solberga (Fig. 13:2) core contain 40 species of which 6 belong to *Cytheropteron*. The bottom part of the core sequence, below 26.0 m, contains good Arctic cold-water assemblages, but from 25.50 m more temperate influences are demonstrated by the appearance of *Semicytherura* and *Cytheromorpha* species. This somewhat warmer water element is present in most other assemblages from the core although varying in importance. The cold, high Arctic species continue to occur in the samples until 17.50 m. The overall trend in the lower half of the core is thus towards replacement of cold water forms by more temperate species, the same broad pattern can be seen in foraminiferal distributions where really cold water types disappear at about 18.0 m and the proportion of Boreal species increases strongly at about the same level. There are variations in this trend, with relatively small cold-water assemblages at certain levels (25.0, 23.0, 22.0, 20.0 m). The richest sample was at 18.25 m, which coincides with the most diverse foraminiferal assemblage. It is worth noting that rich and diverse assemblages can occur at high latitudes, as demonstrated by the Subrecent fauna described by Neale and Howe (1975) from Novaya Zemlya with 45 species and over 4 000 specimens. Above 17.0 m the assemblages decline in numbers of species and specimens, with an essentially barren interval between 10.0 and 4.50 m and good ostracod faunas occur again between 4.50 and 2.50 m. These final and youngest assemblages could occur in the western Baltic (see Rosenfeld 1977) or Øresund (see Hagerman 1965) at the present day, with the important exception of *Paracyprideis fennica* (Hirschmann) which is widespread in living faunas with a salinity range of 3–25‰. It should be noted that the majority of species present in the youngest assemblages also occur sporadically in the poor, low-diversity samples between 17.0 and 10.0 m. It would thus appear that the most modern faunas were being established from approximately 17.0 m, but that the general trend has been interrupted.

The sequence of ostracod assemblages documents a change from arctic cold-water to warmer water conditions approaching those found in the area at the present day. Most of the species are still extant and those which are extinct, or probably so, all occur in the oldest part of the sequence. The leptocytherid *Cluthia cluthae*, a high-latitude, cool shallow-water species, is

SOLBERGA

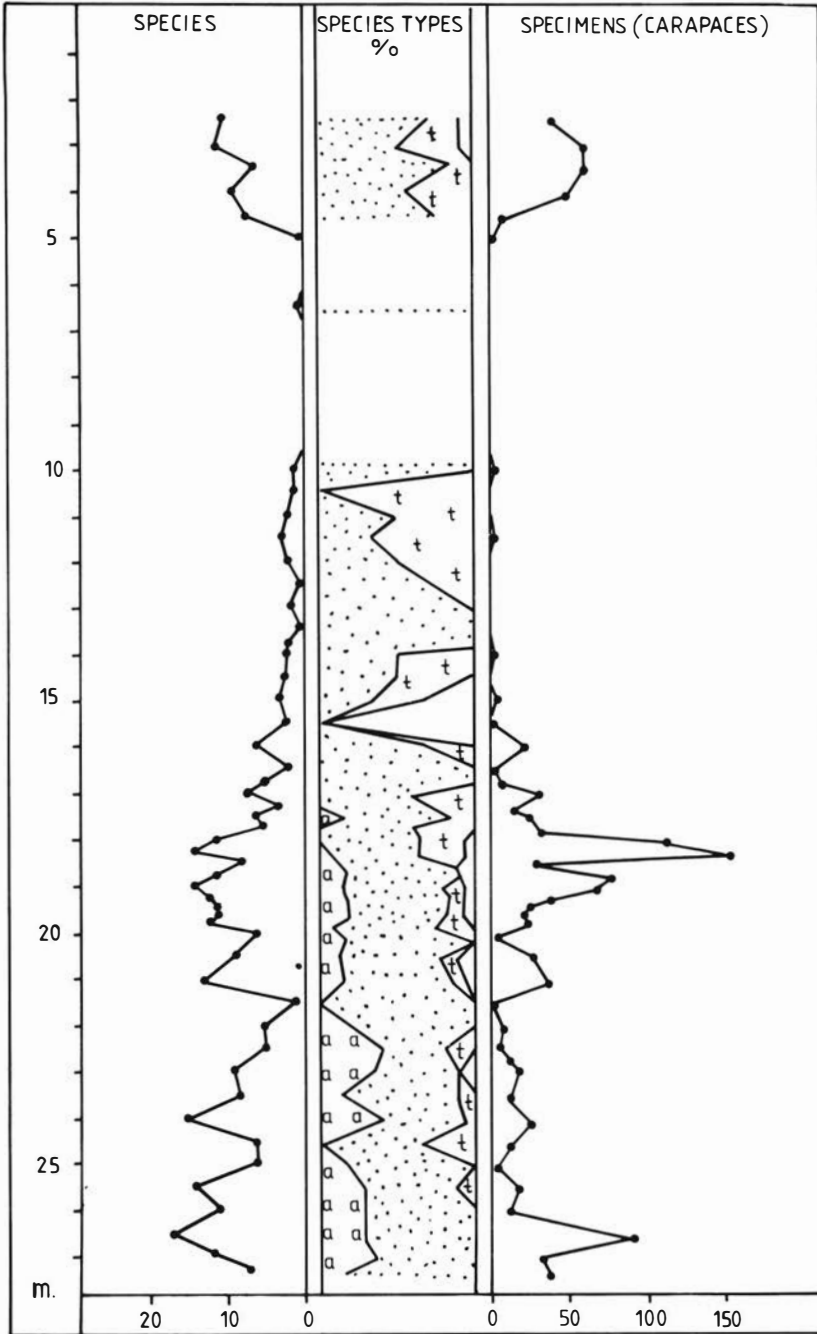


Fig. 13:2. Solberga core density and diversity plots and assemblage analyses. The key to the signs appears at Fig. 13:1.

replaced at c. 18.0 m by its more southerly, warmer water relations *Leptocythere tenera* and *L. pellucida*. Other high latitude/cool-water species disappear in the lower part of the core, e.g. *Rabilimis mirabilis* at 26.50 m, *Cytheropteron pseudomontrosiense* at 22.50 and *C. arcuatum* at 23.50 m. The high-latitude loxoconchid *Roundstonia globulifera* disappears at 22.0 m and is replaced in the more temperate assemblages at the top of the sequence by *Loxoconcha granulata*. The appearance of more temperate, effectively modern faunas can be recognized at c. 18.50 m where *Leptocythere* first occurs accompanied by *Hirschmannia tamarindus*.

MOLTEMYR

Assemblages from Moltemyr (Fig. 13:3) core contain 43 species of which 11 belong to *Cytheropteron*.

At the bottom of the sequence, below 4.7 m, assemblages reflect cold-water arctic conditions, especially the two bottom samples which contain *Cytheropteron montrosiense*, *C. simplex*, *C. biconvexa*, *Roundstonia globulifera* & '*Cytherura*' *complanata*. Other cool-water forms occur at 5.7 m (*Rabilimis mirabilis*, *Krithe glacialis*, *C. elofsoni*), but the number of specimens increases steadily until 4.7 m where high densities occur. Three samples at 4.6–4.7, 4.35–4.40 and 4.15–4.20 m are not only rich and diverse but are also distinguished by the appearance of more temperate, warmer water forms, viz. *Hirschmannia* species, *Leptocythere* species, *Xestoleberis* and *Cytheropteron latissimum*. Certain of these forms may reflect shallow-water conditions. A barren level at 3.95–4.0 m is followed by poorer assemblages with no new appearances. Diversity and density are good between 3.8 and 3.5 m but above this only relatively poor assemblages occur and above 2.66 m the samples were barren. Many or all of the specimens from the 3.5 to 2.66 m interval are clearly reworked and the sporadic occurrences of a number of species probably have little environmental significance.

The Moltemyr sequence shows cold, high-latitude assemblages being replaced by richer, more temperate ones. The barren level at 3.95–4.0 m is curious and is matched by a decrease in foraminiferal density and diversity at 3.9 m. The marked decline in ostracods at c. 3.5 m is matched by a similar reduction in foraminifers. The upper part of the sequence reflects possibly meltwater influences. No non-marine ostracods were found, only species already recorded which appear to have been reworked. Generally the Moltemyr sequence duplicates the lower part of Solberga and the upper barren part compares with the poorly fossiliferous and barren mid-part of the latter site (Fig. 13:4). The appearance of temperate forms accompanied

MOLTEMYR

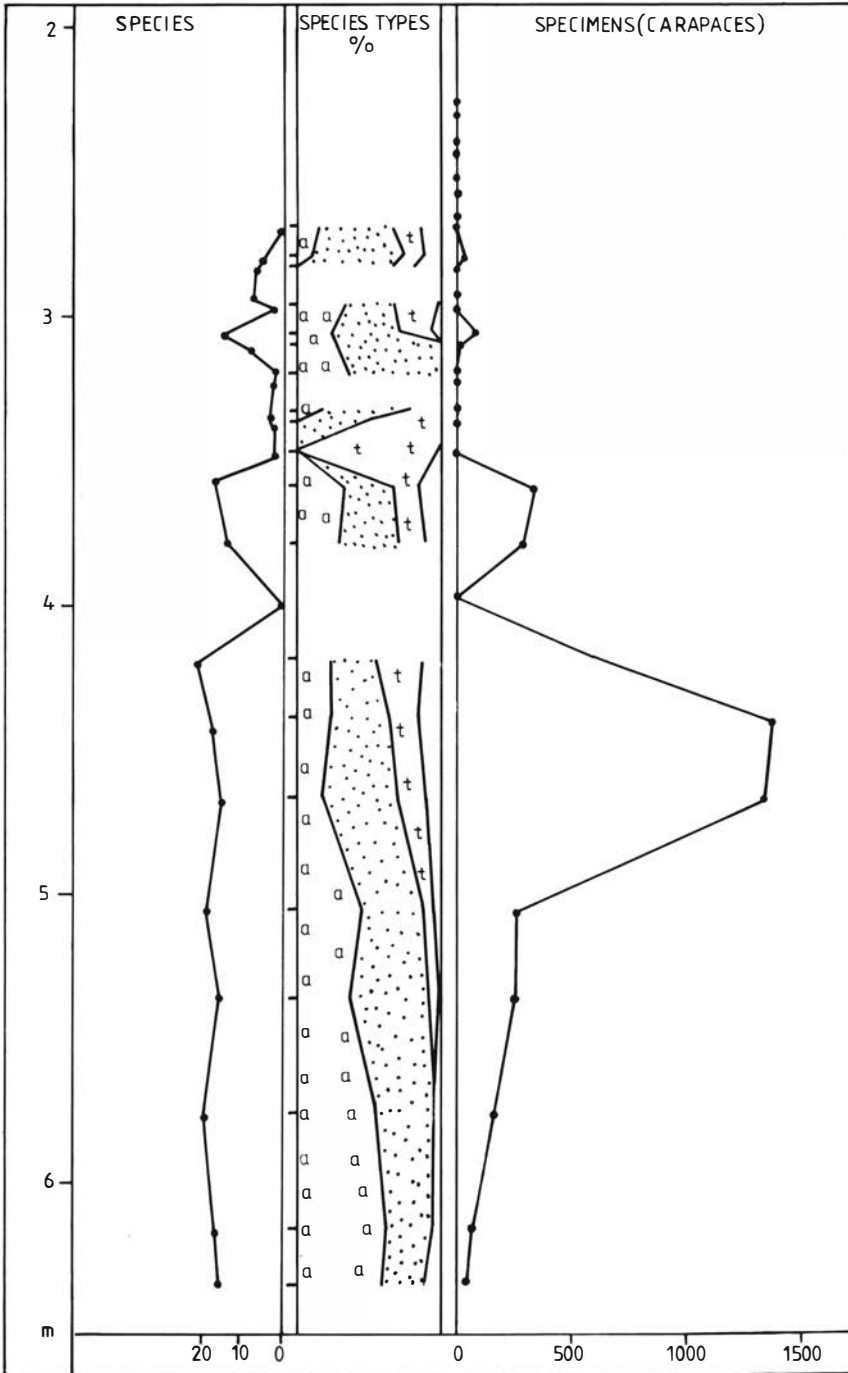


Fig. 13:3. Moltemyr core density and diversity plots and assemblage analyses. The key to the signs appears at Fig. 13:1.

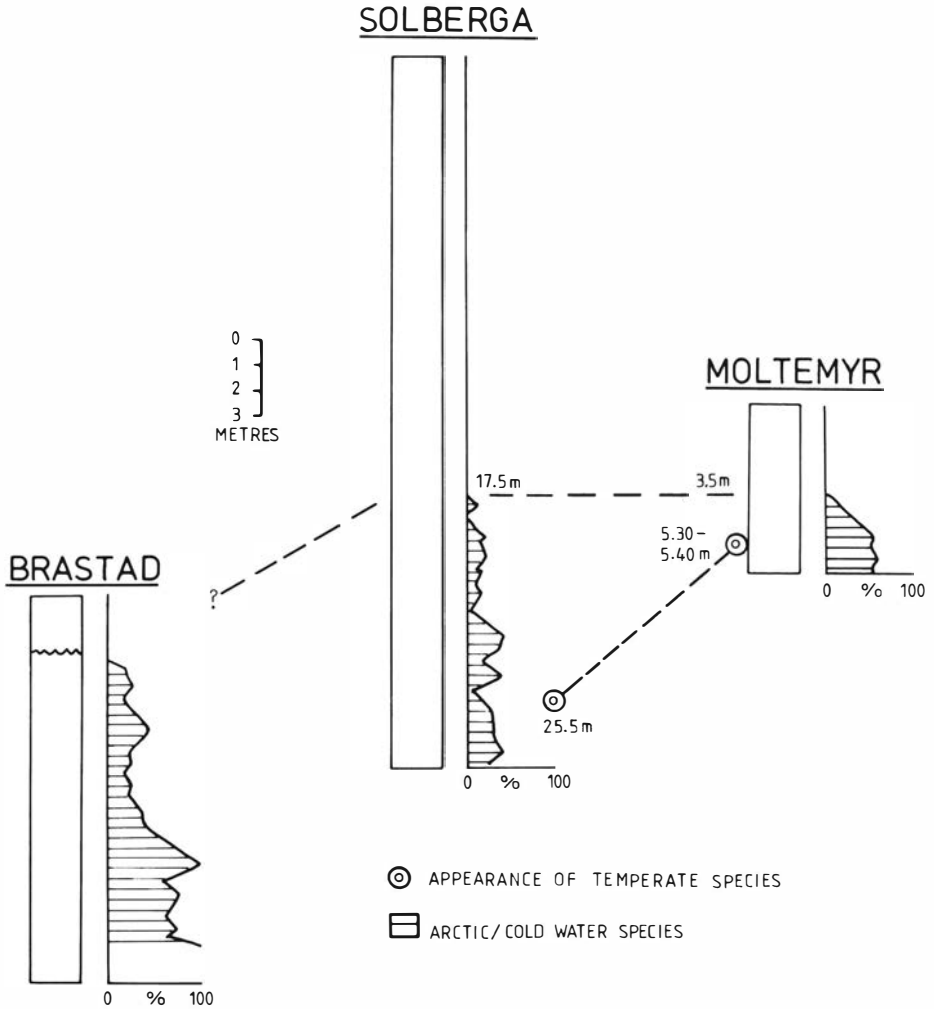


Fig. 13:4. Comparison of ostracod assemblages between the Brastad, Solberga and Moltemyr core.

by high faunal density and diversity at *c.* 4.5 m is matched by similar features at *c.* 18.25 m at Solberga. The cold assemblages at the bottom of the Moltemyr core compare with those from Brastad (Fig. 13:4). The Moltemyr sequence thus overlaps those penetrated at Solberga and Brastad. A clear level, where temperate, more southerly species occur, replacing Arctic, cold-water forms, can be recognized at both Solberga and Moltemyr. The Brastad core contains an essentially arctic series of ostracod assemblages which is suddenly terminated at the top of the sequence.

APPENDIX

THE OSTRACODA

The following species occur in the cores (with annotations to indicate generalised distributional/ecological preferences – p = phytal, i = interstitial, l = littoral, n = neritic, m = full marine, b = brackish. Distributions: A = Arctic, B = Baltic, C = Celtic/Britannic, N = Norwegian. * living; + extinct; ° uncertain living).

<i>Acanthocythereis dunelmensis</i> (Norman)*	n, m, A, B, C, N, etc.
<i>Argilloecia conoidea</i> Sars*	l, m, A, N
? <i>Baffinicythere howei</i> Hazel*	n, m, A, Nova Scotia
<i>Baffinicythere emarginata</i> (Sars)*	n, m, A, N
<i>Bythocythere constricta</i> Sars*	n, m, A, C, N
<i>Cluthia cluthae</i> (Brady, Crosskey & Robertson)*	n, m, A, B, C, N, etc.
<i>Cythere lutea</i> O.F. Müller*	p, l, n, m, A, B, C, N, etc.
<i>Cytheromorpha fuscata</i> (Brady)*	l, m/b, B (?), C, N
<i>C. robertsoni</i> (Brady)*	l/n, m/b, B, C, N
<i>Cytheropteron arcuatum</i> B., C. & R.°	m (cold-fossil)
<i>C. biconvexa</i> Whatley & Masson ⁺	n, m (cold-fossil)
<i>C. brastadensis</i> Lord ⁺	l/n, m (cold-fossil)
<i>C. dimlingtonensis</i> Neale & Howe°	m, A (subrecent)
<i>C. elofsoni</i> Lord ⁺	l/n, m (cold-fossil)
<i>C. inflatum</i> B., C. & R.*	n, m, A, C, N
<i>C. latissimum</i> (Norman)*	l, m/b, B, C, N
<i>C. montrosiense</i> B., C. & R. ⁺	l/n, m (cold-fossil)
<i>C. nodosolatum</i> Neale & Howe*	l, n, m, A
<i>C. nodosum</i> Brady*	n, m, C, N
<i>C. cf. C. pipistrella</i> Brady ⁺	m
<i>C. pseudomontrosiense</i> Whatley & Masson°	m, A
<i>C. simplex</i> Whatley & Masson ⁺	l, m (cold-fossil)
<i>C. cf. C. subcircinatum</i> Sars*	l, n, m, C, N
' <i>Cytherura</i> ' <i>complanata</i> B., C. & R. ⁺	m (? cold-fossil)
<i>Elofsonella concinna</i> (Jones)*	n, m, A, B, N, etc.

<i>Eucytheridea bradii</i> (Norman)*	n, m, A, B, C, N, etc.
<i>E. punctillata</i> (Brady)*	n, m, A, B, C, N, etc.
<i>Finmarchinella (Barentsovia) angulata</i> (Sars)*	n, m, A, C, N, etc.
<i>F. (B.) barentsovoensis</i> Mandelstam*	n, m, A
? <i>F. (B.) curvicosta</i> Neale*	n, m, A
<i>Finmarchinella (Finmarchinella) finmarchica</i> (Sars)*	n, m, A, C, N, etc.
<i>Hemicytherura</i> cf. <i>H. clathrata</i> (Sars)*	l/n, m, A, C, N
<i>Heterocyprideis sorbyana</i> (Jones)*	n, m, A, B, C, N, etc.
<i>Hirschmannia viridis</i> (O.F. Müller)*	p, l, m/b, A, B, C, N
<i>H. tamarindus</i> (Jones)*	p, l, m/b, B, C, N, etc.
<i>Jonesia simplex</i> (Norman)*	n, m, A, B, C, N
<i>Krithe</i> cf. <i>K. bartonensis</i> (Jones)*	l/n, m, C, N
<i>Krithe glacialis</i> B., C. & R.°	l/n, m (cold-fossil/ subrecent)
<i>Leptocythere castanea</i> (Sars)*	i, l, m, B, C, N
<i>Leptocythere pellicuda</i> (Baird)*	p/i, l, m, B, C
<i>Leptocythere tenera</i> (Brady)*	i, l, m/b, B, C, N
<i>Loxoconcha granulata</i> Sars*	p, l, m/b, B, C, N
<i>Loxoconcha</i> cf. <i>L. rhomboidea</i> (Fischer)*	p, l, m, C, N
<i>Normanicythere leioderma</i> (Norman)*	n, m, A, C, N
<i>Palmenella limicola</i> (Norman)*	n, m, A, B, C, N, etc.
<i>Polycope areolata</i> Sars*	n, m, N
<i>Rabilimis mirabilis</i> (Brady)*	n, m, A
<i>Robertsonites tuberculata</i> (Sars)*	n, m, A, B, C, N, etc.
<i>Roundstonia globulifera</i> (Brady) [†]	l, m (cold-fossil)
<i>Semicytherura</i> cf. <i>S. affinis</i> (Sars)*	m, N
<i>Semicytherura ?nigrescens</i> (Baird)*	p, l, m/b, B, C, N
<i>S. similis</i> (Sars)*	p, l, m/b, B, C, N
<i>S. undata</i> (Sars)*	p, l, m/b, B, C, N
<i>Xestoleberis nitida</i> (Liljeborg)*	b, B, C, N

Acknowledgement – to the Royal Society and to University College London for travel costs to two meetings.

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14. FORAMINIFERS

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METHODS

Samples from the borings Solberga, Moltemyr, and Brastad were treated for foraminiferal analysis mainly according to the laboratory methods described by Feyling-Hanssen *et al.* (1971) and by Meldgaard and Knudsen (1979). Between 10 and 100 g sediment (dry weight) were disintegrated in a 5–10% solution of hydrogen peroxide (H₂O₂). The disintegrated samples were washed through two sieves with mesh diameters of 0.1 and 1.0 mm. Foraminifera in the size fraction 0.1 to 1.0 mm were concentrated by means of a heavy liquid made of ethylene dibromide (C₂H₄Br₂) mixed with absolute alcohol (C₂H₅OH) to a specific gravity of 1.75 g/cm.

For quantitative analyses of foraminiferal faunas at least 300 specimens were counted from each sample when possible, and the percentage frequencies of selected taxa of foraminifers are illustrated by symbols in the range charts. In samples with few foraminifers the entire content was analysed. When a sample contained less than 100 specimens the percentages were not calculated, and the occurrences of species are entered in the range chart by their actual number.

The faunal diversities, defined by Walton (1964) as the number of ranked species that accounts for 95% of a counted fauna, are shown to the right in the range chart together with the number of species in the samples and the number of specimens in 100 g sediment.

For the diagrams showing percentages of Boreal elements in the faunas, the following species are included: *Ammonia batavus* (Hofker), *Buccella frigida* (Cushman), var. *calida* (Cushman & Cole), *Bulimina marginata* d'Orbigny, *Buliminella elegantissima* (d'Orbigny), *Cassidulina laevigata* d'Orbigny, *Eggerella scabra* (Williamson), *Elphidium albiumbilicatum* (Weiss), *E. gerthi* van Voorthuysen, *E. guntheri* Cole, *E. incertum* (Williamson), *E. magellanicum* Heron-Allen & Earland, *E. margaritaceum* Cushman, *E. voorthuyseni* Haake, *E. williamsoni* Haynes, *Jadammina polystoma* Bartenstein & Brand, *Nonion germanicum* (Ehrenberg), *Trochammina ochracea* (Williamson), *Uvigerina peregrina* Cushman and *Virgulina fusiformis* (Williamson).

The three forms of *Elphidium excavatum* (Terquem), the mainly Arctic forma *clavata* Cushman, the Boreal-Arctic forma *alba* Feyling-Hanssen and the mainly Boreal forma *selseyensis* (Heron-Allen & Earland), (see Feyling-Hanssen 1972a), are not counted separately in the present faunas. The dominance of one of these forms in proportion to the others in the faunas is estimated and shown by symbols in the frequency column, and the Boreal element represented by *E. excavatum*, forma *selseyensis* is therefore not included in the diagrams.

The foraminiferal "zones" described in the present work are assemblage zones, according to the definition given by Hedberg (1976). The term "zone" is used for the purpose of brevity.

FORAMINIFERAL ZONES AND PALAEOECOLOGY

SOLBERGA

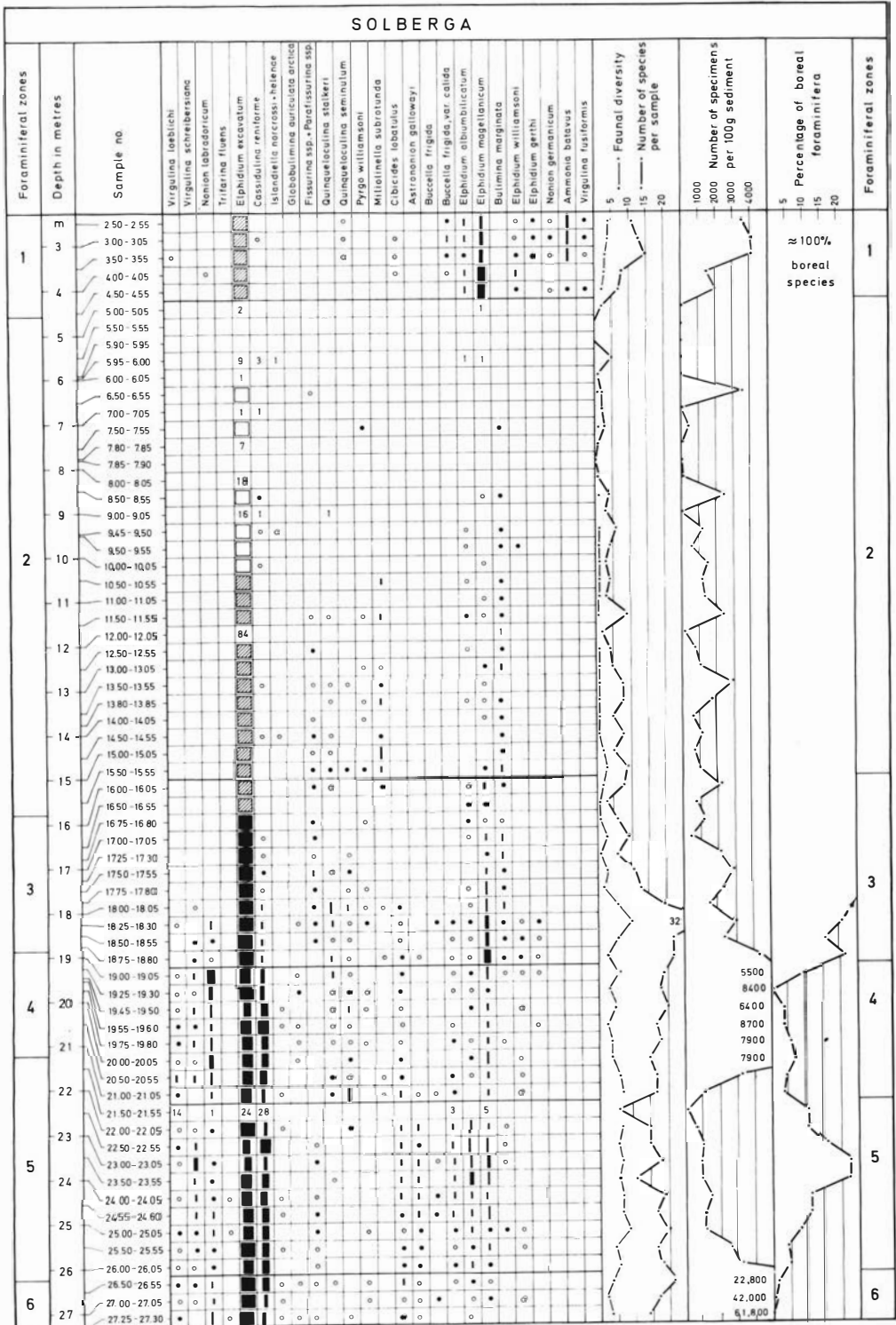
The marine sequence of the Solberga core is subdivided into 6 foraminiferal faunal zones shown in Fig. 14:1.

In the three lowest zones (zones 6, 5 and 4) the two dominant species are *Elphidium excavatum* and *Cassidulina reniforme*. Most specimens of *Elphidium excavatum* occur as the Arctic forma *clavata*, (see Feyling-Hanssen 1972a), but specimens of the mainly Boreal forma *selseyensis* are also found. The composition of these faunas indicates mainly arctic marine-ecological conditions, but there is a varying content of Boreal species. The dominance of *Elphidium excavatum* in all the faunas indicates that the water was ice-free, at least during the summer (Vilks 1970, Vilks and Mudie 1978).

The foraminiferal faunas of zone 6 indicate high-arctic marine-ecological conditions. The content of Boreal species does not exceed 2% and the faunal diversity is low (2-4). The very high number of specimens per 100 g sediment presumably indicates a low rate of sedimentation.

In zone 5 there is a pronounced increase in faunal diversity (5-9) and in content of Boreal species compared to zone 6. In two samples the percentages of Boreal species are as high as 23% of the total faunas. The most common Boreal species in zone 5 are *Elphidium albiumbilitatum*, *Elphidium magellanicum* and the Boreal forma *calida* of *Buccella frigida*. The decrease in number of specimens per 100 g sediment through zone 5 is suggested to reflect a higher rate of sedimentation during the milder period. A foraminiferal fauna from zone 5 is shown in Fig. 14:3.

In zone 4 the faunal diversity is slightly lower than in zone 5, and the influence of Boreal species in the faunas has decreased to between 1 and 7%. There is, however, an increase to 10% of boreal species in the uppermost sample. The most common boreal species in zone 4 is *Elphidium*



magellanicum. The faunas of zone 4 thus indicate colder marine-ecological conditions than in zone 5. The high frequencies of *Nonion labradoricum*, especially in the upper part of zone 4, together with high frequencies of *Cassidulina reniforme* indicate normal marine salinity conditions during deposition. These two species do not tolerate lowered salinity, and they are usually infrequent with water depths of less than about 20 m (Nagy 1965, Buzas 1965). An increased number of specimens per 100 g sediment in zone 4 compared to zone 5 may be a result of lower sedimentation rate during the colder period.

There is a remarkable and sudden change in faunal composition from zone 4 into zone 3, *i.e.* between the samples 19.00–19.05 m and 18.75–18.80 m. The frequency of *Nonion labradoricum* decreases from 21% in the uppermost sample of zone 4 to <0.5–2% in the lower part of zone 3. At the same level the percentages of *Cassidulina reniforme* also decrease distinctly to about 2–4% in the lower part of zone 3. These two species are absent in the upper part of zone 3. At the transition from zone 4 to zone 3 there is a pronounced increase in content of Boreal species, especially of *Elphidium magellanicum*. The faunal change can be interpreted as reflecting a climatic amelioration which caused a sudden increase in the supply of fresh meltwater to the area. The normal marine species disappear from the faunas, and the boreal *Elphidium magellanicum*, which seems to tolerate lowered salinity, takes over. A foraminiferal fauna from the lower part of zone 3 is shown in Fig. 14:4.

The faunal diversity and the number of species decrease towards the

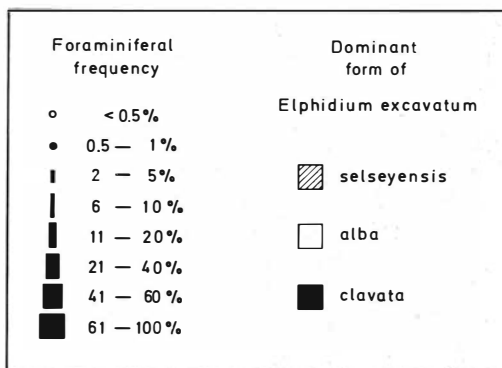


Fig. 14:2. Legend for the range charts in Figs. 14:1, 6 and 7.

Fig. 14:1. Range chart for Solberga core. Legend for foraminiferal frequencies and for forms of *Elphidium excavatum* in Fig. 14:2.

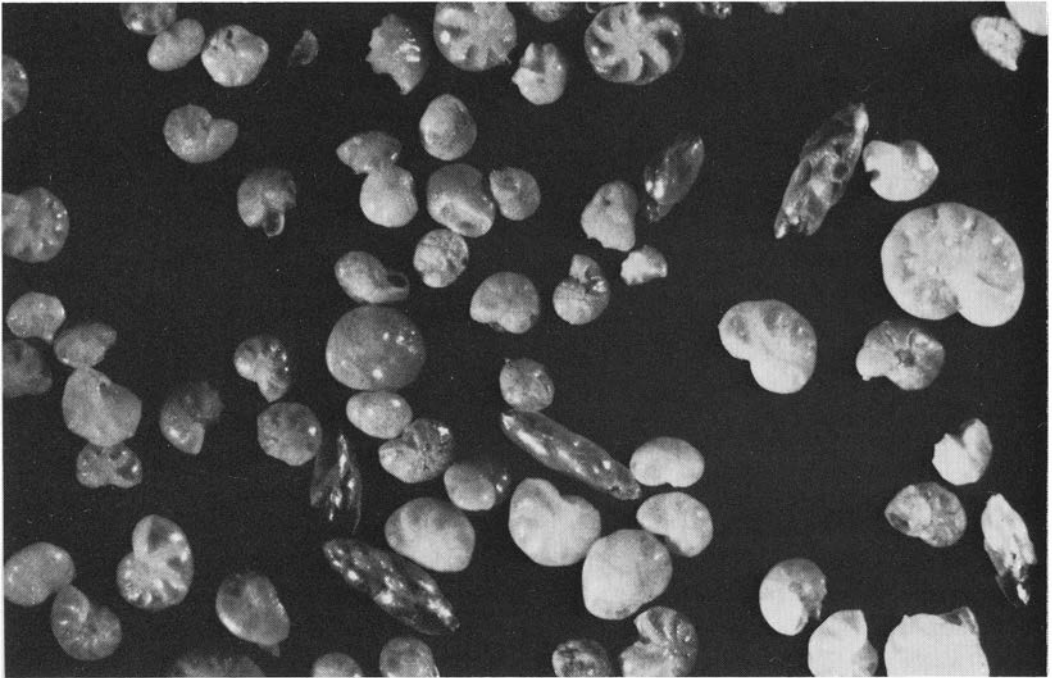


Fig. 14:3. Foraminiferal fauna from Solberga zone 5 (23.00–23.05 m). This is a mainly Arctic fauna with *Elphidium excavatum*, f. *clavata*, *Cassidulina reniforme* and *Virgulina schreibersiana* as the most common species, but there is a strong influence of Boreal species as *Elphidium albiumbilicatum* and *E. magellanicum* in the fauna. x 40.

upper part of zone 3, and in this part of the zone *E. excavatum* becomes extremely dominant. A change in dominant form of *E. excavatum* from the Arctic forma *clavata* to the Boreal forma *selseyensis* in the upper part of zone 3 suggests a continuing rise in temperature during deposition of this zone. As the different forms of *E. excavatum* are not included in the calculation of Boreal content in faunas, it has not been possible to indicate Boreal content for the faunas of zones 3 and 2 in Fig. 14:1.

The most common accessory species in zone 3 besides *Elphidium magellanicum* are the Boreal *Bulimina marginata* (<0.5–4%) and also *Quinqueloculina stalkerii* in the lower part of the zone. A decreasing number of specimens per 100 g sediment through zone 3 probably indicates an increasing rate of sedimentation during deposition.

The extreme ecological conditions indicated by the faunas in the upper part of zone 3 continued during deposition of zone 2, where the dominance of *Elphidium excavatum* is between 90 and 100%. The lower boundary of zone 2 is defined by the appearance of a few per cent of Miliolidae in the faunas. *Bulimina marginata* occurs in most faunas, but it usually only makes

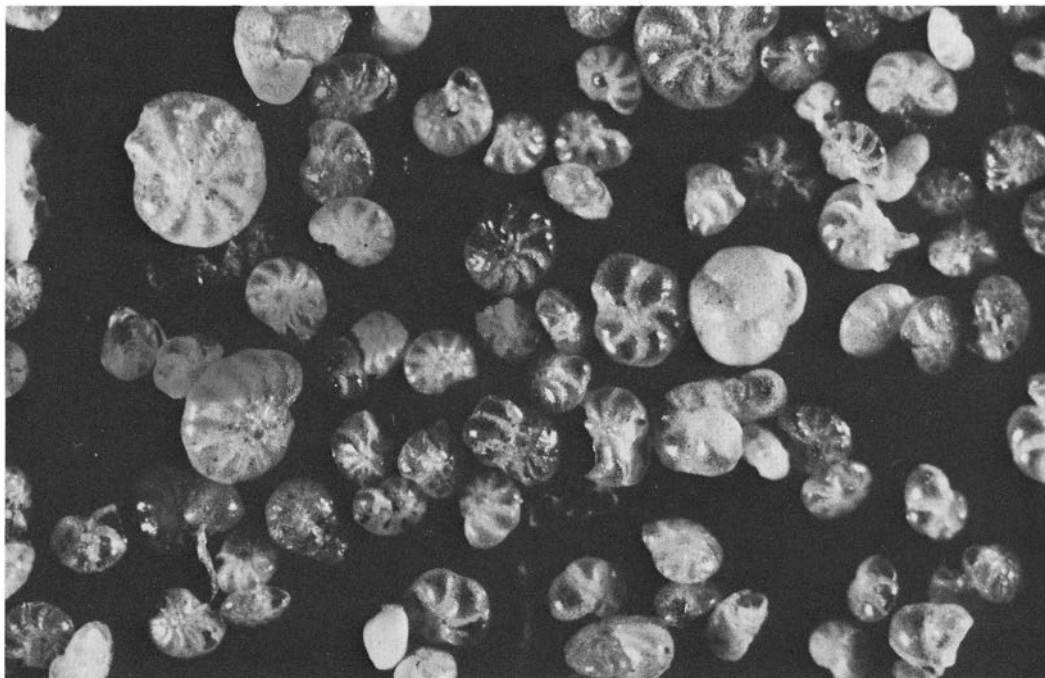


Fig. 14:4. Foraminiferal fauna from the lowermost sample of zone 3 in Solberga (18.75–18.80 m). The boreal species *Elphidium magellanicum* is frequent in this sample and dominates the fauna together with *Elphidium excavatum*, f. *clavata*. x 40.

up about 1% of the faunas. In the lower part of zone 2, *E. excavatum* occurs mainly as forma *selseyensis*, but specimens of forma *clavata* are also present. In a few samples in the upper part forma *alba* (Feyling-Hanssen 1972a) is the dominant form. The number of species and specimens is very low in the upper part of zone 2, and objective ecological interpretation is hardly possible although a continuing high rate of sedimentation seems probable. A great deal of the foraminiferal tests in the upper part of zone 2 are badly preserved and are often etched on the surface. Therefore the poor representation of foraminifera in samples from this part of the sequence may partly be due to postdepositional dissolution of shells in the sediment. A foraminiferal fauna from zone 2 is shown in Fig. 14:5.

The zone 1 faunas are typical Boreal shallow water faunas. *Elphidium excavatum*, forma *selseyensis* dominates, and the most important accessory species *Elphidium magellanicum*, *E. albiumbilicatum*, *E. williamsoni*, and *Ammonia batavus* all occur in Boreal shallow water areas. The low faunal diversity (2–4) indicates extreme ecological conditions during deposition, and the limiting factor for these faunas was presumably shallow water.



Fig. 14:5. Foraminiferal fauna from Solberga zone 2 (13.80–13.85 m) with a very high dominance of one species, *Elphidium excavatum*. It occurs mainly as forma *selseyensis*, but also as forma *clavata*. x 40.

MOLTEMYR

The marine sequence of the Moltemyr core is subdivided into 4 foraminiferal faunal zones, zones K, L, M, and N (Fig. 14:6). *Elphidium excavatum* is the dominant species in most samples. In the two lower zones this species occurs mainly as the arctic forma *clavata*, but specimens of the mainly Boreal forma *selseyensis* also occur, especially in zone M. The *selseyensis* form of *E. excavatum* is the most frequent one in zones L and K.

The foraminiferal faunas of zone N indicate high-arctic marine-climatic conditions. There is a very high dominance of the Arctic forma *clavata* of the species *Elphidium excavatum* together with frequent occurrences of *Cassidulina reniforme*, and a faunal diversity of only 3 indicates severe conditions. The content of Boreal specimens is less than 1% in zone N.

In zone M there is a pronounced increase in Boreal content of the faunas, the most common Boreal species being *Elphidium magellanicum*, *E. albumbilicatum*, *E. williamsoni*, and *Nonion germanicum*. The maximum percentage of Boreal specimens is 41 in sample 430 cm from the middle part of the zone, and in the upper part the boreal content decreases again to 13–19% of the total faunas. Faunal diversities also reach maximum values in the

middle part of this zone. The marine-climatic indication of foraminiferal faunas in zone M thus suggests a change from the high-arctic conditions of zone N to a relatively mild period with gradually increasing temperatures and a return to cooler conditions in the later part. All the faunas of zone M must be characterized as Boreal-Arctic.

There is a marked change in faunal composition from zone M to zone L, all the typical Arctic species disappearing from the faunas. The most frequent form of the dominant species *Elphidium excavatum* is the Boreal forma *selseyensis*, and the most common accessory species are the Boreal *Elphidium magellanicum* and *Nonion germanicum*, a few *E. albiumbilicatum* and *E. williamsoni*, and, in the upper part of the zone, also *E. incertum*. The low faunal diversities suggest extreme marine-ecological conditions during deposition of zone L. The water was probably shallower, and the influence of freshwater was probably higher than in the two lower zones of the Moltemyr core. The conditions during deposition of zone L must be characterized as Boreal.

The foraminiferal faunas of zone K indicate boreal shallow and brackish water conditions. Typical species are *Elphidium excavatum* (as the Boreal forma *selseyensis*), *Nonion germanicum*, *E. williamsoni*, *E. incertum*, and *E. magellanicum*, and in the upper part of the zone other additional Boreal shallow water species such as *E. albiumbilicatum* and *Ammonia batavus*. The low faunal diversities in most of zone K indicate extreme marine-ecological conditions, the limiting factor in this case presumably being shallow and brackish water. The higher diversities of the uppermost samples seem to be due to reworking of foraminiferal tests from older sediments. One sample (255.4–258.1 cm) from zone K did not contain any foraminifers. This might indicate a temporary regression previous to the final regression of the area, but etching of the tests by acid ground water seems also to have occurred in the zone K faunas.

BRASTAD

The marine sequence of the Brastad core is subdivided into 4 foraminiferal faunal zones, zones A–D (Fig. 14:7). *Elphidium excavatum* is the dominant species through all the zones, and *Cassidulina reniforme* is second in number.

The faunal compositions of the Brastad core indicate mainly arctic marine-ecological conditions, but there is a varying content of Boreal species in the faunas. The dominant form of *Elphidium excavatum* is the Arctic forma *clavata* through all zones, but specimens of the mainly Boreal forma *selseyensis* also occur.

In zone D there is high dominance of *Elphidium excavatum*, forma

In zone B there is a distinct increase in faunal diversity and in number of species compared to zone C. The increase in content of Boreal species, which started in the uppermost part of zone C, continues in zone B to reach a maximum of 17% in sample 2.75–2.80 m. The boreal content decreases again to 5% in the upper two samples of zone B. The present faunal composition thus indicates amelioration during deposition of zone B. The most common Boreal species in the faunas are *Elphidium albiumbilicatum* and *E. magellanicum* and the Boreal forma *calida* of *Buccella frigida*. The lower number of specimens in zone B compared to zone C may indicate a higher rate of sedimentation during the milder period, and the decrease in frequency of *Nonion labradoricum*, together with an increase in *Elphidium albiumbilicatum* and *E. magellanicum*, probably also reflect a slight decrease in salinity. As mentioned, there are indications of cooling again in the uppermost part of zone B.

Zone A is very poor in foraminifers. The species are broadly the same as in the preceding zones, but the faunas are much too poor to allow any attempt at ecological interpretations. The specimens may have been reworked from older marine deposits.

CORRELATIONS

A biostratigraphical correlation between the foraminiferal zones in Solberga, from the southern part of the area, and in Moltemyr and Brastad, from the northern part of the area, has been attempted (Fig. 14:9), and the faunas have been compared with corresponding faunas described from adjacent areas.

SOLBERGA, MOLTEMYR AND BRASTAD

Zone 6 in Solberga, which contains high-Arctic faunas, seems to be correlatable with zone N of the Moltemyr core and with the two high-Arctic zones C and D in Brastad. According to the palaeomagnetic results zone D in Brastad is probably not represented in Solberga (see Chapter 11).

In all three cores these zones with high-Arctic faunas are followed by zones with faunal indications of ameliorated conditions, viz., zone 5 in Solberga, zone M in Moltemyr and zone B in Brastad.

The Arctic zone 4 in Solberga is not represented in Brastad, except maybe in the uppermost part of zone B, where a colder period seems to have just set in. This suggested correlation implies that there was a break in sedimentation between zone B and zone A in Brastad.

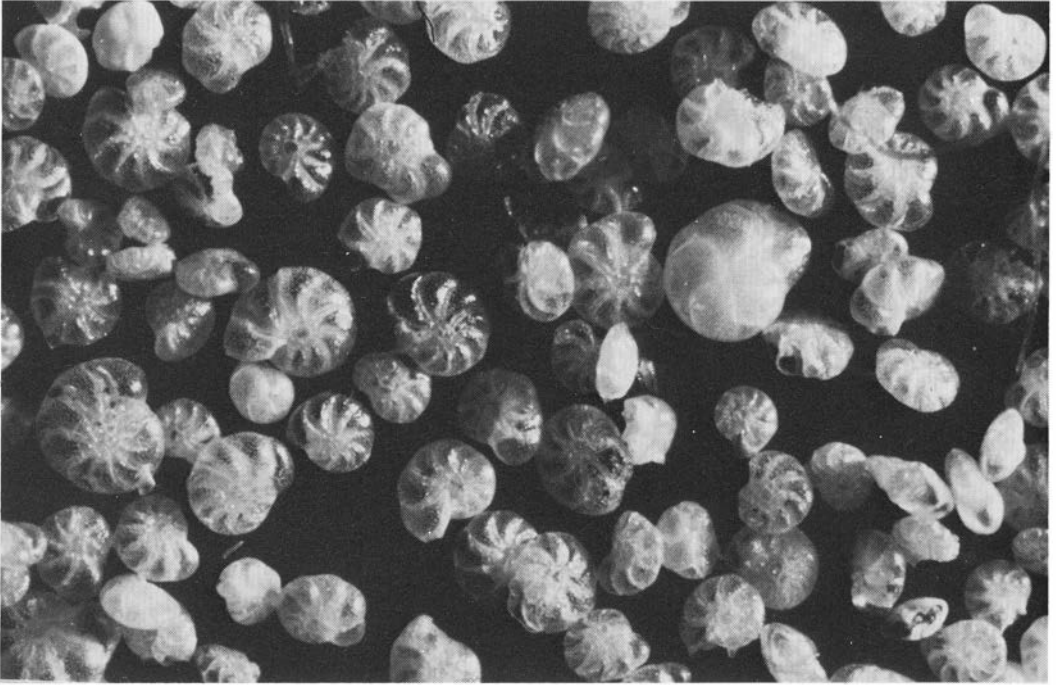


Fig. 14:8. Foraminiferal fauna from Brastad zone D (13.00–13.05 m). This high-Arctic fauna is dominated by only two species, *Elphidium excavatum*, f. *clavata* and *Cassidulina reniforme*. x 40.

The upper relatively cool part of zone M in the Moltemyr core may correspond to zone 4 in Solberga, but as a whole the faunas of zone M in Moltemyr seem to indicate milder conditions than zones 5 and 4 in Solberga. This may simply be a result of much shallower water at Moltemyr. Boreal foraminifers in the zone M faunas are also typical shallow water species.

Zone 3 in Solberga probably correlates with zone L in Moltemyr, and the later transition to real Boreal faunas with the *selseyensis* form of *Elphidium excavatum* at Solberga may also be explained as a consequence of deeper water in this area than in the Moltemyr area.

The faunal indication of the uppermost zone K in Moltemyr is close to that of zone 1 in Solberga. These faunas represent the shallowing of water preceding the regressions in the respective areas.

The upper two zones at Moltemyr and the upper three zones of Solberga seem not to be represented in the Brastad core. Zone A in the Brastad core contains scarcely any foraminifers, and a biostratigraphical correlation with the Moltemyr and Solberga sequences is not possible.

ADJACENT AREAS

A comparison between the foraminiferal zones in Solberga, Moltemyr and Brastad and earlier described foraminiferal faunas from western Sweden has been made. It seems that a transition from the Arctic *Elphidium excavatum*, f. *clavata*–*Cassidulina reniforme* faunas to faunas without *C. reniforme* and some other Arctic species, but with an increasing amount of Boreal species, is characteristic for the whole area. This transition presumably represents the Pleistocene/Holocene boundary in this area.

A very uniform *E. excavatum* fauna is often found higher in the sequences, comparable with the upper part of zone 3 and zone 2 in Solberga. Such faunas indicate very extreme conditions and probably a high rate of sedimentation which might be a result of the high meltwater discharge into the Skagerrak.

TUVE

In Tuve core 18 there is a distinct faunal change at about 8 m depth (Fält 1981.) The Arctic *Elphidium excavatum*–*Cassidulina reniforme* faunas in the lower part of the core are followed by faunas with a pronounced increase in Boreal species. This faunal change can be correlated with the transition from zone 4 to zone 3 in Solberga, and the Pleistocene/Holocene boundary thus seems to be represented at 8 m depth in the Tuve 18 boring.

A corresponding change from *Elphidium excavatum*–*Cassidulina reniforme* faunas to Boreal faunas is also demonstrated by Fält (1977) in cores from Kattegat (about 80 m water depth) north-west of Gothenburg. The Pleistocene/Holocene boundary seems to be represented at about 3.5 m and 5.0 m depth in these borings.

BÄCKEBOL

In a core from Bäckebo the *Cassidulina reniforme* faunas are not represented at all (Klingberg 1977). The faunas with very high dominances of *Elphidium excavatum* in the lower part of the marine sequence at Bäckebo probably correlate with the zone 2 faunas of Solberga, and the Pleistocene/Holocene boundary is presumably not reached in that boring.

GOTHENBURG CORE B873

The foraminiferal faunas from core B873 in the Botanical Garden, Gothenburg show a remarkable change of faunal composition in the deeper part of the boring (Feyling-Hanssen and Knudsen 1976). After samples (113–111) with typical Arctic *Elphidium excavatum*, f. *clavata*–*Cassidulina*

FORAMINIFERAL ZONES

Correlation

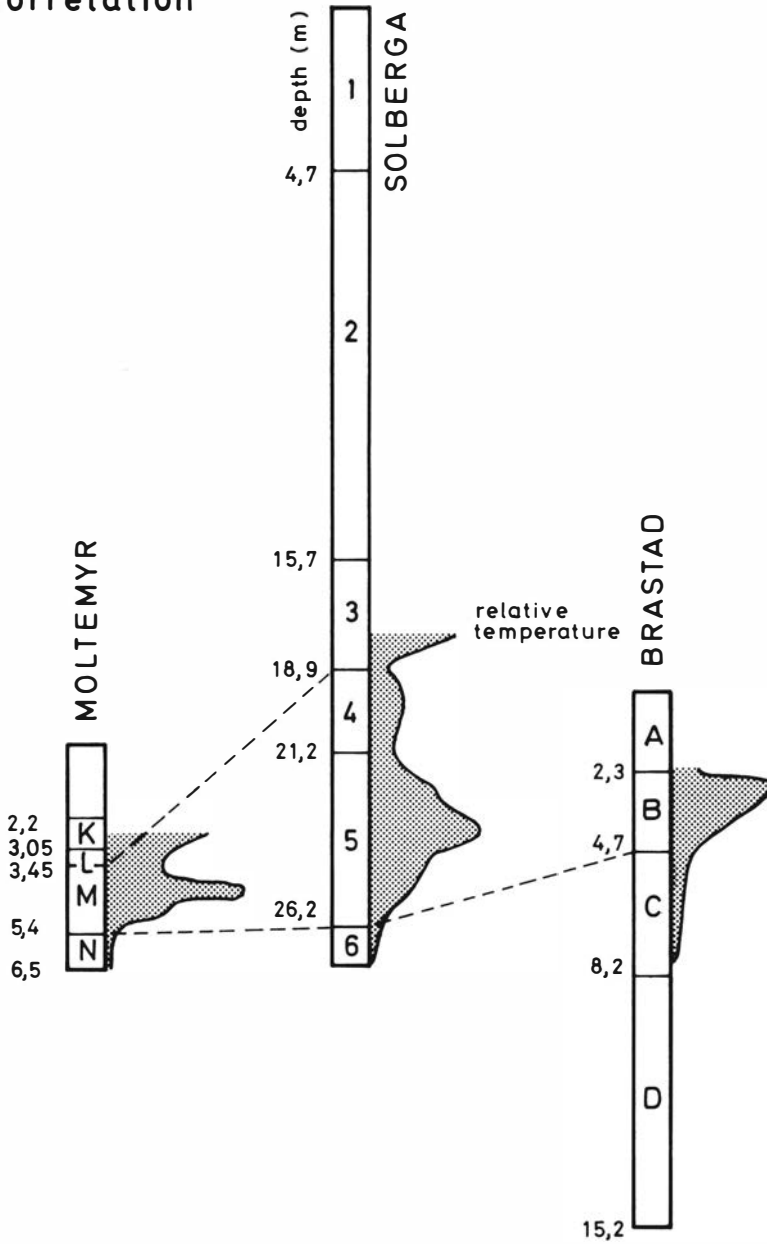


Fig. 14:9. Suggested biostratigraphical correlation between the foraminiferal zones in Solberga, Moltemyr and Brastad.

reniforme faunas follow two samples (110–109) with Boreal-Arctic to Boreal faunas above 13.5 m depth in the borehole. In 1976 this part of the sequence was placed in the Pleistocene, and the amelioration was suggested to represent an interstadial. The faunal indication could, however, just as well be interpreted as a late part of the Pleistocene, followed by the amelioration at the Pleistocene/Holocene boundary, as pointed out by Feyling-Hanssen and Knudsen (1976).

A correlation of the faunal change at 13.5 m depth in Gothenburg core B873 with the zone 4–zone 3 boundary in Solberga would lead to a tentative correlation between zone 2 in Solberga with its poor and very extreme faunas and the sequence without any foraminifers from 13.2 m to 2.5 m depth in Gothenburg. These sequences might represent a period of very rapid sedimentation, giving poor faunas at Solberga and no foraminiferal fauna at all at Gothenburg, such as the drainage of the Baltic Ice Lake and the discharge of meltwater into Skagerrak during the Preboreal times.

INGEBÄCK

By comparing the unpublished foraminiferal diagrams made by Brotzen (see also Brotzen 1961) from Ingebäck with the Solberga sequence, it seems most likely that the boundary between Brotzen's "Late Glacial I" and "Late Glacial II" at 35 m depth should be correlated with the boundary between zone 4 and zone 3 in Solberga. At that level *Cassidulina reniforme* and other Arctic species disappear from the faunas, and the interval from 35 m to 30 m in the Ingebäck boring seems to be correlatable with zone 3 in Solberga. The very uniform *Elphidium excavatum* faunas from 30 m to 15 m depth in Ingebäck points to a correlation with zone 2 in Solberga, and the upper 15 m contain Boreal shallow water faunas similar to the zone 1 faunas in Solberga. This correlation implies a Pleistocene/Holocene boundary deeper in the Ingebäck sequence than originally suggested, *i.e.* between "Late Glacial I" and "Late Glacial II" in Brotzen's zonation.

SURTE

A foraminiferal zonation of the marine sequence at Surte has been made by Brotzen (1951). He found a transition from Lateglacial to Postglacial faunas at the boundary between zone 4 b and zone 5, at 16 m depth. A comparison with the Solberga sequence seems to suggest a correlation of the zone 4 a–zone 4 b boundary in Surte with the zone 4–zone 3 boundary in Solberga. Such a correlation would imply that the Pleistocene/Holocene boundary might be represented at a lower level than Brotzen's Lateglacial-Postglacial boundary, *i.e.* between zone 4 a and zone 4 b at about 20 m depth.

DENMARK

The Arctic faunas in Solberga and Brastad correlate closely with foraminiferal faunas in Lateglacial deposits from Læsø (Michelsen 1967) and from Vendsyssel (Jørgensen 1971, Knudsen 1971 and 1978, Abrahamsen and Knudsen 1979). In some places in Vendsyssel a transition from high-Arctic faunas to Boreal-Arctic faunas is demonstrated in the sections, and radiocarbon dates show that the Boreal-Arctic faunas represent the Bølling Interstadial. There are similarities between the foraminiferal faunas in these deposits and the Boreal-Arctic faunas in zone 5 of Solberga, zone M in Moltemyr and zone B of Brastad, but this may, however, indicate corresponding environments rather than corresponding age. The Pleistocene/Holocene boundary is not represented in marine deposits of Vendsyssel.

NORWAY

The faunal change from zone 4 to zone 3 in Solberga and from zone M to zone L in Moltemyr is characterized by the change from *Elphidium excavatum*, f. *clavata*-*Cassidulina reniforme* faunas to faunas with Boreal species instead of Arctic ones.

A similar faunal change is described from the Late Quaternary deposits of the outer Oslofjord area (Feyling-Hanssen 1964) going from subzone B₁ into subzone B_u. Subzone B₁ is interpreted as having been deposited during stagnation of the ice margin at the Ås-Ski position and the deposition of subzone B_u is connected with the subsequent rapid melting from the Ås-Ski stage. New interpretations of radiocarbon dates from the Oslofjord area (Sørensen 1979) suggest that both the Ra ridges and the Ås-Ski moraines were formed during the Younger Dryas, and that the melting from the Ås-Ski position corresponds to the transition Younger Dryas-Preboreal. This interpretation implies that the boundary between the foraminiferal subzones B₁ and B_u corresponds to the Pleistocene/Holocene boundary and not, as earlier suggested (Feyling-Hanssen 1964, 1972b), the transition from subzone A_m to subzone A_u where a similar faunal succession is seen.

Ormaasen (1977) described corresponding Arctic foraminiferal faunas from Late Quaternary deposits of the Larvik-Porsgrunn area. The zones were compared closely with the Oslofjord zones of Feyling-Hanssen (1964), and the Pleistocene/Holocene boundary in the area was discussed. Late Pleistocene and Holocene foraminiferal zones from borings in the North Sea and Kattegat were described by Moyes *et al.* (1974), who also closely correlated their zones with the Oslofjord zones and discussed the Pleistocene/Holocene boundary in the area.

SUGGESTED AGE

Based on the palaeoecological interpretations and the biostratigraphical correlations with Late Quaternary deposits in adjacent areas, a possible age of the zones in Solberga, Moltemyr and Brastad is suggested.

Assuming continuous sedimentation during deposition of the marine sequence of Solberga, there are obvious reasons to believe that the faunal indication of milder marine-ecological conditions and increase in influence of fresh meltwater at the biostratigraphical boundary between zone 4 and zone 3 corresponds to the major amelioration of climate at the Pleistocene/Holocene boundary. This would imply that zone 4 represents the cold chronozone Younger Dryas (see Mangerud *et al.* 1974), a suggestion which is also supported by the biostratigraphical correlation with subzone B₁ in the Oslofjord area. As a consequence the Boreal-Arctic zone 5 of Solberga would represent the earlier amelioration of the climate, the Allerød Interstadial, and zone 6 would represent the Older Dryas Stadial.

According to the biostratigraphical correlations between Solberga and Moltemyr, the boundary between zones M and L in Moltemyr may correspond to the Pleistocene/Holocene boundary, and the amelioration in zone M is suggested to reflect interstadial conditions, most likely the Allerød Interstadial. The Younger Dryas would thus be represented only by the upper part of zone M, and the Older Dryas by zone N.

Another possibility is that the Pleistocene/Holocene boundary is represented by the first faunal indication of a milder climate in the Moltemyr core. This would lead to a correlation of the biostratigraphical boundary between zone N and zone M with the Pleistocene/Holocene boundary.

In Brastad the amelioration in zone B could represent the Allerød Interstadial. The uppermost cold spell of zone B may belong in the Younger Dryas, and the two arctic zones C and D below zone B may represent the Older Dryas. The poor faunas with only a few Boreal specimens in the lower part of zone D could probably indicate another mild period, *i.e.* Bølling Interstadial, but the faunas are too poor to allow any convincing interpretation.

Zones 3, 2 and 1 in Solberga and zones K and L in Moltemyr thus seem to belong in the Holocene epoch, but it is not possible to give any closer suggestions as to the age of these zones on the basis of foraminiferal faunas. The zone 1 faunas of Solberga and the zone K faunas of the Moltemyr core cannot, however, be much different from present day shallow water faunas in that area.

CONCLUSIONS

The marine sequence of Solberga is divided into 6 foraminiferal assemblage zones (1–6). The faunas of the lower three zones (6, 5 and 4) indicate mainly arctic marine-ecological conditions with a distinct influence of Boreal species in the zone 5 faunas. There is a remarkable change in faunal composition from zone 4 to zone 3, *i.e.* just above 19.00 m depth in Solberga. This faunal change is interpreted as a result of higher temperature and of increasing supply of fresh meltwater to the area, and the biostratigraphical boundary between zone 4 and zone 3 may correspond to the Pleistocene/Holocene boundary. The amelioration seen in zone 5 could thus represent the Allerød Interstadial, with the Arctic faunas of the Older Dryas age below (zone 6) and of the Younger Dryas age above (zone 4).

The foraminiferal faunas of zones 3, 2 and 1 in Solberga contain faunas which reflect increasing temperature during deposition. The faunas of zone 2 indicate very extreme conditions probably caused at least partly by a high rate of sedimentation, and zone 1 contains typical Boreal shallow water faunas.

The marine sequence of the Moltemyr core is divided into 4 foraminiferal assemblage zones (K, L, M and N). The two lower zones (M and N) are characterized by mainly Arctic faunas, but in zone M there is a gradual change to Boreal-Arctic faunas and indications of cooler conditions again in the upper part of this zone. In zone L the Arctic species are absent, and the faunas in this zone and in zone K are Boreal, indicating gradually shallower water through the sequence. The biostratigraphical boundary between zone M and zone L in Moltemyr is correlated with the boundary between zones 4 and 3 in Solberga, and this may correspond to the major amelioration of climate at the Pleistocene/Holocene boundary.

In Brastad the sequence is subdivided into 4 foraminiferal assemblage zones (A, B, C, and D). The faunas of the lower three zones (B, C and D) indicate mainly Arctic environments, but there is an indication of a gradual amelioration through zone B and a return to cooler conditions again in the upper part of that zone. This milder period may be correlatable with zone 5 in Solberga and with the amelioration of zone M in Moltemyr, and thus it may represent the Allerød Interstadial. Zone C in Brastad, which is biostratigraphically correlated with zone 6 in Solberga and with zone N in Moltemyr, would then be of Older Dryas age, and zone D, which seems not to be represented in Moltemyr and Solberga, probably belongs in the same Stadial. The minor influence of Boreal species in some of the poor faunas of the lower part of zone D could, however, be interpreted as a weak indication of another interstadial period, *viz.* the Bølling Interstadial.

Zone A in Brastad contains very few foraminifers, probably reworked, and there seems to have been a break in sedimentation between zone B and zone A. The Pleistocene/Holocene boundary is probably not represented in Brastad.

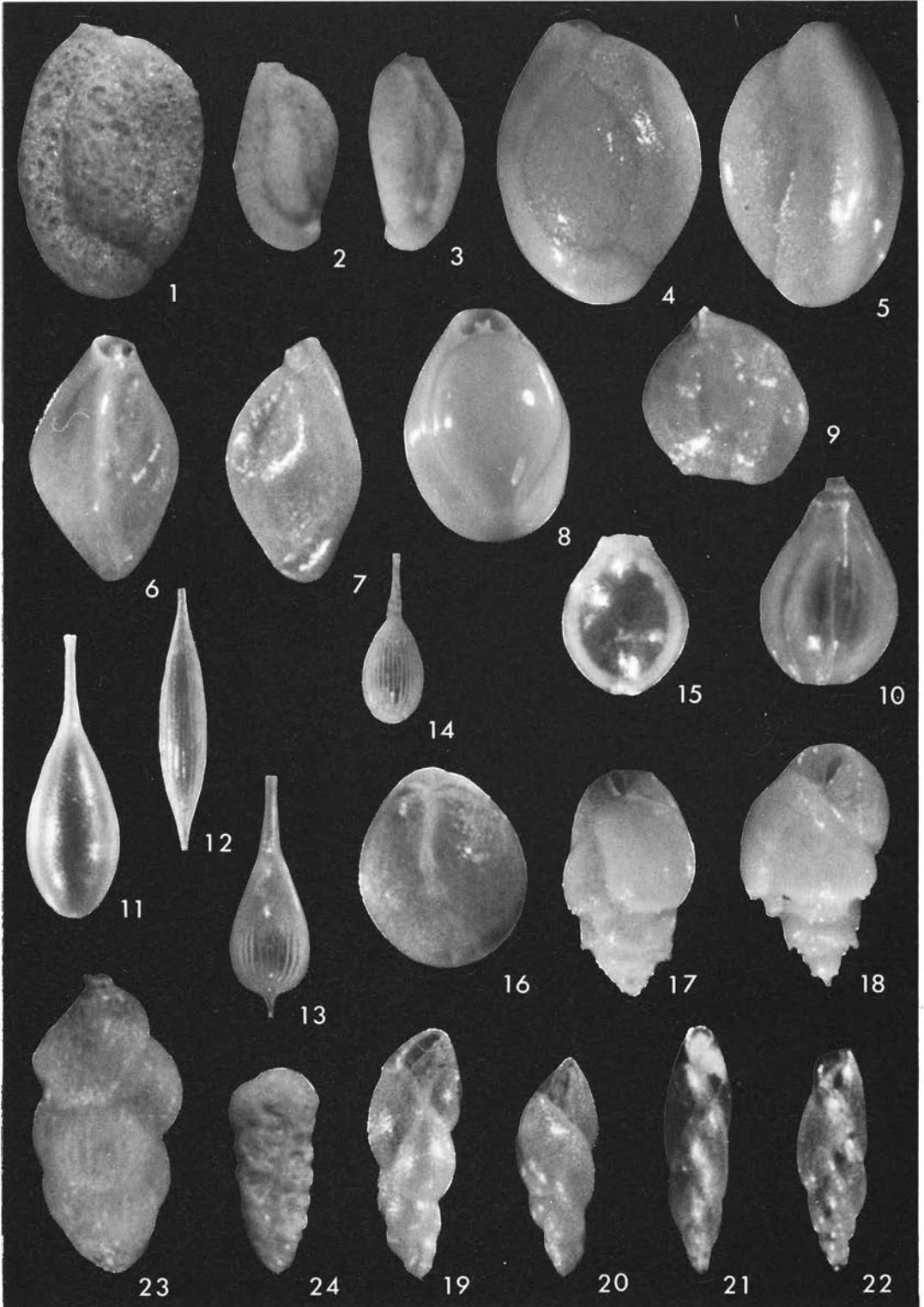
FORAMINIFERA

The foraminiferal species found in the cores Solberga, Moltemyr and Brastad are arranged alphabetically in the following list. The most common species are illustrated by photographs and scanning electron micrographs in Figs. 14:10–14. For original references, synonymy lists, taxonomic remarks and additional illustrations of the species in the present material, the reader is referred to the systematic section by Knudsen (*in* Feyling-Hanssen *et al.* 1971), or to the more recent literature mentioned in the present work (e.g. Feyling-Hanssen 1972a, Hansen and Lykke-Andersen 1976, Knudsen 1978, 1980, Sejrup and Guilbault 1980).

In addition to the 78 listed species, different species within the family Polymorphinidae d'Orbigny, 1839 were found. Together these usually account for less than 0.5% of the fauna, and they have been counted as a single group in the present material.

Fig. 14:10.

1. *Quinqueloculina agglutinata* Cushman from Brastad zone C, spl. 6.00–6.05 m. x 75.
- 2, 3. *Quinqueloculina stalkeri* Loeblich & Tappan from Solberga zone 3, spl. 18.75–18.80 m. x 105.
- 4, 5. *Quinqueloculina seminulum* Linné from Solberga zone 3, spl. 18.00–18.05 m. x 75.
- 6, 7. *Triloculina trihedra* Loeblich & Tappan from Solberga zone 4, spl. 19.45–19.50 m. x 105.
8. *Pyrgo williamsoni* (Silvestri) from Brastad zone C, spl. 6.50–6.55 m. x 75.
9. *Miliolinella subrounda* (Montagu) from Solberga zone 2, spl. 15.00–15.05 m. x 90.
10. *Lagena apiopleura* Loeblich & Tappan from Brastad zone B, spl. 4.00–4.05 m. x 90.
11. *Lagena laevis* (Montagu) from Brastad zone C, spl. 7.50–7.55 m. x 70.
12. *Lagena mollis* Cushman from Solberga zone 3, spl. 17.75–17.80 m. x 70.
13. *Lagena semilineata* Wright from Brastad zone C, spl. 5.00–5.05 m. x 70.
14. *Lagena striata* (d'Orbigny), f. *typica* from Solberga zone 3, spl. 18.75–18.80 m. x 70.
15. *Fissurina lucida* (Williamson) from Solberga zone 3, spl. 18.00–18.05 m. x 105.
16. *Fissurina marginata* (Montagu) from Solberga zone 5, spl. 25.50–25.55 m. x 105.
- 17, 18. *Bulimina marginata* d'Orbigny. 17. From Solberga zone 3, spl. 17.25–17.30 m. x 75. 18. From Solberga zone 3, spl. 18.50–18.55 m. x 75.
- 19, 20. *Virgulina loeblichii* Feyling-Hanssen. 19. From Solberga zone 4, spl. 19.25–19.30 m. x 75. 20. From Solberga zone 4, spl. 19.75–19.80 m. x 75.
- 21, 22. *Virgulina schreibersiana* Czjzek. 21. From Solberga zone 4, spl. 19.55–19.60 m. x 90. 22. From Solberga zone 4, spl. 19.75–19.80 m. x 90.
23. *Trifarina fluens* (Todd) from Brastad zone C, spl. 5.00–5.05 m. x 105.
24. *Bolivina pseudoplicata* Höglund from Solberga zone 3, spl. 18.25–18.30 m. x 105.



The frequencies of the most common and characteristic species in the deposits are shown in the range charts (Figs. 14:1, 6 and 7). Other species in the list only occur scattered in the deposits, and usually they account for 1 or less than 1% of the faunas.

The figured specimens, Catalogue No. 1981-KLK-1 to 1981-KLK-67, are kept in the Department of Micropalaeontology, Geological Institute, University of Aarhus, 8000 Aarhus C, Denmark.

Ammonia batavus (Hofker, 1951)

Fig. 12:20–23

Astaculus hyalacrurus Loeblich & Tappan, 1953

Astrononion gallowayi Loeblich & Tappan, 1953

Fig. 11:24, 25; Fig. 13:3

Bolivina minima Phleger & Parker, 1951

Bolivina pseudoplicata Heron-Allen & Earland, 1930

Fig. 10:24

Bolivina pseudopunctata Höglund, 1947

Bolivina robusta Brady, 1884

Buccella frigida (Cushman, 1922)

Fig. 11:14, 15

Buccella frigida (Cushman), var. *calida* (Cushman & Cole, 1930)

Fig. 11:16, 17; Fig. 13:2

Bulimina marginata d'Orbigny, 1826

Fig. 10:17, 18

Buliminella elegantissima (d'Orbigny, 1839)

Cassidulina laevigata d'Orbigny, 1826

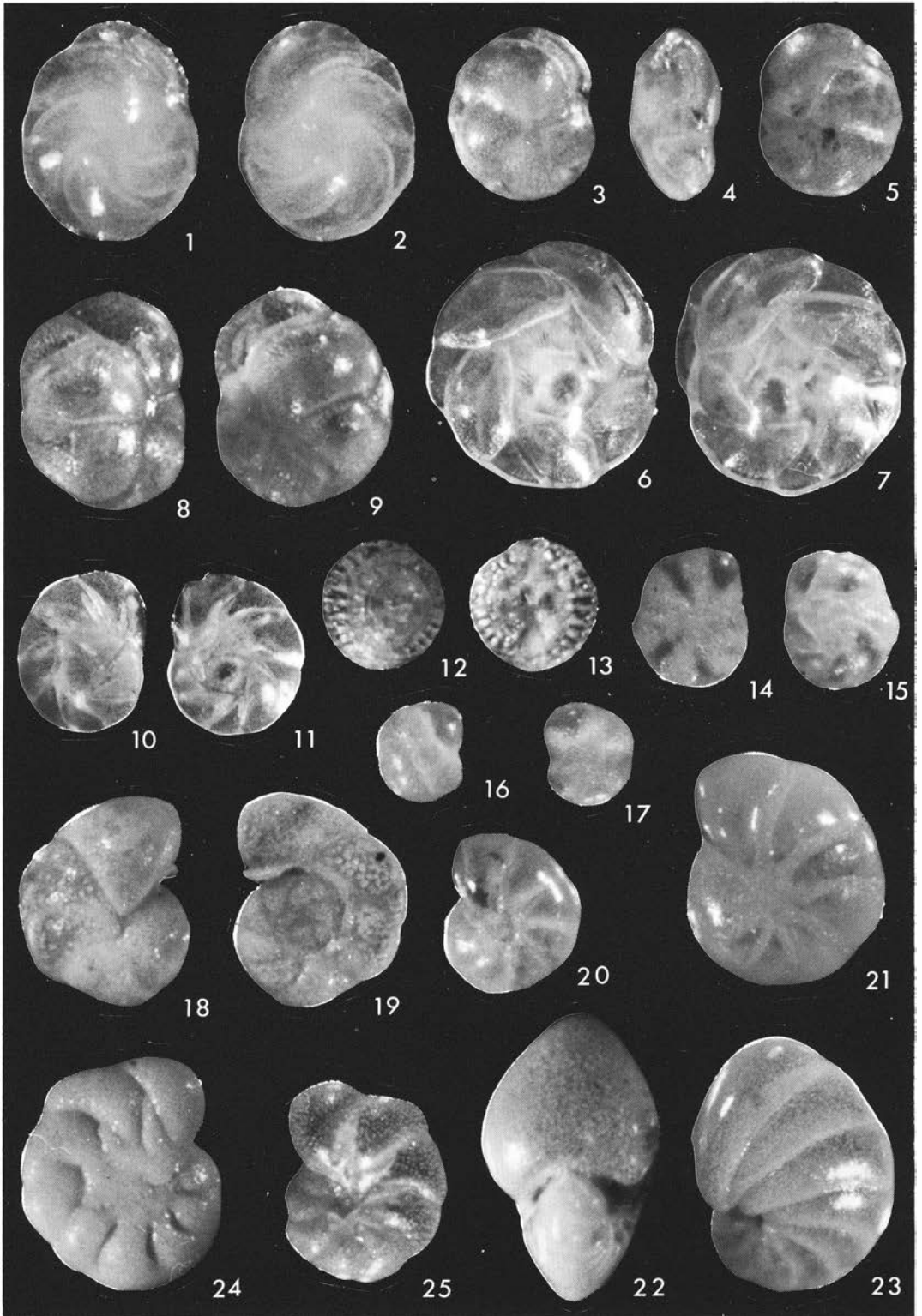
Fig. 11:1, 2

Cassidulina reniforme Nørvang, 1945

Fig. 11:3–5

Fig. 14:11.

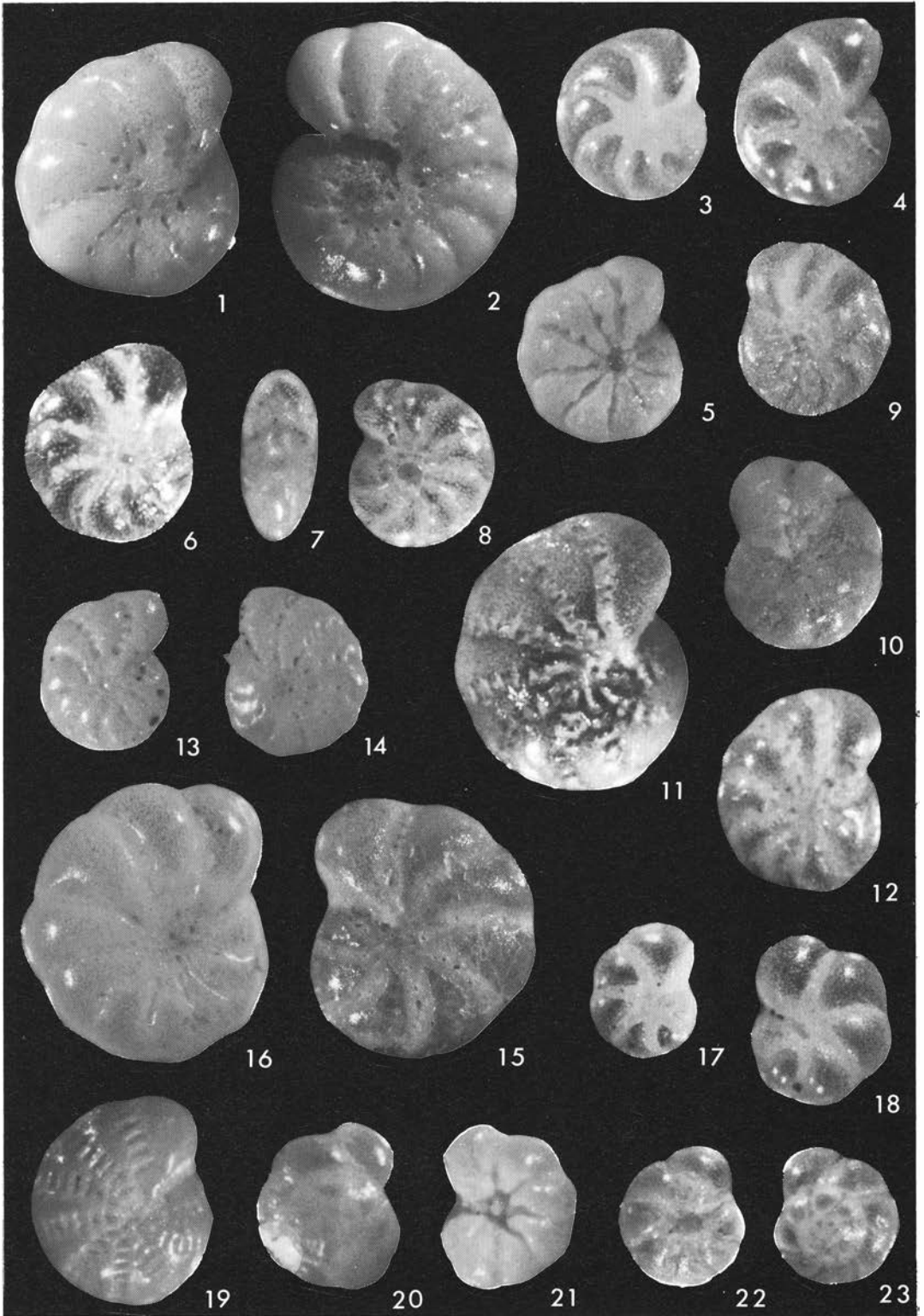
- 1, 2. *Cassidulina laevigata* d'Orbigny from Solberga zone 3, spl. 18.00–18.05 m. x 75.
- 3–5. *Cassidulina reniforme* Nørvang from Solberga zone 4, spl. 19.25–19.30 m. x 75.
- 6, 7. *Islandiella helenae* Feyling-Hanssen & Buzas from Brastad zone B, spl. 4.00–4.05 m. x 60.
- 8, 9. *Islandiella islandica* (Nørvang) from Brastad zone B, spl. 4.00–4.05 m. x 90.
- 10, 11. *Islandiella norcrossi* (Cushman) from Brastad zone C, spl. 6.50–6.55 m. x 75.
- 12, 13. *Patellina corrugata* Williamson from Solberga zone 5, spl. 24.00–24.05 m. x 75.
- 14, 15. *Buccella frigida* (Cushman) from Solberga zone 4, spl. 21.00–21.05 m. x 100.
- 16, 17. *Buccella frigida* (Cushman), var. *calida* (Cushman & Cole) from Solberga zone 4, spl. 21.00–21.05 m. x 100.
- 18, 19. *Cibicides lobatulus* (Walker & Jacob) from Solberga zone 1, spl. 3.00–3.05 m. x 75.
20. *Nonion germanicum* (Ehrenberg) from Solberga zone 1, spl. 2.50–2.55 m. x 75.
21. *Nonion orbiculare* (Brady) from Brastad zone B, spl. 3.50–3.55 m. x 75.
- 22, 23. *Nonion labradoricum* (Dawson). 22. From Solberga zone 4, spl. 19.25–19.30 m. x 75.
23. From Solberga zone 4, spl. 19.25–19.30 m. x 60.
- 24, 25. *Astrononion gallowayi* Loeblich & Tappan. 24. From Brastad zone B, spl. 2.75–2.80 m. x 75. 25. From Solberga zone 6, spl. 26.50–26.55 m. x 75.



- Cibicides lobatulus* (Walker & Jacob, 1798)
 Fig. 11:18, 19
- Cyclogyra involvens* (Reuss, 1850)
- Dentalina ittai* Loeblich & Tappan, 1953
- Eggerella scabra* (Williamson, 1858)
- Elphidium albumbilicatum* (Weiss, 1954)
 Fig. 12:3, 4; Fig. 13:6, 7
- Elphidium asklundi* Brotzen, 1943
 Fig. 12:1, 2
- Elphidium excavatum* (Terquem), forma *alba* Feyling-Hanssen, 1972
 Fig. 12:5; Fig. 14:8, 9
- Elphidium excavatum* (Terquem), forma *clavata* Cushman, 1930
 Fig. 12:6–8; Fig. 14:1–4
- Elphidium excavatum* (Terquem), forma *selseyensis* (Heron-Allen & Earland, 1911)
 Fig. 12:9–12; Fig. 14:5–7
- Elphidium gerthi* van Voorthuysen, 1957
 Fig. 12:13, 14
- Elphidium guntheri* Cole, 1931
- Elphidium hallandense* Brotzen, 1943
 Fig. 12:15
- Elphidium incertum* (Williamson, 1858)
 Fig. 12:16
- Elphidium magellanicum* Heron-Allen & Earland, 1932
 Fig. 12:17, 18; Fig. 13:4, 5
- Elphidium margaritaceum* Cushman, 1930
- Elphidium voorthuyseni* Haake, 1962
- Elphidium williamsoni* Haynes, 1973
 Fig. 12:19; Fig. 14:10, 11
-

Fig. 14:12.

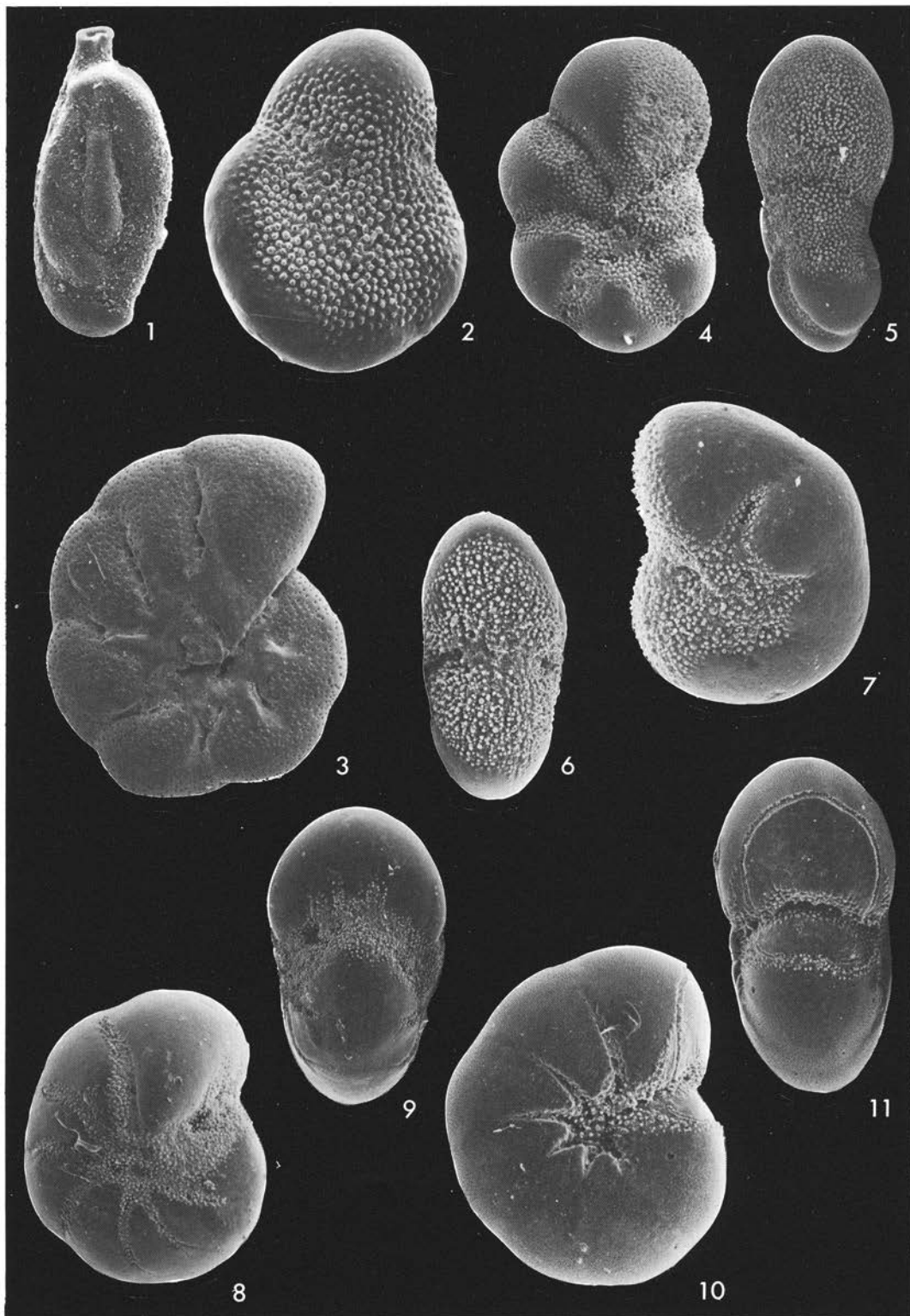
- 1, 2. *Elphidium asklundi* Brotzen. 1. From Solberga zone 6, spl. 26.50–26.55 m. x 60. 2. From Brastad zone D, spl. 8.50–8.55 m. x 60.
- 3, 4. *Elphidium albumbilicatum* (Weiss). 3. From Brastad zone C, spl. 6.50–6.55 m. x 90. 4. From Solberga zone 3, spl. 18.00–18.05 m. x 75.
5. *Elphidium excavatum* (Terquem), forma *alba* Feyling-Hanssen from Solberga zone 2, spl. 8.50–8.55 m. x 75.
- 6–8. *Elphidium excavatum* (Terquem), forma *clavata* Cushman. 6. From Solberga zone 3, spl. 16.00–16.05 m. x 75. 7, 8. From Solberga zone 3, spl. 18.75–18.80 m. x 75.
- 9–12. *Elphidium excavatum* (Terquem), forma *selseyensis* (Heron-Allen & Earland). 9. From Solberga zone 3, spl. 16.00–16.05 m. x 75. 10. From Solberga zone 2, spl. 11.00–11.05 m. x 75. 11. From Solberga zone 2, spl. 11.50–11.55 m. x 75. 12. From Solberga zone 1, spl. 4.00–4.05 m. x 90.
- 13, 14. *Elphidium gerthi* van Voorthuysen. 13. From Solberga zone 1, spl. 3.50–3.55 m. x 90. 14. From Solberga zone 1, spl. 3.00–3.05 m. x 90.
15. *Elphidium hallandense* Brotzen from Solberga zone 3, spl. 18.00–18.05 m. x 60.
16. *Elphidium incertum* (Williamson) from Moltemyr zone K, spl. 295.9–298.6 cm. x 60.
- 17, 18. *Elphidium magellanicum* Heron-Allen & Earland. 17. From Solberga zone 3, spl. 18.75–18.80 m. x 75. 18. From Solberga zone 3, spl. 18.75–18.80 m. x 90.
19. *Elphidium williamsoni* Haynes from Solberga zone 4, spl. 20.00–20.05 m. x 75.
- 20–23. *Ammonia batavus* (Hofker). 20, 21. From Solberga zone 1, spl. 3.00–3.05 m. x 75. 22, 23. From Solberga zone 1, spl. 3.00–3.05 m. x 75.



- Eoeponidella laesoensis* Michelsen, 1967
Epistominella takayanagii Iwasa, 1955
Fissurina laevigata Reuss, 1850
Fissurina lucida (Williamson, 1848)
 Fig. 10:15
Fissurina marginata (Montagu, 1803)
 Fig. 10:16
Fissurina serrata (Schlumberger, 1894)
Globobulimina auriculata (Bailey), forma *arctica* Höglund, 1947
Islandiella helenae Feyling-Hanssen & Buzas, 1976
 Fig. 11:6, 7
Islandiella islandica (Nørvang, 1945)
 Fig. 11:8, 9
Islandiella norcrossi (Cushman, 1933)
 Fig. 11:10, 11
Jadammina polystoma Bartenstein & Brand, 1938
Lagena apiopleura Loeblich & Tappan, 1953
 Fig. 10:10
Lagena hirtshalsensis Andersen, 1971
Lagena gracillima (Seguenza, 1862)
Lagena laevis (Montagu, 1803)
 Fig. 10:11
Lagena mollis Cushman, 1944
 Fig. 10:12
Lagena semilineata Wright, 1886
 Fig. 10:13
Lagena striata (d'Orbigny), forma *substriata* Williamson, 1848
Lagena striata (d'Orbigny, 1839) forma *typica*
 Fig. 10:14
Lamarckina haliotideae (Heron-Allen & Earland, 1911)
Laryngosigma hyalascidia Loeblich & Tappan, 1953
Lenticulina cf. *angulata* (Reuss, 1851)
Lenticulina gibba (d'Orbigny, 1839)
Lenticulina limbosus (Reuss, 1863)
Miliolinella subrotunda (Montagu, 1803)
 Fig. 10:9

Fig. 14:13. (SEM).

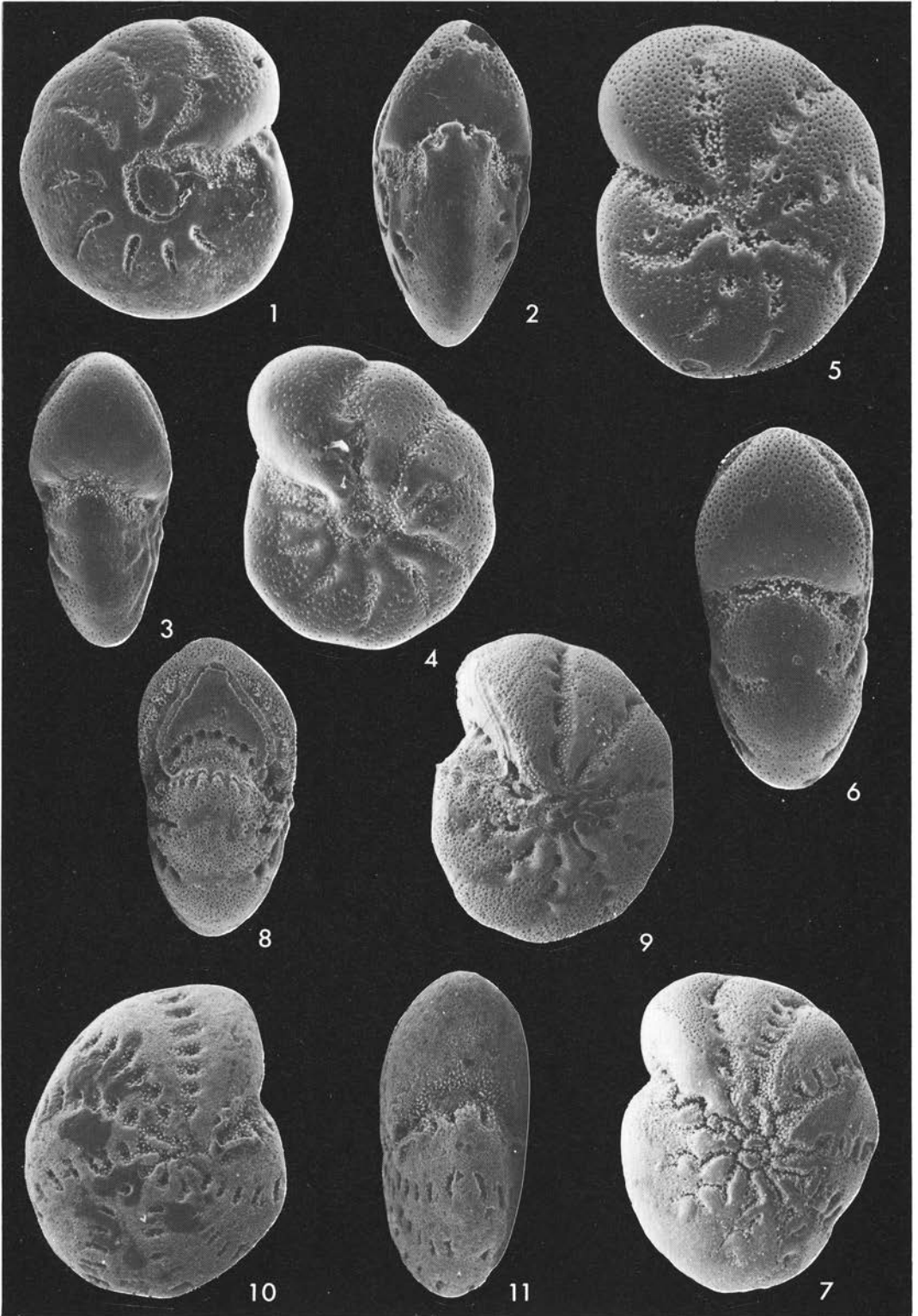
1. *Quinqueloculina stalkerii* Loeblich & Tappan from Solberga zone 3, spl. 18.25–18.30 m. x 190.
2. *Buccella frigida* (Cushman), var. *calida* (Cushman & Cole) from Solberga zone 3, spl. 18.25–18.30 m. x 340.
3. *Astrononion gallowayi* Loeblich & Tappan from Solberga zone 5, spl. 26.00–26.05 m. x 140.
- 4, 5. *Elphidium magellanicum* Heron-Allen & Earland from Solberga zone 1, spl. 3.00–3.05 m. x 180.
- 6, 7. *Elphidium albiumbilicatum* (Weiss) from Solberga zone 5, spl. 24.00–24.05 m. x 280.
- 8, 9. *Nonion orbiculare* (Brady) from Brastad zone B, spl. 3.50–3.55 m. x 100.
- 10, 11. *Nonion germanicum* (Ehrenberg) from Solberga zone 1, spl. 2.50–2.55 m. x 170.



- Nonion germanicum* (Ehrenberg, 1840)
 Fig. 11:20; Fig. 13:10, 11
- Nonion labradoricum* (Dawson, 1960)
 Fig. 11:22, 23
- Nonion orbiculare* (Brady, 1881)
 Fig. 11:21; Fig. 13:8, 9
- Nonionella auricula* Heron-Allen & Earland, 1930
- Oolina hexagona* (Williamson, 1848)
- Oolina lineata* (Williamson, 1848)
- Oolina melo* d'Orbigny, 1839
- Oolina williamsoni* (Alcock, 1865)
- Parafissurina tectulostoma* Loeblich & Tappan, 1953
- Patellina corrugata* Williamson, 1858
 Fig. 11:12, 13
- Pullenia bulloides* (d'Orbigny, 1826)
- Pullenia osloensis* Feyling-Hanssen, 1954
- Pyrgo williamsoni* (Silvestri, 1923)
 Fig. 10:8
- Quinqueloculina agglutinata* Cushman, 1917
 Fig. 10:1
- Quinqueloculina seminulum* (Linné, 1758)
 Fig. 10:4, 5
- Quinqueloculina stalkerii* Loeblich & Tappan, 1953
 Fig. 10:2, 3; Fig. 13:1
- Rosalina praegeri* (Heron-Allen & Earland, 1913)
- Sigmoilopsis schlumbergeri* (Silvestri, 1904)
- Trifarina fluens* (Todd, 1947)
 Fig. 10:23
- Triloculina trigonula* (Lamarck, 1804)
- Triloculina trihedra* Loeblich & Tappan, 1953
 Fig. 10:6, 7
- Trochammina ochracea* (Williamson, 1858)
- Uvigerina peregrina* Cushman, 1923
- Virgulina fusiformis* (Williamson, 1858)
- Virgulina loeblichii* Feyling-Hanssen, 1954
 Fig. 10:19, 20
- Virgulina schreibersiana* Czjzek, 1848
 Fig. 10:21, 22

Fig. 14:14. (SEM).

- 1-4. *Elphidium excavatum* (Terquem), forma *clavata* Cushman. 1, 2. From Solberga zone 6, spl. 27.00-27.05 m. x 180. 3, 4. From Solberga zone 6, spl. 27.00-27.05 m. x 190.
- 5-7. *Elphidium excavatum* (Terquem), forma *selseyensis* (Heron-Allen & Earland). 5, 6. From Solberga zone 1, spl. 3.00-3.05 m. x 210. 7. From Solberga zone 2, spl. 11.00-11.05 m. x 110.
- 8, 9. *Elphidium excavatum* (Terquem), forma *alba* Feyling-Hanssen from Solberga zone 2, spl. 6.50-6.55 m. x 135.
- 10, 11. *Elphidium williamsoni* Haynes from Solberga zone 1, spl. 4.50-4.55 m. x 140.



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15. CALCAREOUS NANNOFOSSILS

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INTRODUCTION

Coccoliths, the 2–20 microns large calcareous plates covering the cells of marine coccolithophorid algae, are common constituents of open ocean sediments. The coccolithophorids are living in the euphotic zone of the oceans and are not thriving in brakish or fresh water environments.

Fossil coccoliths provide an important tool for biostratigraphical and palaeoecological work. Within the Quaternary period, five calcareous nannofossil zones are recognized (Gartner 1977), but none of these define the Pleistocene/Holocene boundary. In palaeoceanographic work coccoliths have provided useful information on the deglaciation history of the North Atlantic (McIntyre 1967), and at present the postglacial history of the Skagerrak is being investigated by multidisciplinary studies including coccoliths of corematerial from that area (Thiede *et al.*, in prep.).

Coccoliths generally leave a minor imprint in near-shore sediments compared to open ocean deposits due to dilution by clastic material. The sediments deposited during the Pleistocene-Holocene period along the Swedish West Coast represent such a depositional environment with a pronounced influence of terrestrial material. This material includes rock fragments and a number of microfossil groups reworked from sediments of various ages. As a result, Quaternary coccoliths have a very sparse occurrence in the cores studied and the coccolith assemblages are dominated by reworked species. In the present paper the occurrence of Quaternary and reworked coccoliths in the south-western Swedish cores is outlined and the palaeoecological significance of their distribution discussed.

MATERIAL AND METHODS

The occurrence of calcareous nannofossils has been investigated in samples from three cores, the Brastad core (37 samples), the Moltemyr core (46

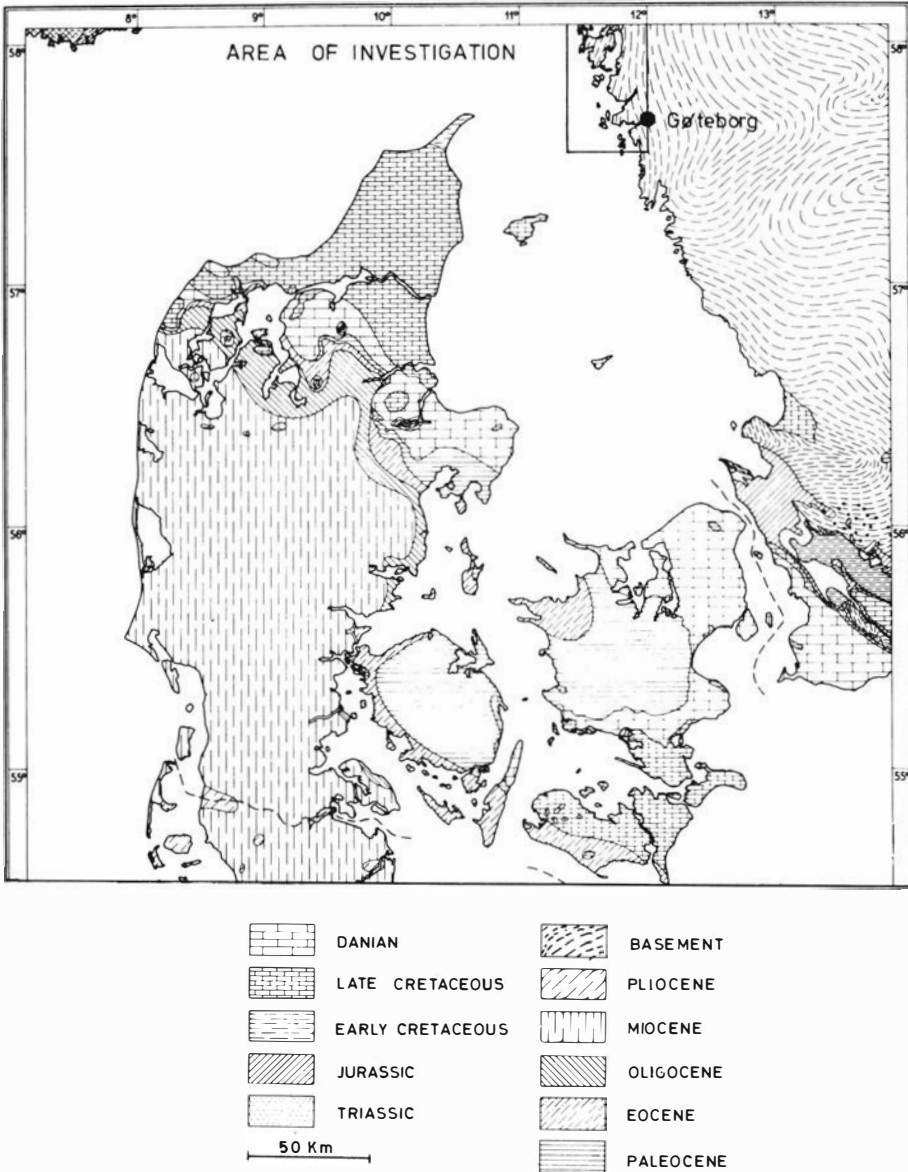


Fig. 15:1. Subsurface map of Denmark and Southern Sweden (after T. Sorgenfrei). Reworked material of Late Cretaceous and Early Tertiary ages occurs frequently in the cores selected for the study of the Pleistocene/Holocene boundary north of Gothenburg. In this area, only Quaternary sediments are overlying the basement. Accordingly the reworked material represents long distance transport by currents and/or ice.

samples) and the Solberga core (66 samples) in south-western Sweden (see Chapter 4).

A smear slide was prepared from each sample by smearing a small piece of the sample and a drop of distilled water on a glass-slide with a flat toothpick. The coarse fraction (larger than about 20 microns) was kept on one side of the slide, while the finer particles containing the calcareous nannofossils (approximately 2 to 15 microns) were allowed to flow over the middle part of the slide. The dried slide was covered with artificial canadabalsam and a cover-glass and left to cook on a hot-plate for about half a minute to harden the canadabalsam. The slides were studied by K. Perch-Nielsen with a Zeiss microscope fitted with 12.5x oculars and a 100x pol-objective, and parallel and crossed nicols were used for species determination.

RESULTS

Calcareous nannofossils are usually rare or absent in the three cores selected for the study of the Pleistocene/Holocene boundary. The coccoliths constitute less than 1% of the fine fraction of the sediments, and the coccolith assemblages are dominated by reworked species. These reworked forms are especially representing Early Tertiary and Late Cretaceous (Maastrichtian and Campanian) assemblages. The Quaternary contribution to the coccolith assemblages is less than 10% and it is characterized by a few species, *Emiliania huxleyi*, *Coccolithus pelagicus* and *Coccolithus leptoporus*, all of which are fairly solution resistant (Berger 1973).

In the Brastad and Solberga cores, Quaternary as well as reworked forms are present. In the Moltemyr core no Quaternary coccoliths were noted and only reworked species of Late Cretaceous, Danian and Eocene ages were observed.

Outcrops with sediments of Late Cretaceous and Tertiary ages are not present on land near by the Gothenburg area and possible sub-sea outcrops are almost uninvestigated. Coccoliths of ages comparable to the reworked forms are, however, described from Maastrichtian and Danian onshore localities in Denmark (Perch-Nielsen 1968, 1969, 1979) and Sweden (Forcheimer 1972, Åberg 1966) and from Danish Eocene-Oligocene localities (Perch-Nielsen 1971, Mikkelsen 1975, Thiede *et al.* 1980). These localities are located several hundred kilometers from the studied core localities (Fig. 15:1) and thus point to long distance transport of the reworked material, if we assume the reworked coccoliths to originate from there.

BRASTAD CORE

In the core from Brastad, coccoliths were found in varying, low quantities – very rare to rare – in the samples from 240 cm downwards (Fig. 15:2). The assemblages are dominated by reworked Maastrichtian and Eocene coccoliths. Together with the occasional autochthonous *Emiliana huxleyi*, *Gephyrocapsa* sp. and *Coccolithus pelagicus*, coccoliths always constitute far less than 1% of the sediment.

The reworked Cretaceous forms include usually *Watznaueria barnesae*, *Micula decussata*, *Prediscosphaera cretacea*, *Arkhangelskiella cymbiformis*, and occasionally *Nephrolithus frequens*, a marker for the Late Maastrichtian, and *Reinhardtites anthophorus*, *R. levis* and *Eiffellithus eximius*, markers for the Late Campanian and Early Maastrichtian, when occurring together with *A. cymbiformis*. The reworked Tertiary forms include mainly Prinsiaceae of different sizes and *Ericsonia ovalis* with an occasional *Reticulofenestra umbilica*, *Zygrhablithus bijugatus*, *Discoaster binodosus*, *Chiasmolithus solitus*, *Transversopontis* sp., and *Ericsonia formosa*. None of these forms allow a precise age assignment, but an Eocene and/or Early Oligocene age is likely.

The coccolith assemblages and their abundance (Fig. 15:2) provide no conclusive evidence for the palaeoenvironment during the Pleistocene/Holocene transition. The data, however, support the signals provided by the foraminifers (Chapter 14), the ostracods (Chapter 13), and the sedimentology (Chapter 6). The lowermost 5 meters of the Brastad core thus have a low content of coccoliths compared to the overlying section from approximately 10 to 6 m below surface. According to the ostracods this lower part of the core represents a shallow-water environment which upwards grades into open-sea conditions. This situation is reflected in the abundance of coccoliths, where the masking of the coccoliths by input of clastic material is reduced from the lower to the middle part of the core.

At a depth of approximately 2.4 m the sedimentological studies indicate a sedimentation brake (Chapter 6), and the Holocene interval is apparently missing in the core.

MOLTEMYR CORE

Coccoliths have a scattered and rare occurrence throughout the Moltemyr core (Fig. 15:2), and they are absent in the upper part of the core down to 270 cm. Below this level, very rare and moderately well to poorly preserved, reworked Late Cretaceous and/or Eocene coccoliths occur in samples 280, 320, 350, 410, 420, and 460 cm, while the samples inbetween (a sample for

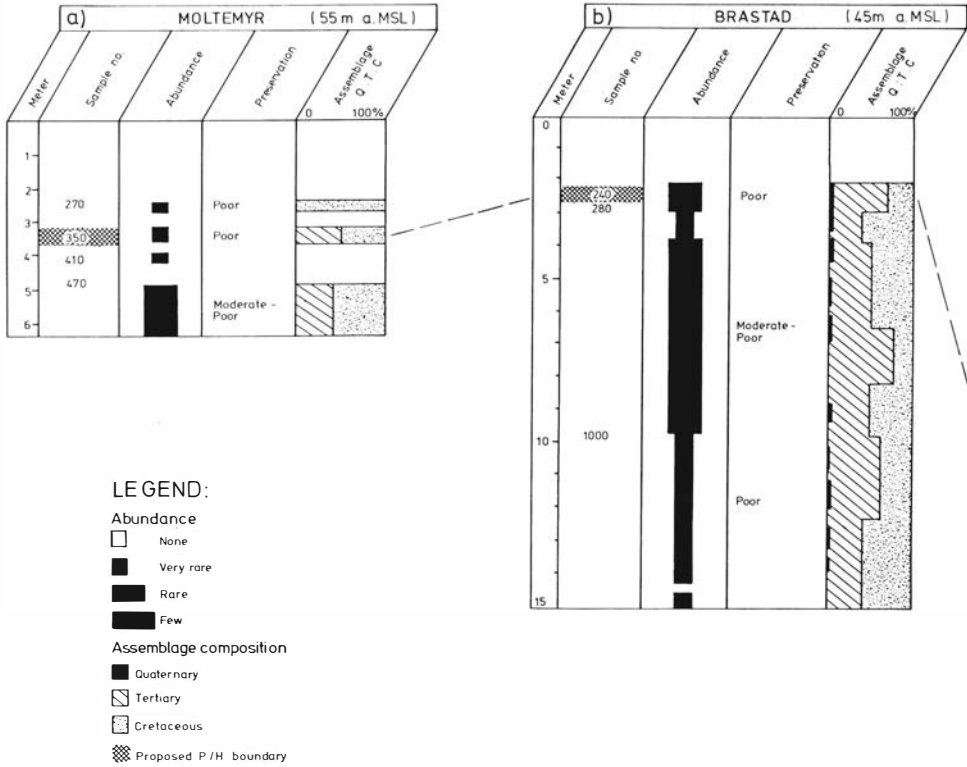
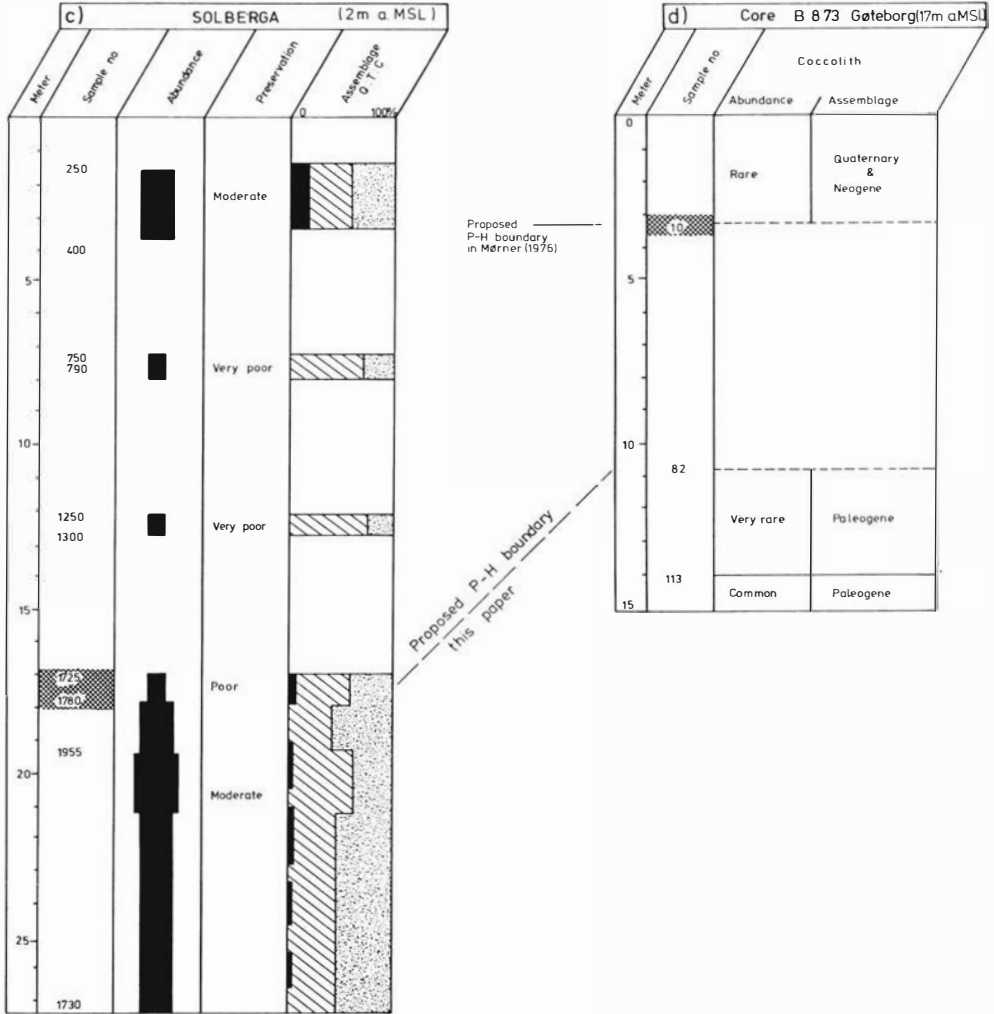


Fig. 15.2. Distribution of nannofossils in the Moltemyr core (a) the Brastad core (b), the Solberga core (c) and the Botanical Garden core B873 (d). A tentative correlation is made between the proposed Pleistocene/Holocene boundaries in the cores.

every 10 cm was studied) are barren of coccoliths. While coccoliths are still very rare in sample 460 cm, they are rare in the following three samples and coccoliths are very rare to rare in the remainder of the core, down to 650 cm. Throughout the core, only reworked coccoliths were found. Among the Late Cretaceous assemblage, the same forms were observed as in the Brastad core, including the markers for the Late Maastrichtian (*Nephrolithus frequens*) and the Maastrichtian/Campanian interval (*Reinhardtites anthophorus*). Danian forms include *Chiasmolithus danicus*, *Cyclagelosphaera reinhardtii*, *Markalius inversus*, *Placozygus sigmoides*, and *Biscutum* sp. The probably Eocene forms include mainly *Ericsonia ovalis* and small Prinsiaceae, but also *Neococcolithes dubius*, *Cyclicargolithus floridanus*, *Reticulofenestra umbilica*, *Transversopontis* sp., *Chiasmolithus expansus*, *Ericsonia formosa* and, in sample 560 cm, a specimen of *Isthmolithus recurvus*, a form which is limited to the Eocene/Oligocene boundary interval in high latitudes.



Reworked coccoliths were deposited and preserved at the Moltemyr locality during most of the presumed Late Quaternary interval, but with a more constant occurrence in the lower than in the upper part of the core. The apparent lack of Quaternary species in samples containing reworked coccoliths indicates that their absence is not a result of dissolution.

The occurrence of coccoliths in the Moltemyr core parallels other micropalaeontological observations. According to both ostracods and foraminifers (Chapters 13 and 14) the lower part of the core is deposited in an open marine environment which shows a shallowing upwards. This

shallowing influences on the coccolith abundance by diluting the coccolith assemblages with clastic material. The diatom assemblages as well as the ostracods show the influence of freshwater from a core depth of approximately 3.5 m upwards. According to the diatoms (Chapter 16) the Moltemyr area was isolated from the sea at a time corresponding to deposition of the sediments at a core depth of approximately 3 meters. This isolation may account for the lack of Quaternary coccoliths in this part of the core.

SOLBERGA CORE

The Solberga core represents the most complete section of coccolith-events recorded in the cores studied (Fig. 15:2). Reworked and Quaternary coccoliths are consistently present and moderately well preserved in two parts of the Solberga core – between 250 and 400 cm and between 1 800 cm and the bottom of the core at 2 730 cm. The assemblage of reworked coccoliths furnishes the same forms as in the Brastad core, but includes also the Danian forms *Cruciplacolithus tenuis*, *Chiasmolithus danicus* and *Neochiastozygus* sp. as well as the Eocene form *Neococcolithes dubius* besides the more common Campanian/Maastrichtian and other Eocene coccoliths. The probably Quaternary assemblage includes *Emiliania huxleyi*, *Gephyrocapsa* sp., *Coccolithus pelagicus* and some well preserved *Braarudosphaera bigelowii*.

The configuration of coccolith abundance and species composition in the lowermost 10 meters of the Solberga core are comparable to the distribution pattern of coccoliths covered by the entire Brastad core. In the Solberga core this lower section is followed by an almost barren interval between 17 and 4 meters below the top of the core. Poorly preserved coccolith assemblages may occur sporadically in this interval where they are characterized by the total absence of Quaternary species. The coccoliths reappear at a depth interval between 3.6 and 2.5 m below the top of the core. These assemblages still furnish a lot of reworked coccoliths but also provide some Quaternary forms.

The configuration of coccoliths in the Solberga core again mirrors the foraminifer and ostracod distribution (Chapters 13 and 14). The mentioned fossil groups indicate normal marine conditions during deposition of the lower part of the Solberga core. At the depth interval between approximately 17 and 4.5 m foraminifers and ostracods point to extreme conditions which may represent a period of high sedimentation rates which diluted the coccoliths. Above this interval Quaternary coccoliths reappear in detectable abundances parallel with a normalized sedimentation rate.

THE BOTANICAL GARDEN B873-CORE

Backman (in Mörner 1976) described the occurrence of coccoliths in the Botanical Garden core, B873, selected for a study of a possible stratotype for the Pleistocene/Holocene boundary. The information given by Backman is summarized in Figure 15:2. Reworked Paleogene coccoliths are stated to be common in the lower part of this core. The coccolith abundance diminishes upwards into a barren zone. In the uppermost 2 meters of the core both Quaternary and reworked coccoliths reappear in a considerable quantity according to the published information. This distribution pattern conforms with the preceding three cores. However, there is a striking discrepancy relative to the almost identical micropalaeontological events recorded in the four cores between the proposed location of the Pleistocene/Holocene boundary in the Botanical Garden core and the three cores mentioned. In the Botanical Garden core the boundary seems to have been placed at an interval corresponding to a period considerably younger than the Pleistocene/Holocene transition as suggested here.

SUMMARY AND CONCLUSION

The four cores discussed above all penetrate Upper Quaternary sediments which furnish Quaternary and older, reworked coccoliths. According to their coccolith content the cores share some common features which facilitate a correlation of the penetrated sections. The abundance of coccoliths shows a consistent occurrence below the Pleistocene/Holocene boundary. Just above this boundary coccoliths become very rare or entirely absent but they reappear in the uppermost part of the section.

The coccolith assemblages by themselves provide only minor information on the changing conditions in the area during the Late Quaternary. The Quaternary assemblages are thus highly diluted by clastic material including a high percentage of reworked coccoliths transported to the area from distant land- or submarine outcrops. However, the abundance and sequences of appearance and disappearance of Quaternary coccoliths in the cores tied to the distribution of the reworked coccoliths provide some information on the changing depositional environment. The lower part of the Quaternary sequence with a fairly high abundance of coccoliths including Quaternary forms may correspond to the period of existence of the Baltic Ice Lake, when open marine conditions prevailed in the area. During the regression period following the Pleistocene/Holocene transition, the marine conditions deteriorated and the Quaternary coccoliths disappeared. Reworked coccoliths were, however, still deposited occasionally

due to current and ice transport. The almost coccolith barren sediments were presumably deposited at the time of the pronounced meltwater discharge. This resulted in a very rapid sedimentation of the clastic material which totally masked the coccolith occurrences. On a global scale this and similar drainages could be reflected in the "meltwater spike" observed in the open ocean sediments (Berger *et al.* 1977). During the Postglacial Transgression normal marine conditions were reestablished and the production of Quaternary coccoliths could once again leave an imprint in the upper part of the Quaternary sequences of south-western Sweden.

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16. DIATOMS

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INTRODUCTION

The diatom studies concentrate mainly on the cores from Brastad, Moltemyr and Solberga, which were included in the Pleistocene/Holocene boundary programme. The interpretation is based on many diatom investigations in Bohuslän. Some of the studies from more than 20 localities are published (Miller 1964, Miller 1966, Miller and Robertsson 1974, Miller 1981), others were carried out in connection with geological mapping and documentation programmes in Bohuslän for the Geological Survey of Sweden (Frédén, Miller and Robertsson, in progress).

The location of the cores presented in the following text is shown in Fig. 4:2 (Chapter 4).

MATERIAL

The following numbers of samples from the cores were prepared and studied.

	Prepared	Studied	Analyses performed	Barren or almost barren
Brastad	30	23	13	10
Moltemyr	40	39	39	—
Solberga	50	40	28	12
	120	102	80	22

Diatoms were also studied in cores from Rörmyr and Vägen to establish the sedimentary environment and relation to sea level.

TECHNIQUE

From each sample, 100 mm³ ($\cong 0.25$ g wet weight) sediment is concentrated for diatom analysis. Lime is dissolved with dilute hydrochloric acid (5% HCl). Coarse mineral grains are separated by sedimentation. Organic material is bleached and destroyed by heating in hydrogen peroxide (30% H₂O₂) for 2 h in a water bath. Clay particles and colloids are eliminated by repeated washings in distilled water (Miller 1964, p. 13).

Slides of the residue are prepared for analysis. One drop (0.05 ml) of the concentrated sample (5 ml) is spread over a coverglass, dried and embedded in a strongly refractive embedding medium (Mikrops $n = 1.65$). A difference in refractive index between the diatom frustule ($n = 1.43$) and the embedding medium means that fine structures of the diatoms appear more distinct, which promotes identification.

Analysis is carried out at maximum magnification of the light microscope (about 1 000 x) with oil immersion and phase contrast. When necessary a scanning electron microscope with magnification up to 50 000 x is used.

For relative quantitative analysis, all the diatom frustules identified are counted. The total diatom frustules counted in a sample slide forms a basic figure (ΣD) for percentage calculations. The percentages are calculated for the individuals of each identified diatom species/taxon separately, or for a group having the same ecological or environmental requirements.

ΣD should preferably be 300. In this study it was sometimes less (100–300), because of low diatom frequency.

Diatom frequency (DF) was calculated both as semi-absolute (per microscope traverse of the slide) and absolute (per 1 g wet sediment). In general, the absolute frequency DF_g corresponds approximately to 100 000 x semi-absolute frequency DF_t .

$$(DF_g \cong DF_t \cdot 10^5).$$

ECOLOGICAL GROUPING AND DIAGRAM CONSTRUCTION

Grouping of diatom taxa and construction of diatom diagrams are dependent on the aim of the investigation and composition of the diatom flora.

Here, the fossil diatom flora is divided into two major groups: sea- and freshwater diatoms. These groups are subdivided into planktonic and littoral (epiphytic and benthic) floras as follows:

1. Sea-water diatoms (marine and brackish: poly-, eury- and mesohalobous)
 - 1.1. Planktonic
 - 1.1.1. Mainly Arctic plankton (a)
 - 1.1.2. Mainly coastal and temperate plankton, incl. *Melosira sulcata*, (c)
 - 1.2. Littoral
 - 1.2.1. Marine (polyhalobous) diatoms (M+MB) – sublittoral or deep water flora
 - 1.2.2. Brackish (eury- and mesohalobous) diatoms (BM+B) – littoral or shallow water flora
2. Freshwater diatoms (oligohalobous)
 - 2.1. Freshwater plankton (mainly *Melosira islandica* subsp. *helvetica*)
 - 2.2. Other freshwater diatoms

Representatives of the ecological groups are illustrated in Fig. 16:1.

Graphs of diatom frequency and number of diatom taxa, with sea-water (here called marine *s.l.*) diatoms as separate curves, are added to the diagrams.

The sediments (except for the Brastad, Moltemyr and Solberga cores, see Chapter 7) were classified according to SGU 1978.

RESULTS

Because of obvious differences in diatom stratigraphy the cores will be presented in two groups. The first group comprises cores from central, the second those from southern Bohuslän.

DIATOM STRATIGRAPHY IN CORES FROM CENTRAL BOHUSLÄN: THE BRASTAD, MOLTEMYR AND RÖRMYSR CORES

Brastad has marine sediments, at Moltemyr there is a transition from marine to brackish to limnic sediments, and at Rörmyr a transition from brackish to limnic sediments.

Brastad (45 m above sea level)

Figure 16:2 illustrates the diatom spectra of the sediments. Three diatom assemblage zones were distinguished.

Zone 1 (15–8 m). Almost barren. The few diatom frustules noted belong to Arctic plankton species.

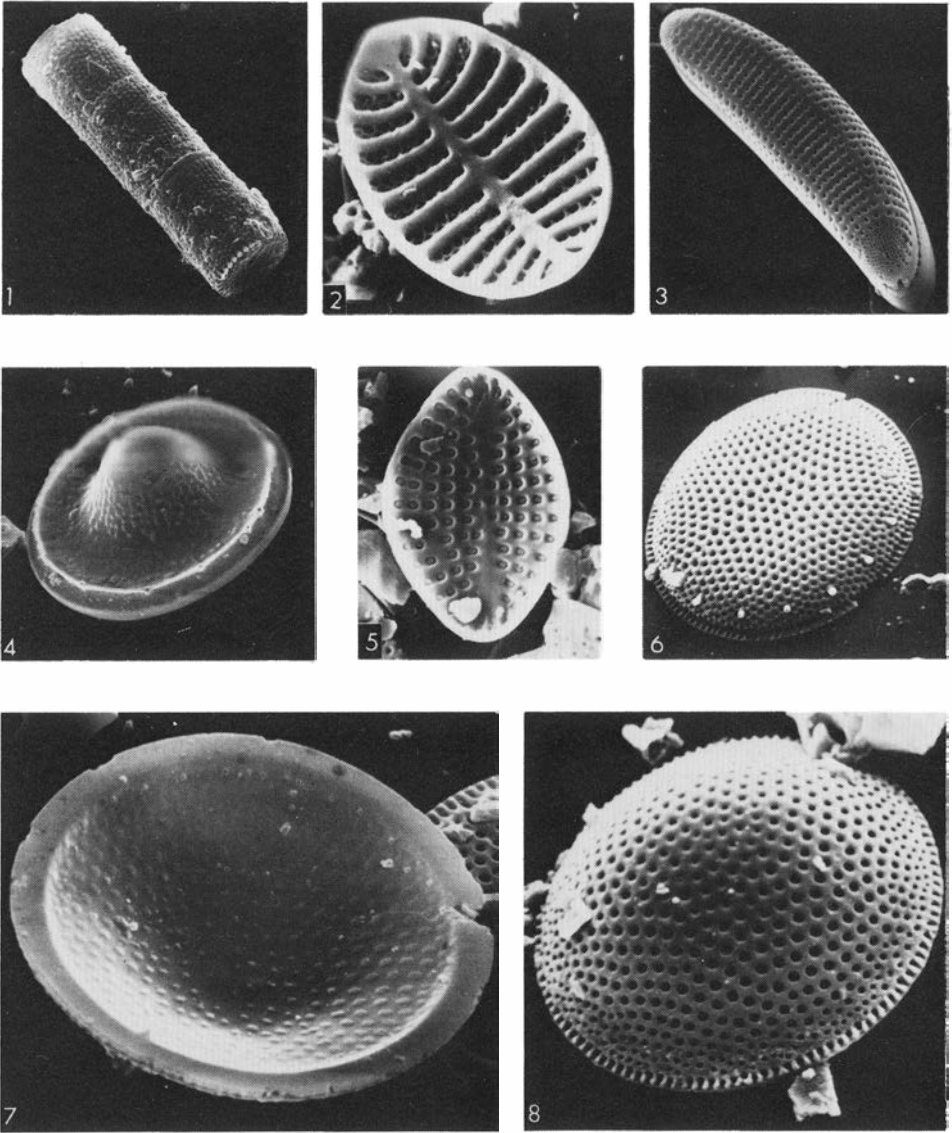
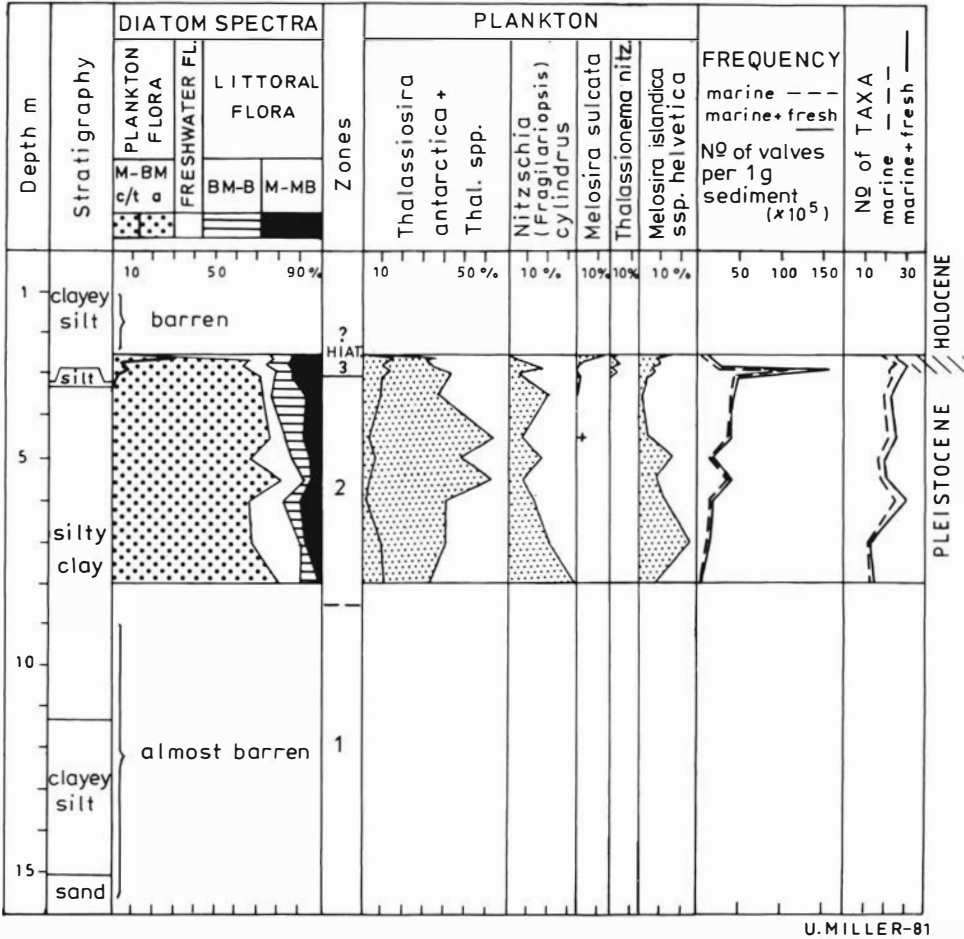


Fig. 16:1. Diatoms from the Pleistocene/Holocene sediments in Bohuslän, western Sweden. Stereoscan micrographs. Magnification $\times 2000$. - 1. *Melosira islandica* subsp. *helvetica* O. Müller. - 2. *Cocconeis costata* Gregory. - 3. *Grammatophora arcuata* Ehrenberg. - 4. *Chaetoceros* resting spore. - 5. *Rhaphoneis surirella* (Ehrenberg) Grunow. - 6. *Thalassiosira angulata* (Greg.) Hasle. - 7. *Thalassiosira antarctica* Comber. Resting spore, internal view. 8. *Do.*, external view.

BRASTAD, altitude 45 m a.s.l.
DIATOMS



U. MILLER-81

Fig. 16:2. Diatom spectra of the Brastad core, with separate curves of characteristic planktonic diatom species, diatom frequency and number of taxa.

Zone 2 (8–3 m). Mainly Arctic-oceanic plankton (*Thalassiosira antarctica* + *T. spp.*, *Nitzschia cylindrus*).

Zone 3 (3–2.5 m). First occurrence of coastal planktonic species (*Thalassionema nitzschioides*, *Melosira sulcata*). The diatom frequency has a marked peak at 3 m.

Zone 4 (2.5–1 m). Almost barren to barren samples. The few frustules and fragments belong mostly to coastal plankton and littoral flora, or are reworked and originate from Lower Tertiary marine deposits. There seems to be a hiatus above 2.5 m.

The diatom spectra of the Brastad core register a change in sedimentary conditions at 3 m. The sediments above 2.5 m appear to be reworked.

MOLTEMYR, altitude 55 m a.s.l.
DIATOMS

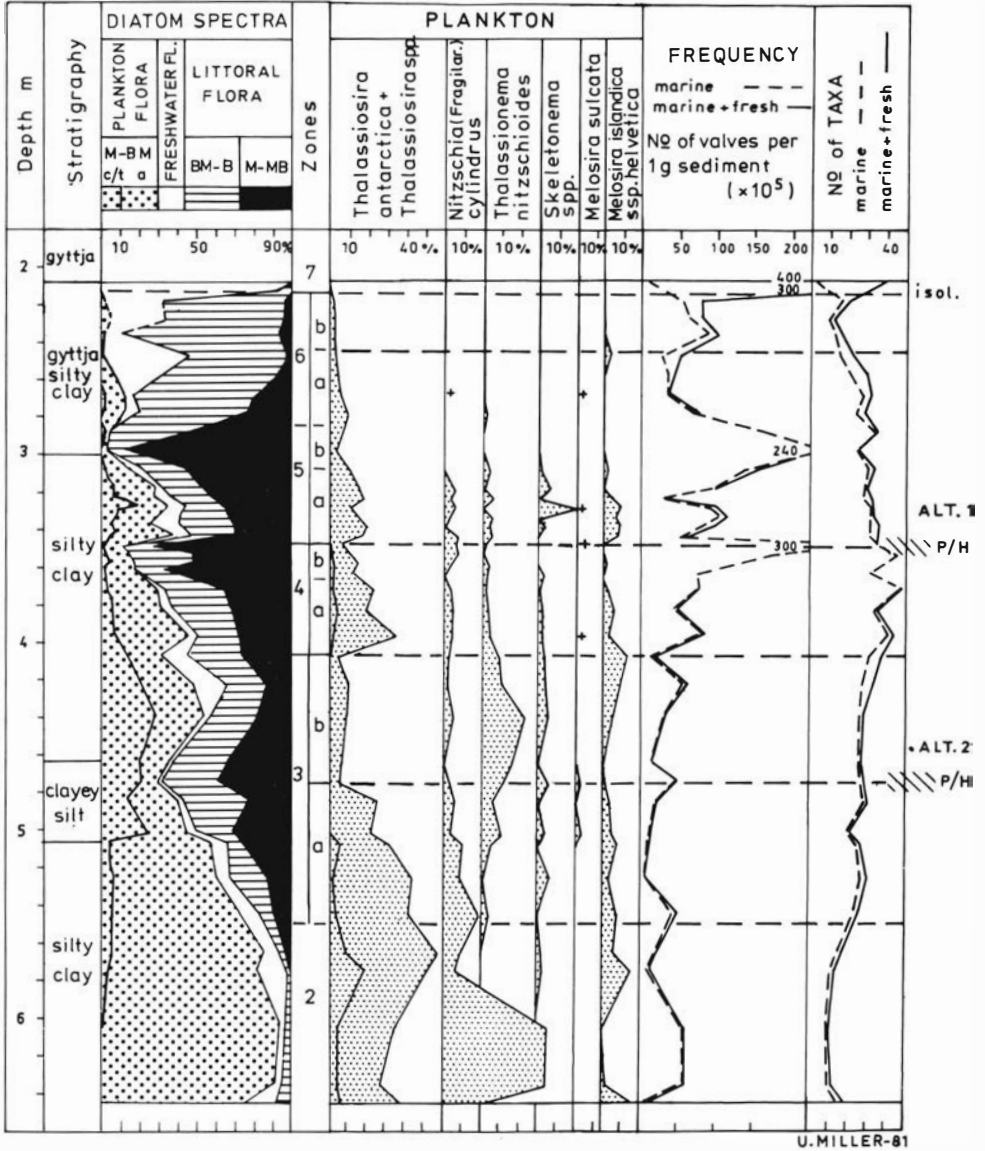


Fig. 16.3. Diatom spectra of the Moltemyr core, with separate curves of characteristic planktonic diatom species, diatom frequency and number of taxa.

Moltemyr (55 m above sea level)

Figure 16:3 shows the diatom spectra of the sediments, subdivided into 6 diatom assemblage zones (zones 2–7).

Zone 2 (6.4–5.4/5.0 m) has a dominance of Arctic plankton flora.

Zone 3 (5.4/5.0–4.1 m), lower part, subzone 3a (5.4/5.0–4.8 m), shows continuous increase in marine and brackish littoral flora, indicating shallowing and/or inlet.

In the lower part of 3a the Arctic plankton group decreases, but still dominates.

At 5 m there is a marked rise in coastal/temperate plankton. The upper part of zone 3, subzone 3b (4.8–4.1 m) is characterized by decrease in littoral flora and low values of Arctic plankton. Marine coastal plankton (*Thalassionema nitzschioides*) increase.

Zone 4 (4.1–3.45 m) registers return of Arctic plankton (*Thalassiosira* species) combined with increase in marine sublittoral flora. This may relate to colder climatic conditions with almost no freshwater influence. The high diatom frequency in the upper part of zone 4 indicates stable conditions with low sedimentation rate.

Zone 5 (3.45–2.8 m). Diatom frequency decreases. Coastal/temperate plankton return in the lower part. Arctic plankton are present, but may be reworked. In the upper part, a marine littoral/sublittoral flora predominates.

Zone 6 (2.8–2.15 m). Brackish littoral, and freshwater flora increase, indicating shallower water and the start of isolation of the Moltemyr basin from the sea. At 2.40 m, interruption of the freshening is shown by a small increase in brackish littoral flora. Diatom frequency is relatively low between 2.8 and 2.4 m.

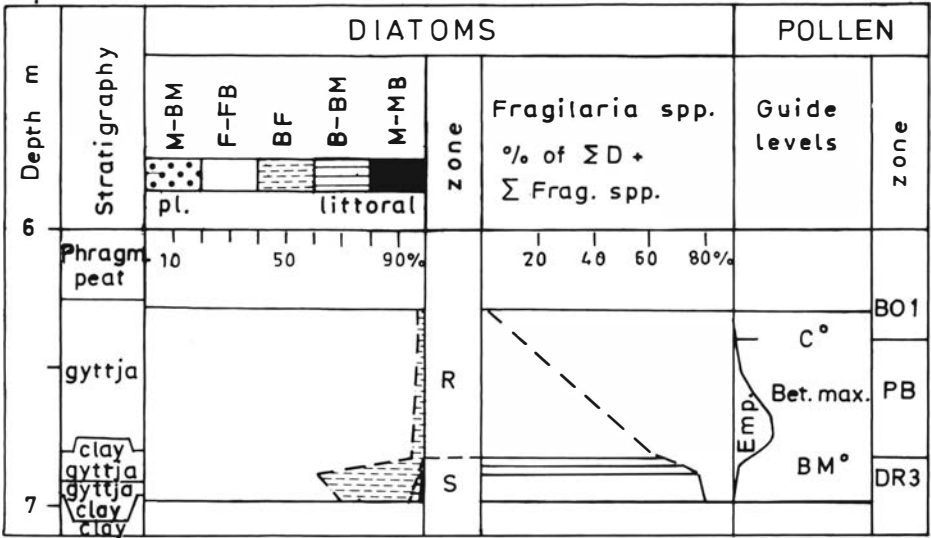
Zone 7 (2.15–2.0 m). Isolation from the sea is completed at 2.15 m. Upwards, a freshwater diatom flora of small lake type occurs.

The diatom stratigraphy of Moltemyr core registers two main changes in sedimentary conditions, which may relate to climate and sea level. The first change starts at 5.4 m and shows a pronounced amelioration of climate between 4.8 and 4.1 m (subzone 3b). The second change occurs at 3.5/3.45 m, at the boundary between zone 4 and 5 and indicates change from marine littoral Arctic/Subarctic to more temperate conditions before isolation of the Moltemyr basin (zones 6 and 7).

Rörmyr (115 m above sea level), Bp 1 and 2

Figure 16:4 shows that isolation of the Rörmyr basin from the sea is registered in Rörmyr Bp 2 at 7.8 m. Before isolation the sediments were deposited in a shallow, brackish littoral environment. After isolation, the *Fragilaria* spp. predominates in the sediments (uppermost clay and clay gyttja). In the gyttja layer, *Fragilaria* spp. disappears being replaced by a small lake flora. A more detailed description of the sediments and development is given in Chapter 18.

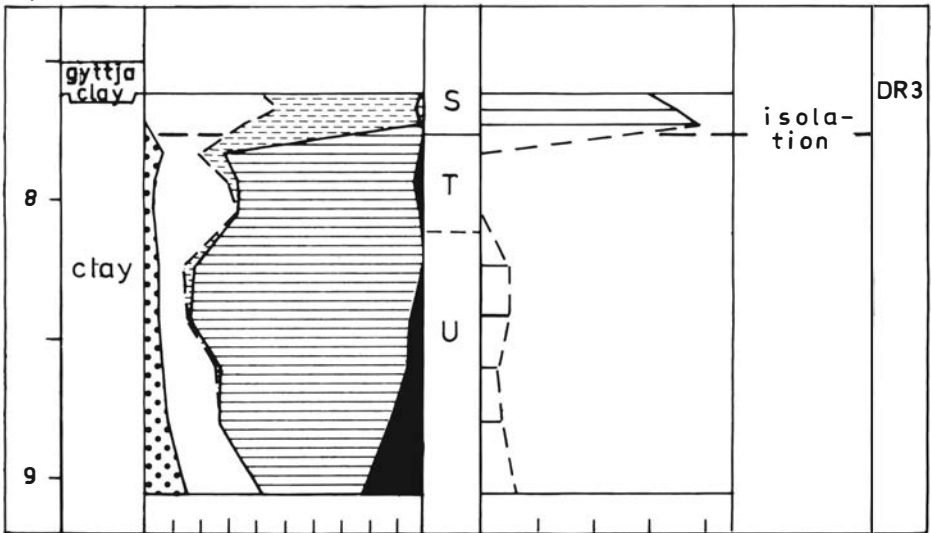
RÖRMYR, altitude 115 m a.s.l.
Bp.1



H. MODIG, U. MILLER

A.-M. ROBERTSSON

Bp 2



H. MODIG, U. MILLER-81

Fig. 16:4. Diatom spectra of the Rörmyr Bp 1 and 2, showing the isolation of the basin from the sea.

SOLBERGA, altitude 2 m a.s.l.
DIATOMS

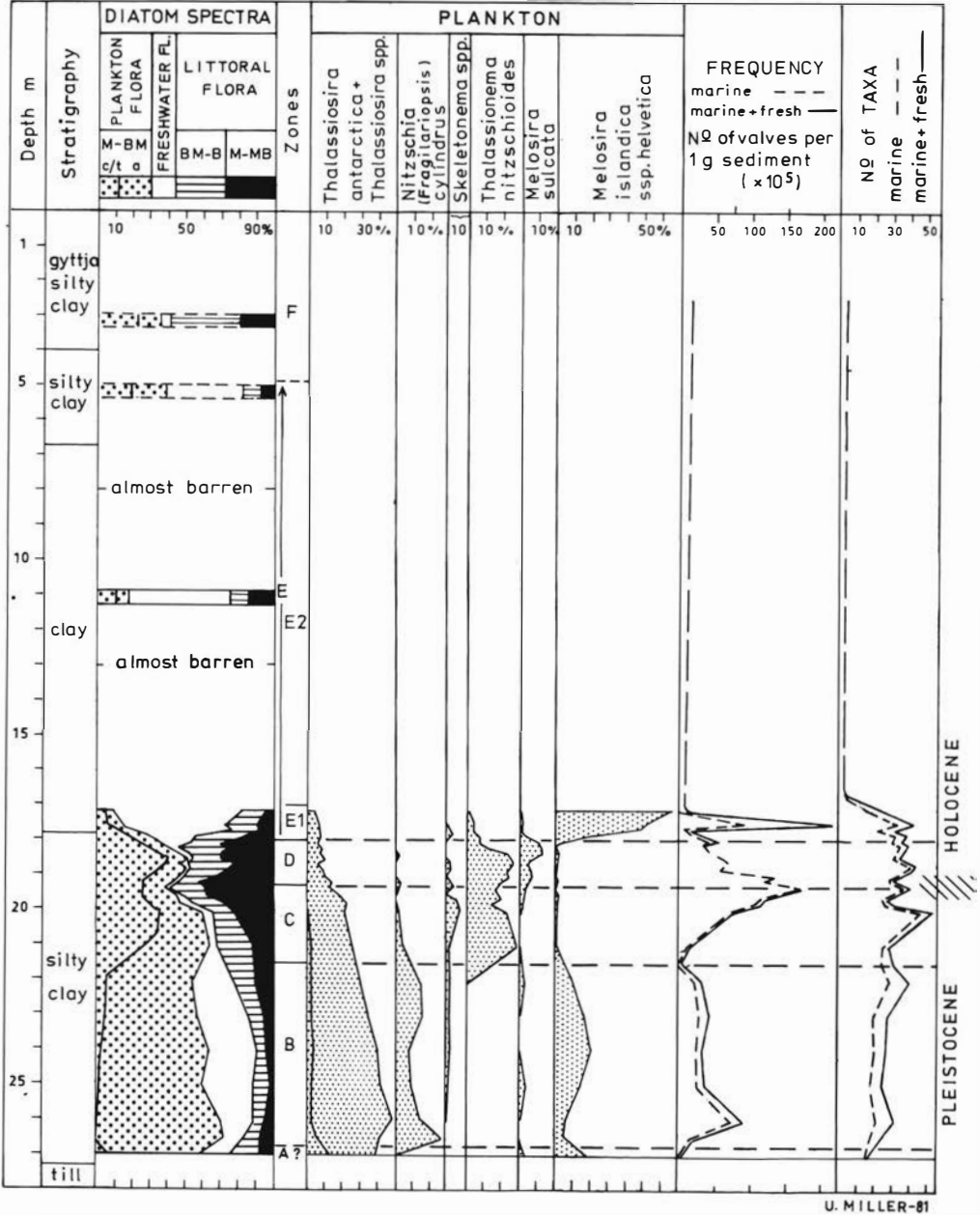


Fig. 16:5. Diatom spectra of the Solberga core with separate curves of characteristic planktonic diatom species, diatom frequency and number of taxa.

VÄGEN, altitude 112 m a.s.l.

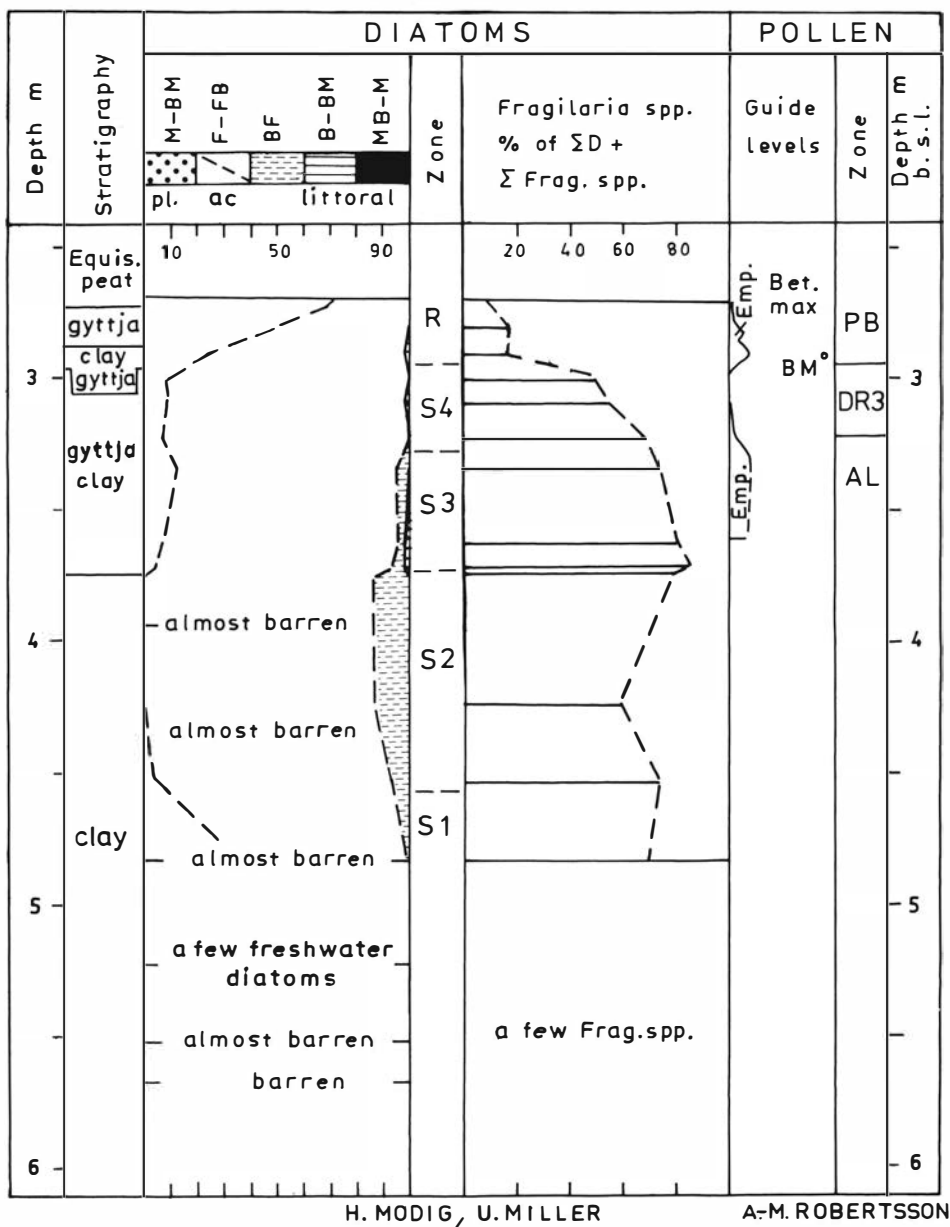


Fig. 16:6. Diatom spectra of the Vägen core, showing that the basin was not connected to the sea. The diatom spectra indicate a small lake environment above the highest shore line and marine limit.

DIATOM STRATIGRAPHY IN CORES FROM SOUTHERN BOHUSLÄN:
THE SOLBERGA AND VÄGEN CORES

The whole sediment sequence at Solberga is marine, while at Vägen it is limnic. Vägen is situated above the highest shore line.

Solberga (2 m above sea level)

Figure 16:5 illustrates the diatom stratigraphy with subdivision into 6 diatom zones (A–F).

Zone A (below 27.0 m). Barren or almost barren.

Zone B (27.0–21.5 m). Dominance of Arctic plankton. The valves of marine and brackish littoral flora is more or less constant, not exceeding 25%. Freshwater plankton *Melosira islandica* is present, but not dominant.

Zone C (21.5–19.2). Marine littoral flora increases upwards. Coastal plankton (*Thalassionema nitzschioides*) show a marked increase, but Arctic plankton still have values of 20–30%. At 19.5–19.2 m the frequency of marine diatoms is extremely high. Freshwater plankton (*Melosira islandica*) has almost disappeared.

Zone D (19.2–18.0 m). Dominance of littoral flora and coastal/temperate plankton (*Melosira sulcata*, *Thalassionema nitzschioides*). Arctic plankton has decreased to about 10%. Almost no freshwater diatoms.

Zone E (18.0–c. 5 m). Predominance of freshwater plankton *Melosira islandica*. A frequency peak of freshwater diatoms occurs between 18 and 17.5 m (subzone E 1). Upwards the diatom frequency is very low, but the diatom spectra show a clear dominance of freshwater plankton (subzone E2).

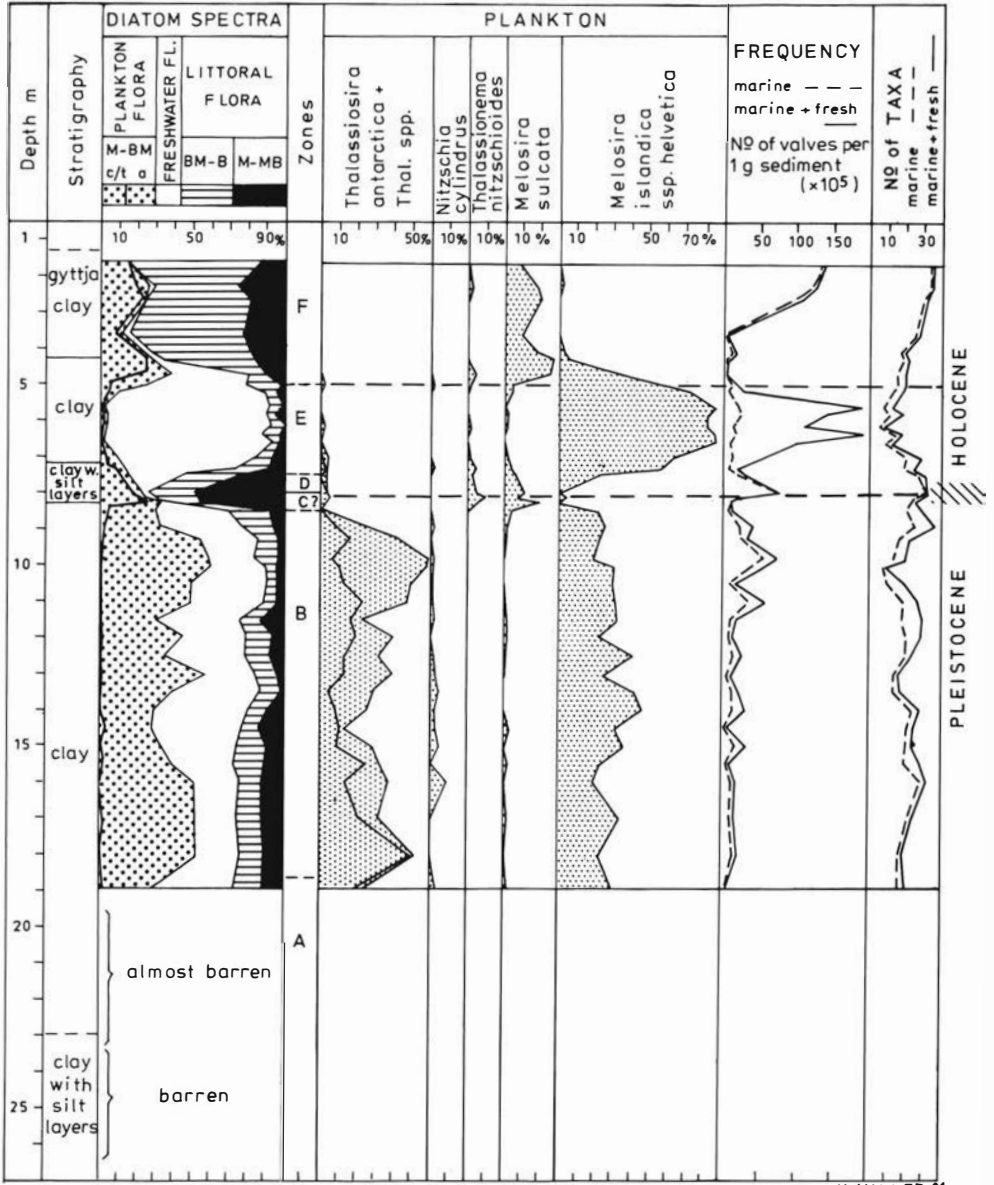
Zone F (c. 5–1.5 m). Diatom frequency still very low. A change in composition of diatom flora occurs at about 5 m. Littoral brackish flora and coastal/temperate plankton dominate. Freshwater diatoms have almost disappeared.

Changes in sedimentary environment are best registered at zone boundaries B/C at 21.5 m and C/D at 19.2 m. Zone D represents a change to improved conditions before the huge freshwater outflow registered by high frequency of *Melosira islandica* (E 1), followed by high sedimentation rate characteristic of subzone E1.

Vägen (112 m above sea level)

Figure 16:6. According to diatom analysis sedimentation occurred in a limnic environment. The stratigraphy of the core is described in detail, together with the pollen diagram in Chapter 18. Diatom spectra show a shallow, small lake environment, with predominance of *Fragilaria* spp. in the minerogenic sediments. In the gyttja layer acidophilous diatoms, which prefer pH <7, manifest a marked increase.

TUVE, altitude 5 m a.s.l.
DIATOMS



U. MILLER-81

Fig. 16:7. Diatom spectra of the Tuve core, with separate curves of characteristic planktonic diatom species, diatom frequency and number of taxa.

COMPARISON WITH OTHER CORES
FROM SOUTHERN BOHUSLÄN - GÖTEBORG

Tuve (5 m above sea level)

Tuve core was studied in the course of investigations carried out after the 1977 landslide (Miller 1981).

The diatom stratigraphy of Tuve (Fig. 16:7) is comparable with Solberga. Zones A–F are present, with some reservation for zone C. The most marked change in sedimentary conditions occurs at 8.4/8.3 m. Increase in littoral flora, in combination with appearance of coastal plankton, indicates diminishing water depth. No freshwater influence is registered in zones C–D. High frequency of freshwater plankton *Melosira islandica* in zone E, followed upwards by brackish-marine littoral flora together with coastal plankton in zone F, corresponds well with the diatom stratigraphy of Solberga.

Botanical Garden Göteborg, B 873 (17.4 m above sea level)

For correlation, the diatom diagram of the Botanical Garden core (Du Saar in Mörner 1976) is drawn as for Tuve and Solberga (Fig. 16:8). The unpublished list of diatom taxa by Du Saar has been used for grouping and percentage calculations.

There is an obvious absence of the Arctic plankton characteristic of zone B in the Solberga and Tuve cores. If sediments between 14.0 and 3.5 m in core B 873 were deposited during the Late Weichselian, Arctic plankton should have been present.

The higher altitude and proximity to the Göta River Valley may have influenced the composition of the diatom flora, but other dissimilarities are also present in the diatom stratigraphy.

Bottom sediments at 13.5 m contain a diatom flora characterized by *Melosira sulcata* and littoral species. *Melosira islandica*, which reflects influx of freshwater, is very poorly represented. The diatom flora indicates a marine coastal environment of about 30 m depth of water, in contrast to the sedimentary conditions interpreted by Mörner (1976) as denoting the transition from Arctic pre-Bölling to Bölling at a depth of about 90 m.

The sediments between 13.5 and 2.5 m are dominated by freshwater plankton *Melosira islandica*, except for those between 6.2 and 4.2 m which are almost barren. The diatom flora corresponds with the flora in zone E of Solberga and Tuve, *i.e.* the drainage of the Baltic Ice Lake and the influx of freshwater during the Preboreal.

The diatom flora in the top sediments (2.5–1.8 m) of core B 873 corresponds well with the flora of zone F of Solberga and Tuve, *i.e.* the

BOTANICAL GARDEN, GÖTEBORG, altitude 17.4 m a.s.l.

DIATOMS (Du Saar)

Core B 873

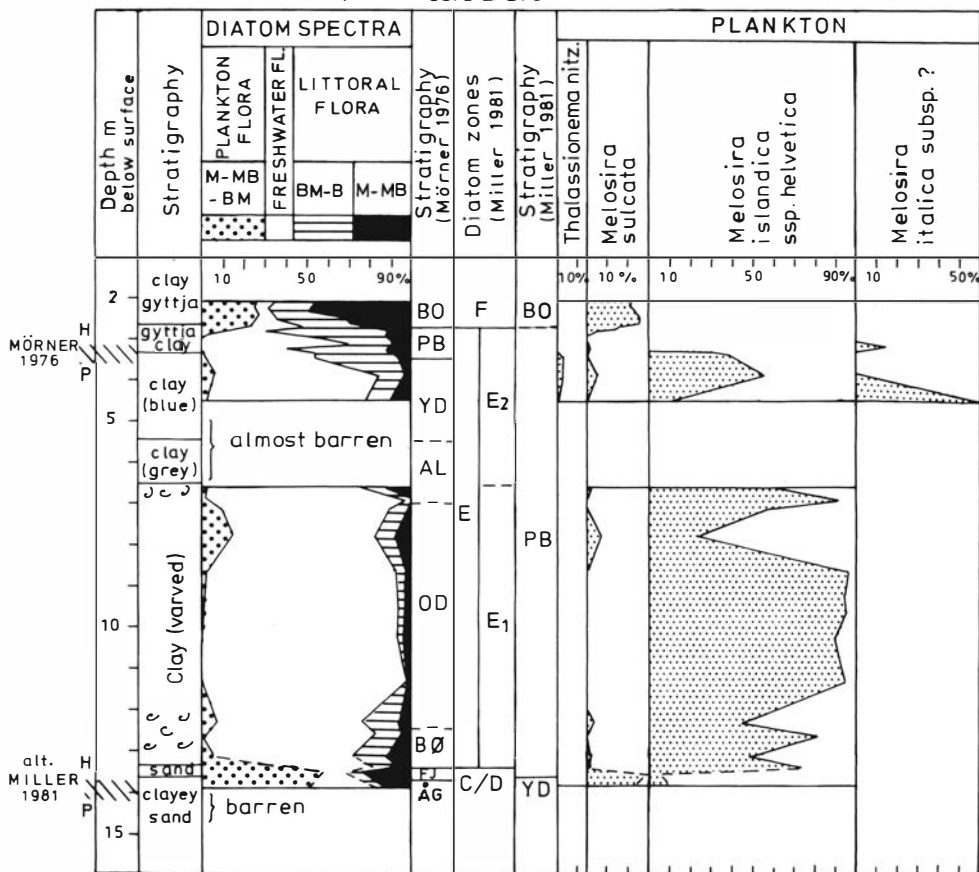


Fig. 16:8. Diatom spectra of the Botanical Garden core B 873 (redrawn after Du Saar in Mörner 1976), combined with the frequency values from the unpublished list of diatom taxa by Du Saar.

Boreal transgression with marked increase of coastal plankton and littoral flora. There is almost no influx of freshwater plankton in the uppermost sediments.

Mörner's stratigraphical interpretation (1976) of core B 873 from the Botanical Garden, Göteborg, has been revised on the basis of diatom stratigraphy. The lower part of the sequence may register the Pleistocene/Holocene boundary, while the boundary proposed by Mörner reflects the sedimentary conditions at the end of the Preboreal.

GÖTA RIVER VALLEY

Comparison has also been made with cores from the Göta River Valley: Tingstad (or Hisinge Tunnel), Träpiren, Surte, and Ingebäck.

Tingstad (about 2 m above sea level)

The stratigraphy of the Tingstad core is described by Tullström and Brotzen (Tullström 1961, Brotzen 1961a and b). A preliminary diatom diagram is shown in Figure 16:9.

The sediments between 82 and 77 m are almost barren (zone A). In zone B (77–54 m) Arctic plankton predominate in the lower part, with increase of freshwater plankton in the upper. Zone B here may also represent older interstadial sediments with almost Arctic conditions in the lower part and more Boreal-Arctic conditions in the middle. Between zones B and E there may be a hiatus at 54 m (sand layer).

The sediments of Tuve and Solberga zones C and D, which represent the Pleistocene/Holocene boundary, are absent, probably eroded by vigorous freshwater outflow.

The transition from zones E to F (the Preboreal/Boreal) occurs at 37 m. The diatom spectra of the uppermost zones, G and H, show Holocene conditions after the Atlantic transgression maximum. Zone H may be contaminated by filling.

Träpiren (8 m below sea level)

The results of the biostratigraphical studies of the Träpiren core made by Mohrén (pollen), Florin (diatoms) and Brotzen (foraminifers) were published in Mohrén 1945. The pollen and diatom spectra combined with foraminiferal stratigraphy show that the Pleistocene/Holocene boundary may occur at about 50 m or still lower, probably eroded (hiatus?).

Surte (1.5 m above sea level)

The Surte core E 14 is described by Mohrén 1956. Pollen (Mohrén) and foraminiferal analyses (Brotzen) were carried out, but no diatom analysis. The Late Glacial/Post Glacial boundary, according to Mohrén, is at 21.5 m depth. This boundary represents a transition from the Preboreal to the Boreal. The boundary of the Younger Dryas/Preboreal or the Pleistocene/Holocene is presumed by Mohrén to be at 23.5 m. It is more likely that the level registers the Preboreal regression maximum. The sediments in the lower part of the core are probably of Preboreal age.

TINGSTAD (HISINGEN), altitude 2 m a.s.l.
DIATOMS

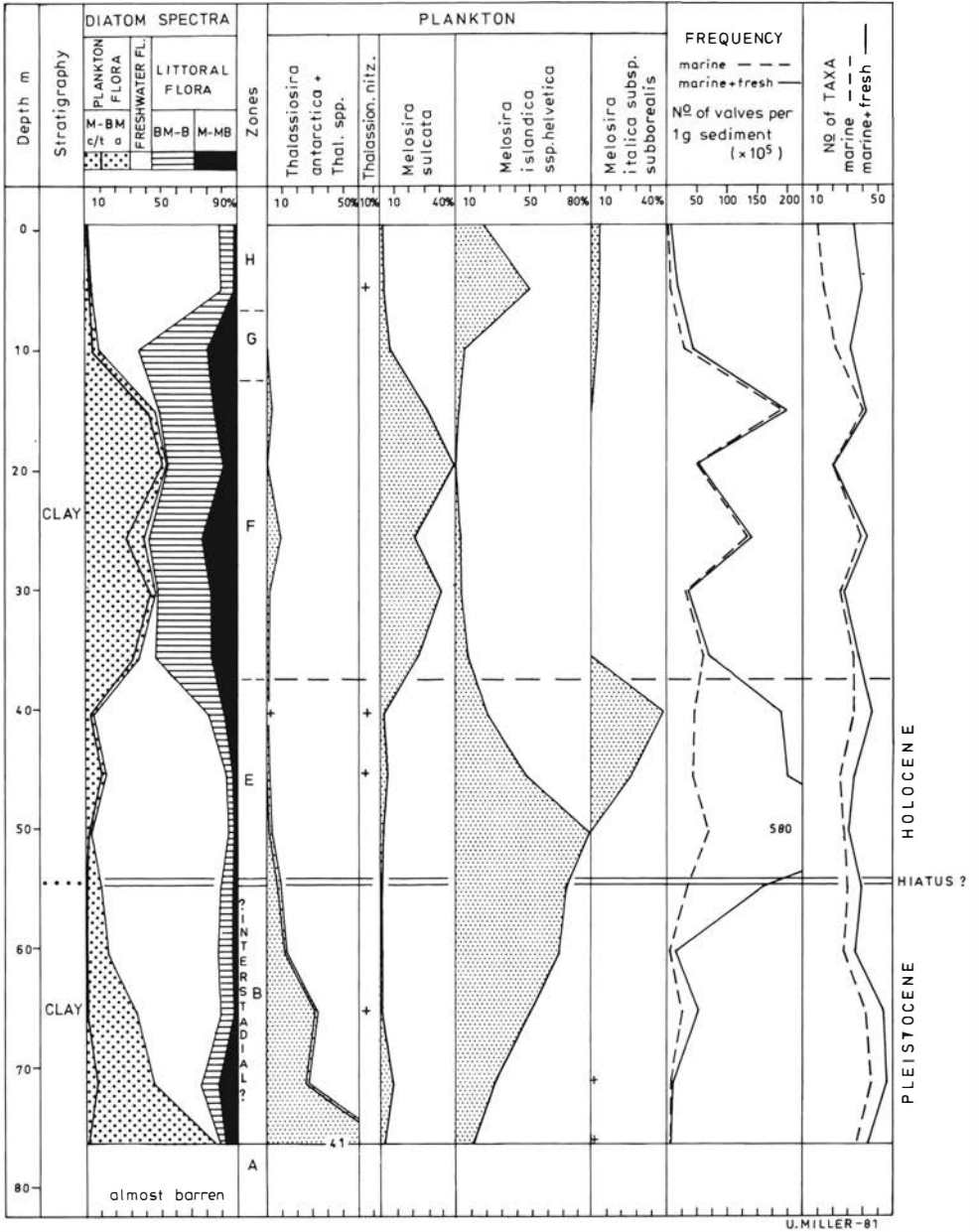


Fig. 16:9. Preliminary diatom spectra of the Tingstad core with separate curves of characteristic planktonic diatom species, diatom frequency and number of taxa.

INGEBÄCK, altitude 5m a.s.l.
DIATOMS

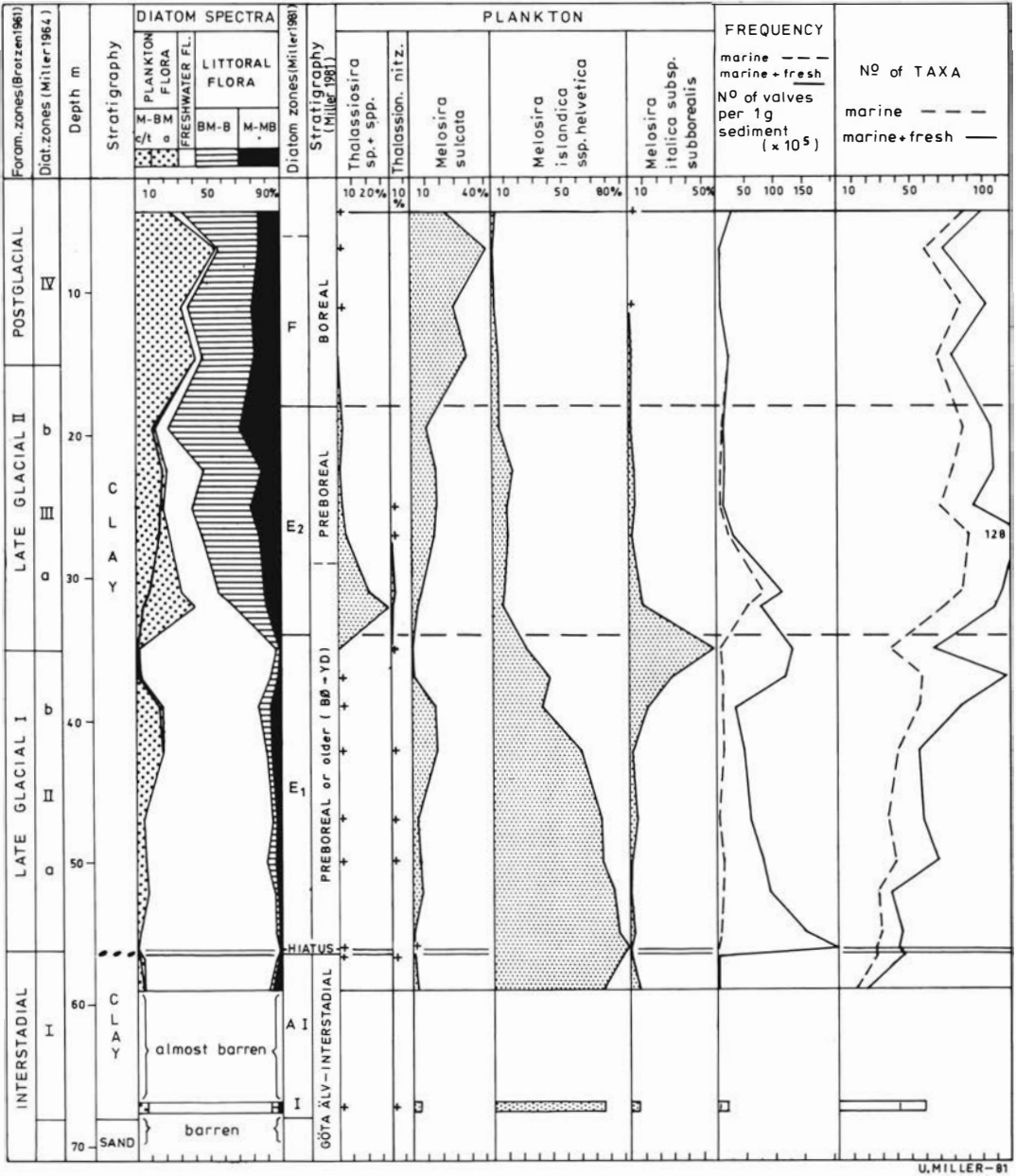


Fig. 16:10. Diatom spectra of the Ingebäck core with separate curves of characteristic planktonic diatom species, diatom frequency and number of taxa.

Ingebäck (5 m above sea level)

The locality is situated 12 km north of Göteborg. The Ingebäck core has been investigated biostratigraphically: foraminifers by Brotzen (1961), diatoms by Miller (1964) and preliminary pollen analyses by Robertsson (unpublished).

The diatom diagram, Fig. 16:10, is redrawn after Miller 1964. The diatom stratigraphy of Ingebäck core is difficult to compare with other cores from the Göta River Valley. The lowermost part of the core (67.5–56 m) is presumed to represent interstadial sedimentation (zones I and I/A). The diatom frequency is very low, except at 67 m (zone I). At 56 m there is a layer of gravel and sand indicating a hiatus. The sediments between 56 and 35 m have a dominance of *Melosira islandica* subsp. *helvetica*, characteristic of zone E, which represents the meltwater discharge of the Baltic basin. The absence of Arctic plankton makes comparison with Late-Weichselian sedimentation difficult. Diatom zones B, C and D seem to be eroded by violent freshwater outflow. Accordingly, the sediments between 35 and 19 m may represent the Preboreal regression with decreasing influx of freshwater plankton and increase in littoral flora.

Between 19 and 15 m the diatom spectra clearly indicate a change to boreal conditions with marked increase in *Melosira sulcata* (zone F).

This revision of the diatom stratigraphy of the Ingebäck core is only preliminary. It may be that special sedimentary conditions in the Göta River Valley were more important than has so far been considered. The presence of Götaälv Interstadial (Brotzen 1961) in the lowermost clay sediment of the Ingebäck core is proven. The age of the sediment is still in question, whether Middle Weichselian or Late Weichselian.

CORRELATION OF THE DIATOM ASSEMBLAGE ZONES IN THE CORES

Figure 16:11 shows a tentative correlation of the diatom assemblage zones. The characteristic composition of diatom spectra of zones in cores from southern Bohuslän is as follows.

Zone F	<i>Melosira sulcata</i> + brackish-marine littoral flora. Almost no influx of freshwater plankton	The BOREAL transgression
Zone E	The upper part (subzone E2) is poor in diatoms, sometimes barren, because of high sedimentation rate. <i>Melosira islandica</i> subsp. <i>helvetica</i> indicates influx of	

	freshwater. Brackish littoral flora, coastal plankton	The PREBOREAL regression
	In the lower part (subzone E1) <i>Melosira islandica</i> subsp. <i>helvetica</i> dominates with high frequency indicating vigorous outflow of freshwater	Beginning of the PREBOREAL with meltwater discharge from the Baltic basin
Zone D	Sublittoral marine-brackish flora + <i>Melosira sulcata</i> . Amelioration of the climate. Almost no influx of freshwater plankton	Transition the YOUNGER DRYAS/PREBOREAL the PLEISTOCENE/HOLOCENE boundary
Zone C	Increase of sublittoral marine-brackish flora and coastal plankton (<i>Thalassionema nitzschioides</i> , <i>Skeletonema costatum</i>)	The YOUNGER DRYAS regression
Zone B	Arctic plankton flora dominates (<i>Thalassiosira antarctica</i> , <i>Thalassiosira</i> spp., <i>Nitzschia cylindrus</i>). Some influx of freshwater plankton <i>Melosira islandica</i> subsp. <i>helvetica</i>	The YOUNGER DRYAS and/or older (ALLERÖD, OLDER DRYAS, BÖLLING)
Zone A	Almost barren to barren. Arctic conditions	The OLDER DRYAS or older
Zone I/A	Diatom flora of the same type as zone E	MIDDLE WEICHSELIAN Götaälv Interstadial (or Late Weichselian)
In cores from central Bohuslän:		
Zone 1 =	zone A: almost barren to barren	The OLDER DRYAS or older
Zone 2 =	zone B: Arctic plankton dominate	The YOUNGER DRYAS and/or older
subzone 3a =	zone C: increase of sublittoral flora and coastal plankton	The YOUNGER DRYAS/PREBOREAL or the OLDER DRYAS/ALLERÖD.
subzone 3b =	zone D: Sublittoral marine – brackish flora with <i>Melosira sulcata</i>	Beginning of the PREBOREAL or the ALLERÖD
and zone 4	zone 4 seems to register a temporary deterioration of the climate with some increase of Arctic plankton	Oscillation in the PREBOREAL or the YOUNGER DRYAS
Zone 5 =	zone E, except for the great influx of freshwater plankton	The PREBOREAL
Zone 6	(subzone 6b) = the beginning of zone F	Start of the BOREAL transgression

DIATOM STRATIGRAPHY CORRELATION OF THE ZONES

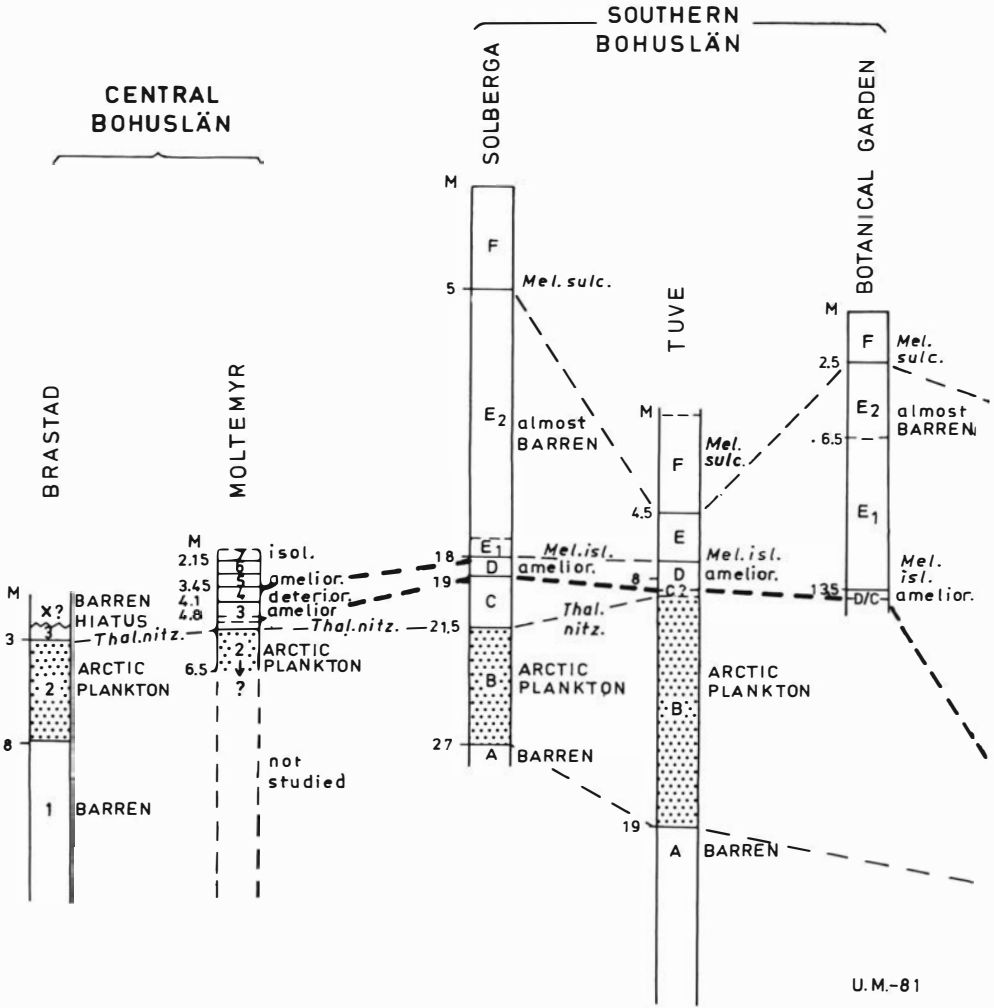
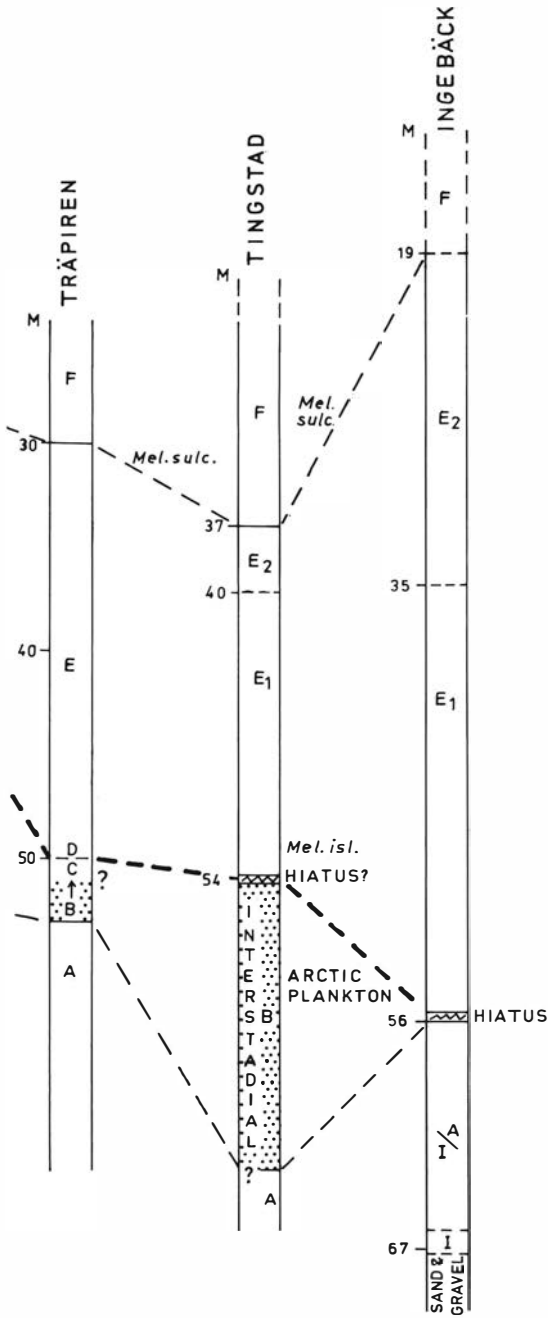


Fig. 16:11. Tentative correlation of diatom assemblage zones in cores from central and southern Bohuslän.



CONCLUDING REMARKS AND DISCUSSION

The Pleistocene marine sediments (the Younger Dryas and older) are characterized by dominance of Arctic plankton and some influx of freshwater plankton. The rapid diminution of water depth at the end of the Younger Dryas is registered in the diatom flora by increase of coastal plankton and littoral flora. The influx of freshwater plankton decreases.

In southern Bohuslän (Solberga and Tuve cores) the Preboreal sediments are characterized by dominance of freshwater plankton *Melosira islandica*. The influx of freshwater plankton begins with marked peaks in frequency. The frequency decreases upwards because of the high sedimentation rate, but *Melosira islandica* as the most common species indicates meltwater discharge or redeposition of freshwater sediments.

In central Bohuslän, the Preboreal sediments register only a minor influx of freshwater plankton. The basins situated at higher altitudes (above 55 m) gradually became isolated from the sea during the rapid Preboreal shore displacement. In basins at lower altitudes (below 55 m), the Boreal transgression corresponds to a more or less stable sea level. In Boreal sediments, there is an increase in coastal plankton (incl. *Melosira sulcata*) and littoral flora. The influx of freshwater plankton stops.

In Moltemyr core, two transitions comparable with the Pleistocene/Holocene boundary are registered in the diatom stratigraphy (at 5–4.7 m and at 3.5–3.45 m). Possibly because of the higher altitude (55 m) of the Moltemyr basin, and its relatively small area, the diatom flora registers more clearly the sea level changes. The increase of littoral flora and coastal plankton at 5–4.7 m may reflect conditions at the transition from the Older Dryas to the Alleröd as well as from the Younger Dryas to the Preboreal. The Older Dryas/Alleröd transition is the more likely because there is no marked frequency peak in marine diatoms at 5–4.7 m. The littoral diatoms in these sediments may have been washed in from nearby shores. However, the frequency peak at 3.5–3.45 m seems to represent autochthonous littoral flora characteristic of 20–30 m water depth, which agrees with the sea level at the Pleistocene/Holocene boundary, about 80–90 m above the present.

Studies in progress on shore displacement in central Bohuslän (Fredén, Miller and Robertsson) are based mainly on the sites studied by Fries (1951), supplemented by new sites at altitudes important for interpretation of the shore displacement. The preliminary results show that a rapid regression of the sea took place during the Older Dryas/Alleröd, followed by a period of more or less stable sea level during the Alleröd. At the end of the Younger Dryas, a further rapid regressive shore displacement started and continued during the Preboreal.

Contemporary shore displacement and sea-level changes should also have

occurred in southern Bohuslän (Göteborg region), but because of the low altitudes of the basins studied the Older Dryas/Alleröd sea-level changes are not so clearly registered in the diatom floras. However, the Younger Dryas/Preboreal regression is recognizable in the cores from southern Bohuslän.

SUMMARY

In diatom stratigraphy of the marine clay sequences in Bohuslän the Pleistocene/Holocene boundary is registered by the following changes:

- 1, decrease of Arctic plankton
- 2, marked increase, a peak, in diatom frequency, mainly caused by increase of marine littoral flora
- 3, almost no influx of freshwater plankton
- 4, increase of coastal and temperate plankton and littoral flora
- 5, in southern Bohuslän the sediments deposited after the Pleistocene/Holocene boundary are characterized by marked influx of freshwater plankton (meltwater discharge and/or redeposition of freshwater sediments). The influx of freshwater plankton stops at the transition to Boreal conditions.

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17. DINOFLAGELLATE CYSTS

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INTRODUCTION

Dinoflagellate cyst analysis was carried out on three cores (Brastad, Moltemyr and Solberga) taken in south-western Sweden to assist in an attempt to establish a stratotype section for the Pleistocene/Holocene boundary. Unfortunately the recovery of dinoflagellate cysts was in general so poor as to make the interpretation of the results rather difficult.

A total of one hundred and seventy-two samples were submitted and subjected to normal palynological processing techniques. These techniques included the digestion of the sediments in hydrochloric and hydrofluoric acids and the concentration of the cysts by sieving but no oxidation. After mounting and examination, in which one slide/sample was counted to give the proportions of the contained cysts, all the slides were deposited in the MPA palynological collections of the Institute of Geological Sciences, Leeds, United Kingdom. A full list of all the dinoflagellate cyst species recovered is appended (p. 216), giving both their palaeontological (cyst) and equivalent thecate names where known.

BRASTAD

DATA

Forty-three samples from the Brastad core were submitted and analysed. The results of this analysis are set out in Table 17:1. The relative proportions of the three major species and/or cyst groups *i.e.* *Operculodinium centrocarpum*, *Bitectatodinium tepikiense* summed with *Spiniferites* spp., and *Protoperidinium* spp. together with the number of individuals counted per sample are shown in Figure 20:1b (Chapter 20). The results are poor with only the samples at 6.5, 11.5 and 13.5 m core depth giving counts of over one hundred specimens. The following subdivision of the core into four units must, therefore, be regarded with some caution.

Unit D, 11.00–15.15 m depth – Characterised by high percentages of *O. centrocarpum* with some *B. tepikiense* and minor amounts of both *Spiniferites* and *Protoperidinium* cysts. There is some suggestion of a change at the base of this unit with a downhole increase of *Protoperidinium* cysts, but the evidence is too slight for further comment. Recovery good.

Unit C, 6.50–10.55 m depth – Dominated by *O. centrocarpum* but with greater percentages of *B. tepikiense* than in Unit D. *B. tepikiense* tends to increase in proportion in the upper part of the unit whilst the total *Spiniferites* spp. tends to increase downhole. The proportion of *Protoperidinium* cysts increases dramatically in the lower part of the unit. This unit contains *S. elongatus*, *S. ramosus* and the two *Multispinula* species, *M. minuta* and *M. quanta*. Recovery good.

Unit B, 2.00–6.05 m depth – Dominated by *Protoperidinium* cysts with significant proportions of *O. centrocarpum* but with poor *B. tepikiense* and *Spiniferites* spp. *B. tepikiense* occurs only in the lower part of this unit. Recovery poor.

Unit A, 1.00–1.55 m depth – This unit is essentially characterised by an assemblage virtually monospecific for *O. centrocarpum*. Recovery good.

INTERPRETATION

The poor productivity of the samples makes the diagram difficult to interpret. The species present do, however, characterise north-temperate environments although perhaps the productivity indicates a rather poor climatic regime. The environmental requirements of most of the species mentioned are not known in any detail and so this interpretation must remain largely tentative.

Unit D – *O. centrocarpum* is a cosmopolitan cyst species, Wall *et al.* (1977), which judging by the lack of many accompanying species may be indicative of poor climate and/or less than fully marine conditions. Reid and Harland (1977) described one cyst assemblage that is comparable with the present assemblage and that is their Norwegian Shelf Assemblage, but it differs in having common *Protoperidinium* cysts.

Unit C – This assemblage is more diverse than that below and can be compared to the Intermediate Neritic Assemblage of Reid and Harland (1977). The distribution of *B. tepikiense*, *Spiniferites* spp. and *Protoperidinium* spp. possibly indicates a slightly more ameliorative environment of deposition early in Unit C, than in the later sediments of the unit.

Unit B – A comparable *Protoperidinium* dominated assemblage is found today in the southern North Sea (see Reid and Harland 1977) and this may indicate the presence of a similar type of water mass at Brastad at this time. The nature of the *Protoperidinium* curve on Figure 20:1b, (Chapter 20) does seem to suggest an increasingly ameliorative climate. Wall *et al.* (1977) regard grouped *Protoperidinium* cysts as cosmopolitan estuarine-neritic species.

Unit A – This unit may be interpreted the same as for unit D. *O. centrocarpum*, because of its tolerance, may be expected as a “pioneer” species in certain difficult environmental circumstances.

MOLTEMYR

DATA

Forty samples were submitted for analysis from the Moltemyr core. The results of this analysis are set out in Table 17:2. The data are displayed in Figure 20:2b (Chapter 20) and shows the changing proportions of the major cyst groups and the number of individuals counted per sample. Assemblages of over one hundred specimens come from levels at about 5.6 and 5.7 m core depth, but otherwise recovery was poor. The core has been tentatively subdivided into a number of units and these are discussed below.

Unit D, 6.10–6.50 m depth – Dominated by *Protoperidinium* cysts with subsidiary *O. centrocarpum*. Recovery poor.

Unit C, 5.10–6.10 m depth – Characterised by high *O. centrocarpum* with subsidiary *Protoperidinium* and *Spiniferites* cysts (for example *S. elongatus* and *S. ramosus*) together with some *B. tepikiense*. Recovery good.

Unit B, 2.90–5.03 m depth – Characterised by *Protoperidinium* cysts with subsidiary *O. centrocarpum* but very few *Spiniferites* cysts or *B. tepikiense*. The only specimens of *Stelladinium stellatum* were recovered from this unit, and also *M. quanta* was present throughout.

Unit A, 2.50–2.82 m depth – Dominated by *O. centrocarpum* with occasional *B. tepikiense* and *Spiniferites* cysts at the base.

INTERPRETATION

The interpretation for the Moltemyr core is much the same as for Brastad. All the cysts recovered are north temperate species and the generally poor recovery suggests difficult environmental conditions.

Unit D is dominated by *Protopteridinium* cysts. The poor recovery and low diversity suggest poor conditions possibly in a nearshore environment. Unit C, however, indicates some amelioration in the increased productivity and diversity and the dominance of the cosmopolitan species *O. centrocarpum*. This species can also indicate an increased influence of North Atlantic water. The overlying subdivision, Unit B, may indicate some increased amelioration in a nearshore situation with a possible lowering of salinity. The final unit, A, is, like that of Brastad, an almost monospecific assemblage of *O. centrocarpum* probably indicative of a special environment, capable of supporting "pioneer" species only.

SOLBERGA

DATA

Ninety-four samples were submitted and analysed for dinoflagellate cysts. The results of this analysis are set out in Table 17:3. These data have been displayed in Figure 20:3b (Chapter 20) to show the changing proportions of the three major species and/or cyst groups together with the number of individuals counted per sample. This core yielded even fewer specimens than the Brastad or Moltemyr cores and it is doubtful if much of the sediment was deposited in favourable conditions. Good assemblages of over one hundred specimens came only from the levels at 19.45, 19.55 and 20.00 m core depth. An attempt has been made, however, to subdivide the core into five dinoflagellate units and these are described below.

Unit E, 21.50–27.30 m depth – Characterised by high percentages of *Protopteridinium* cysts and a lesser amount of *O. centrocarpum*. *Spiniferites* cysts occur in the lower and upper parts of the unit with *B. tepikiense* occurring in the lower sediments. Poor recovery.

Unit D, 18.50–21.05 m depth – Dominated by *O. centrocarpum* with subsidiary *Protopteridinium* cysts and minor *Spiniferites* cysts, including reasonable numbers of *S. ramosus*. The presence of *Stelladinium stellatum* is particularly noteworthy. Good recovery.

Unit C, 16.20–18.45 m depth – Characterised by *Protopteridinium* cysts with subsidiary *O. centrocarpum* and *B. tepikiense*. The presence of *M. quanta* is noteworthy. Good recovery.

Unit B, 11.50–16.05 m depth – Dominated by *Protopteridinium* cysts with minor amounts of *O. centrocarpum*, *M. minuta* and *M. quanta*. Poor recovery.

Unit A, 2.50–11.05 m depth – Characterised by *O. centrocarpum* and *Protopteridinium* cysts. Poor recovery.

INTERPRETATION

The general paucity of cysts throughout the sequence makes any interpretation difficult, and only units D and C are commented upon.

Unit D – This corresponds with the first influx of good assemblages of dinoflagellate cysts indicating either a transition to favourable environments or a change in sedimentary conditions. The assemblage is dominated by *O. centrocarpum* with *Protoperidinium* cysts and is quite comparable to that from the Norwegian shelf (Dale 1976) and referred to as the Norwegian Shelf Assemblage by Reid and Harland (1977). This is indicative of a good north-temperate climate and a neritic environment of deposition.

Unit C – Again a rich assemblage but different from above in the dominance of *Protoperidinium* cysts which may mean a further amelioration of climate or some other environmental change possibly with the establishment of a water mass somewhat similar to that in southern North Sea today (Reid and Harland 1977). The rapidly fluctuating proportions of *B. tepikiense* may indicate periods of colder climate or possibly changes in the water-mass configuration. It is a unit closely linked with Unit D as a part of the marine transgression.

CONCLUSIONS

The results of the dinoflagellate cyst analysis on the Brastad, Moltemyr and Solberga cores are disappointing. The cores have, however, been subdivided using the dinocyst evidence and some tentative interpretations made.

In the Brastad and Moltemyr cores the results may suggest a climatic amelioration up to the so-called Pleistocene/Holocene boundary with a number of fairly clearly defined assemblages characterising slightly different water-mass situations. The presence of the cyst species *Stelladinium stellatum* in Moltemyr and Brastad may be of some particular environmental significance and has also been found by B. Dale (pers. comm.) in a similar stratigraphical situation offshore. Further comment on the Solberga core is precluded by the poor recovery except that, during the time of deposition of units E, B and A, conditions were either climatically unfavourable and/or less than fully marine, or sedimentary conditions were unfavourable. None of the species appears to be age diagnostic and so further comment on age is not reasonable. These results should be taken into account together with others described in any discussions on the Pleistocene/Holocene boundary.

APPENDIX

List of Dinoflagellate Taxa recovered from Pleistocene/Holocene Cores
in South West Sweden

CYST NAME	THECATE NAME
Order <i>PERIDINIALES</i> Haeckel 1894	
Family <i>GONYAULACACEAE</i> Lindemann 1928	
<i>Bitectatodinium tepikiense</i> Wilson	<i>Gonyaulax spinifera</i> (Claparède & Lachmann) Diesing
<i>Lingulodinium machaerophorum</i> (Deflandre & Cookson) Wall	<i>Gonyaulax polyedra</i> Stein
<i>Operculodinium centrocarpum</i> (Deflandre & Cookson) Wall	<i>Gonyaulax grindleyi</i> (Reinecke) Von Stosch
<i>Planinosphaeridium choanum</i> (Reid) Wall <i>et al.</i>	<i>Gonyaulax</i> sp. indet.
<i>Spiniferites belerius</i> Reid	<i>Gonyaulax scrippsae</i> Kofoid
<i>Spiniferites elongatus</i> Reid	<i>Gonyaulax spinifera</i> (Claparède & Lachmann) Diesing
<i>Spiniferites lazus</i> Reid	<i>Gonyaulax</i> sp. indet.
<i>Spiniferites membranaceus</i> (Rossignol) Sarjeant	<i>Gonyaulax spinifera</i> (Claparède & Lachmann) Diesing
<i>Spiniferites ramosus</i> (Ehrenberg) Loeblich & Loeblich	<i>Gonyaulax</i> sp. indet.
<i>Spiniferites</i> spp. indet.	<i>Gonyaulax</i> spp. indet.
Family <i>PERIDINIACEAE</i> Ehrenberg 1832	
<i>Brigantedinium simplex</i> (Wall) Reid	<i>Protooperidinium conicoides</i> (Paulsen) Balech
<i>Brigantedinium cariacensis</i> (Wall) Reid	<i>Protooperidinium avellana</i> (Meunier) Balech
Cyst B of Harland 1977	<i>Protooperidinium</i> sp. indet.
Cyst	<i>Protooperidinium punctulatum</i> (Paulsen) Balech
Cyst indet.	<i>Protooperidinium</i> sp. indet.
<i>Lejeunia paratenella</i> Benedek	<i>Protooperidinium</i> sp. indet.
<i>Multispinula minuta</i> Harland & Reid	<i>Protooperidinium</i> sp. indet.
<i>Multispinula quanta</i> Bradford	<i>Protooperidinium conicum</i> (Gran) Balech
<i>Selenopemphix nephroides</i> Benedek	<i>Protooperidinium subinermis</i> (Paulsen) Loeblich III
<i>Stelladinium stellatum</i> (Wall) Reid	<i>Protooperidinium compressum</i> (Abé) Balech
<i>Trinovantedinium sabrinum</i> Reid	<i>Protooperidinium leonis</i> (Pavillard) Balech
<i>Quinquecuspis concretum</i> (Reid) Harland	<i>Protooperidinium leonis</i> (Pavillard) Balech
Order <i>GYMNODINALES</i> Lemmermann 1910	
Family <i>POLYKRIKACEAE</i> Kofoid & Swezy 1921	
Cyst	<i>Polykrikos schwartzii</i> Bütschli

TABLE 17:1. Dinoflagellate cyst counts for the Brastad core.

MPA No	Depth	Species	01	02	03	04	05	06	07	08	09	10	11	12	13
8333	100-105	cms	5												
8334	150-155		87	1			1	1							
8335	200-205														
8336	210-215													4	
8337	215-220														
8338	220-225		2										1	5	
8339	225-231														
8340	231-235		9			1	1		1	1			1	3	
8341	235-240		5						1	1			1	6	
8342	240-245		13			1				1				9	
8343	250-255		5							1			3	6	
8344	260-265					1						1		6	
8345	270-275		1											10	
8346	275-280		6											18	
8347	290-295													3	
8348	300-305		1											2	1
8349	350-355		4									2		16	
8350	400-405		9	1					1		1	2	2	13	
8351	450-455		6	2						1		3	3	21	
8352	500-505		9	6						3				10	
8353	550-555		6											2	12
8354	600-605		20	16		1				5			5	7	
8355	650-655		125	38				1	5	14		4	9	46	
8356	700-705		31	3					4	3			2	8	
8357	750-755		18	11		3				4			7	8	
8358	800-805		15	7		2				3			1	6	
8359	850-855		11	9		1	1		11			2	2	9	
8360	900-905		7	2						2		1		7	
8361	950-955		32	2					4	7				8	
8362	1000-1005		10	2						10		1	4	37	
8363	1050-1055		1									1		11	
8364	1100-1105		72	2										2	
8365	1150-1155		180	6											
8366	1200-1205													3	
8367	1250-1255		12	3										1	
8368	1300-1305		53							1					
8369	1310-1315		9												
8370	1332-1335		14	1											
8371	1350-1355		111	6	1							2			
8372	1400-1405		3												
8373	1450-1455		74	4						1				3	
8374	1503-1509													16	
8375	1509-1515														

The code numbers refer to the following species: 01. *Operculodinium centrocarpum*. 02. *Bitectatodinium tepikiense*. 03. *Spiniferites belerius*. 04. *Spiniferites elongatus*. 05. *Spiniferites lazus*. 06. *Spiniferites membranaceus*. 07. *Spiniferites ramosus*. 08. *Spiniferites* spp. indet. 09. *Brigantedinium simplex*. 10. *Multispinula minuta*. 11. *Multispinula quanta*. 12. *Protoperidinium* spp. indet. 13. Cyst B of Harland 1977.

TABLE 17:2, continued.

MPA No	Depth	Special	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
13051	470-480		28	1			7		2												
13052	480-490		27			3	9		2									1	1		
13053	490-500		22	2			49		4											1	
13054	500-503		11		1		14		4												
13055	510-520		17	1	2	2	7		1											1	
13056	520-530		13	1	7	3	2		1											2	
13057	530-540		52	4	6	9	14		5				1	1						1	
13058	540-550		30	3	15	2	14		7				1								
13059	550-560		14	2	8		9		4					1							
13060	560-570		140	13	23	4	9		11					5						8	
13061	570-580		136	17	12	36	11		1			1	1	4						5	
13062	580-590		47	12	5	22	5					1	1	1						1	
13063	590-600		51	1	17		10		1					3						1	
13064	600-610		29	2	5		27		3					4							
13065	610-620		10		2		18							2							
13066	620-630		3				31							7							
13067	630-640		4				24														
13068	640-650		13		4		21		1												1

The code numbers refer to the following species: 01. *Operculodinium centrocarpum*. 02. *Bitectatodinium tepikiense*. 03. *Spiniferites* spp. indet. 04. *Spiniferites ramosus*. 05. *Protoperidinium* spp. indet. 06. *Spiniferites lazus*. 07. *Stelladinium stellatum*. 08. *Multispinula quanta*. 09. *Brigantedinium cariacensis*. 10. *Polykrinos schwartzii* cyst. 11. *Brigantedinium simplex*. 12. *Multispinula minuta*. 13. *Lejeunia paratenella*. 14. *Spiniferites belerius*. 15. *Protoperidinium punctulatum* cyst. 16. *Selenopemphix nephroides*. 17. *Planinosphaeridium choanum*. 18. *Spiniferites elongatus*. 19. *Quinquacuspis concretionum*.

TABLE 17.3. Dinoflagellate cyst counts for the Solberga core.

MPA No	Depth	Species	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	18	19
8376	250-255		10		1										6				17	
8377	300-305		13	1			1	1		4	13				2	1	2		31	
8378	350-355		9	2	1					2	8				6				11	
8379	400-405		3												1				2	
8380	450-455		2	2															3	
8381	470-475		3																5	
8382	480-485		5																1	
8383	490-495		3	3															2	
8384	500-505		7	1															2	
8385	510-515		11	2											1				6	
8386	520-525		4							1									8	
8387	530-535														1				4	
8388	550-555		2																2	
8389	590-595		6	9						1									2	
8390	595-600		3	3								1							3	
8391	600-605		1			1													8	
8392	650-655		1																6	
8393	700-705		6	2															4	
8394	750-755		2																1	
8395	780-785		4																3	
8396	785-790		4	3											2				9	
8397	800-805		7					1											4	
8398	850-855		4																7	1
8399	900-905		2	2													1		13	
8400	945-950		2	2										1					1	
8401	950-955		1																13	
8402	1000-1005		2																8	2
8403	1050-1055		7																1	
8404	1100-1105		2																1	
8405	1050-1155																			
8406	1200-1205																		3	
8407	1250-1255		2	1										2	1		1		1	6

TABLE 17:3, continued.

MPA No	Depth	Special	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
8408	1300-1305																		3		
8409	1350-1355		1							1									6		
8410	1380-1385																		1		
8411	1400-1405													2	1				1		
8412	1450-1455		2	1						1				1					4		
8413	1500-1505									2									5		
8414	1550-1555													1					5		
8415	1600-1605		2											1					7		
8416	1620-1625		2	1											1				1		
8417	1635-1640		1	2										1	1				2		
8418	1650-1655		2																6		
8419	1665-1670		1												1				7		
8420	1675-1680		67							1					1				15		
8421	1690-1695		3							3					1				19		
8422	1700-1705																		11		
8423	1710-1715		3											1					1		
8424	1720-1725		2						1										9		
8425	1725-1730		1	4										1					6		
8426	1730-1735		3	5															8		
8427	1740-1745		2	2															15		
8428	1750-1755		2	2															16		1
8429	1760-1765		3											2					11		1
8430	1770-1775		8	7															20		
8431	1775-1780		6	34										1	4				18		
8432	1780-1785		7		1					3									34		
8433	1790-1795		16	4															65		
8434	1800-1805		4											1			2		30		
8435	1810-1815		5	46															17		1
8436	1820-1825		2							3	1			3					33		1
8437	1825-1830		6																25		
8438	1830-1835		9									1							3		20
8439	1840-1845		10														1		2		26
8440	1850-1855		9																1		30
8441	1860-1865		7							1									1		46

TABLE 17:3, continued.

MPA No	Depth	Special	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
8442	1870-1875		5												1		1		14		
8443	1875-1880		6							1								1	8		
8444	1880-1885		14	2					1	1						2			16		
8445	1890-1895		8	1				1					1			1			26		
8446	1900-1905		35		1				1				1			7			37		
8447	1910-1915		48						1						5	4			22		
8448	1920-1925		20						1				1						39		
8449	1925-1930		53						4				1						39		
8450	1930-1935		43	2				3					1	2					12		
8451	1945-1950		69	2			1	1	9				1	1	3				33	1	
8452	1955-1960		78					2	7				1	1	1				35		
8453	1975-1980		20						1				2	3	1				20		
8454	2000-2005		151	1			2			1		2		2	2		1		47		
8455	2050-2055		27					2		2					1				35		
8456	2100-2105		4										1	1					7		
8457	2150-2155																		4		
8458	2200-2205		4																1		1
8459	2250-2255		2						1										3		3
8460	2300-2305																		2		2
8461	2350-2355																		3		1
8462	2400-2405		2																3		3
8463	2455-2460		4																4		4
8464	2500-2505		1																8		2
8465	2550-2555		5																12		3
8466	2600-2605		3	2										1					2		2
8467	2650-2655		15	11				1	3					3	2				4		4
8468	2700-2705		11	6					1					1					2		2
8469	2725-2730																		13		

The code numbers refer to the following species: 01. *Operculodinium centrocarpum*. 02. *Bitectatodinium tepikiense*. 03. *Spiniferites belerius*. 04. *Spiniferites elongatus*. 05. *Spiniferites lazus*. 06. *Spiniferites membranaceus*. 07. *Spiniferites ramosus*. 08. *Spiniferites* spp. indet. 09. *Lingulodinium machaerophorum*. 10. *Brigantidinium simplex*. 11. *Lejeunia paratenella*. 12. *Multispinula minuta*. 13. *Multispinula quanta*. 14. *Selenopemphix nephroides*. 15. *Stelladinium stellatum*. 16. *Trinovantedinium sabrinum*. 17. *Protoperidinium* spp. indet. 18. Cyst B of Harland 1977. 19. *Polykrikos schwartzii* cyst.

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18. POLLEN

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INTRODUCTION

Pollen analysis was used to envisage the vegetational changes which occurred in the archipelago in the vicinity of the sites under study. As reference for the marine sequences at Solberga and Moltemyr, two localities with limnic sediments on the adjoining land areas were investigated, *i.e.* Vågen and Rörmyr (Fig. 4:4, Chapter 4). In the case of the sediments in the Brastad core, only preliminary pollen analyses were made.

Pollen-analytical investigations have been used to reconstruct the vegetational changes, which took place in the late Pleistocene and early Holocene in south-western Sweden (Fries 1951, Berglund 1976, 1979, Digerfeldt 1979, Hilldén 1979). Fries made an extensive pollen-analytical study of about 20 localities in Bohuslän on the west coast of Sweden (Fries 1951). His material included both marine and limnic sediments. Two of the sites, Moltemyr and Rörmyr, were reviewed in connection with the boundary project.

In Sweden pollen analysis of marine sediments has rarely been performed with a view to deduction of the late Pleistocene and early Holocene vegetational history. Nevertheless the pollen flora in marine sediments has been shown to reflect the main features of the vegetational history of their continental (inland) source (e.g. Stanley 1969, Florer 1973, Heusser 1978, Balsam and Heusser 1976). The interpretation from marine, minerogenic sediments may be affected by limiting factors such as low pollen frequencies, corrosion and irregular transportation of pollen causing over-representation of some species. The presence of reworked pollen and spores, of pre-Quaternary and older Quaternary age, may indicate the origin and source areas of sediments. Increasing frequency of secondary pollen also marks increased erosion due to base-level lowering during periods of continental glaciation (Stanley 1966).

According to Fries 1951 and Berglund 1979, Fig. 6, the vegetational

sequences in south-western Sweden during the late Pleistocene and early Holocene were as follows:

- Preboreal (PB), transition from tundra to open woodland with shrubs and, later, closed woodland dominated by birch
 a, *Betula* – *Empetrum*
 b, *Betula* – *Juniperus*
 c, *Betula* – *Pinus*
- Younger Dryas (DR 3), shrub and herb tundra
Juniperus – *Artemisia* – Gramineae – Cyperaceae
- Alleröd (AL), woodland – open woodland – heaths
Betula – (*Pinus*) – *Empetrum* – Gramineae – *Artemisia*
- Older Dryas (DR 2), shrub tundra – open tundra
Juniperus – Gramineae – Cyperaceae
- Bölling (BÖ), open woodland – *Betula* woods
Artemisia – Gramineae – Cyperaceae
- Oldest Dryas (DR 1), open tundra with shrubs and herbs
Artemisia – Cyperaceae – *Dryas*

TECHNIQUES, ANALYSIS AND DIAGRAM CONSTRUCTION

All samples were first treated by standard methods, hydrofluoric acid and acetolysis (Faegri and Iversen 1975). The pollen concentrations at Solberga and Moltemyr were low, and at Brastad extremely low. A sedimentation-separation method was therefore used (Påsse 1976) for the samples from Solberga, Moltemyr and Brastad. The pollen frequencies in the samples processed then increased noticeably.

Solberga and Moltemyr presented an abundance of both reworked pre-Quaternary pollen and spores and redeposited Quaternary pollen of interstadial and/or interglacial origin. About 500 pollen grains of terrestrial plants, excluding reworked pollen, were counted in each sample.

The diagrams were constructed in accordance with Berglund (1976). Rebedded pollen and spores are represented in three different curves:

SOLBERGA, altitude 2m a.s.l.
POLLEN

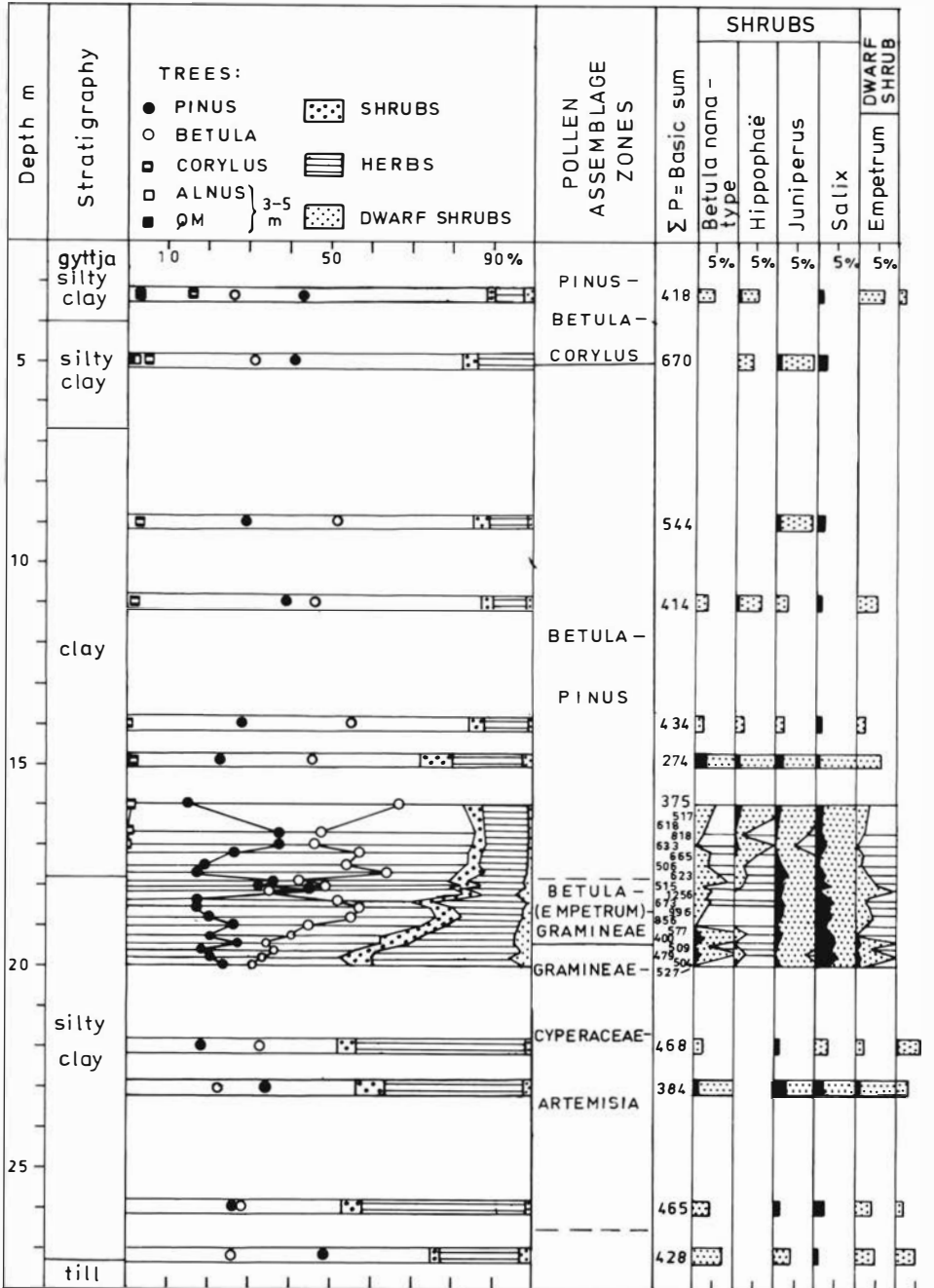
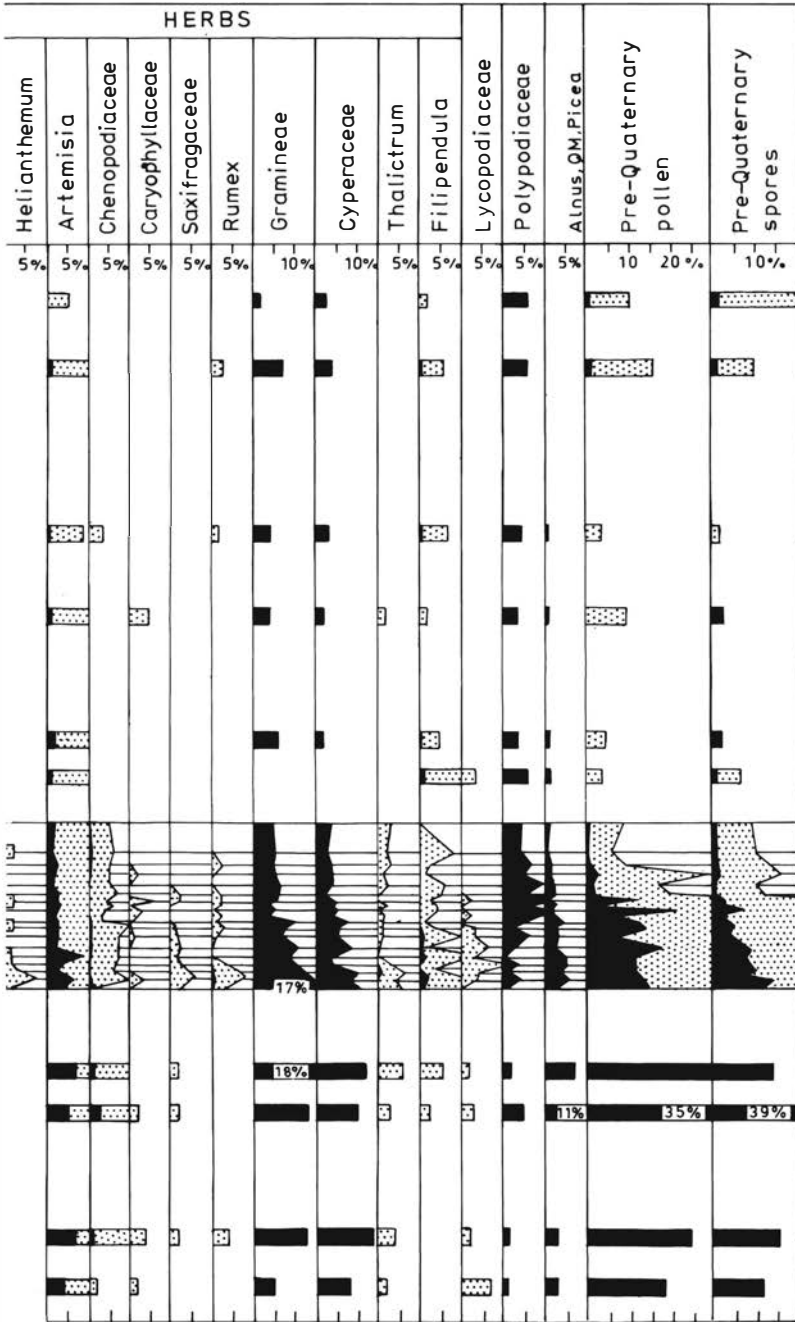


Fig. 18:1. Pollen diagram of the core from Solberga.





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(1) Quaternary tree pollen including *Alnus*, QM and *Picea*, (2) pre-Quaternary pollen and (3) pre-Quaternary spores. The pollen diagrams were divided into pollen assemblage zones, PAZ. The boundary between the chronozones Younger Dryas (DR 3) and Preboreal (PB) was defined by radiocarbon datings of sediments from Vågen and Rörmyr. The sediments in the cores from Vågen and Rörmyr were classified according to the system, used at the Geological Survey (SGU 1978).

DIAGRAM DESCRIPTION

Solberga, 2 m above sea level

Stratigraphy: see Chapters 6 and 7.

Gramineae – Cyperaceae – *Artemisia* PAZ (26.5–19.5 m)

Pollen spectra characterized by high frequencies of herbs (about 30 %) such as *Artemisia*, Gramineae and Cyperaceae (Fig. 18:1). Pollen of shrubs and dwarf shrubs occur with 4–6 %. There are high values for reworked pre-Quaternary and Quaternary pollen. The pre-Quaternary pollen types include Jurassic, Cretaceous, and Tertiary assemblages with e.g. *Classopollis*, *Tricolporopollenites*, *Caytonipollenites*, *Carya*, *Platycarya*, and *Sciadopitys* (Fig. 18:2). Palaeozoic palynomorphs were also observed. The rebedded interglacial pollen flora is represented by tree pollen of *Picea*, *Alnus*, QM, and *Corylus*. But some of the herb pollen and spores may also derive from early Quaternary deposits. Triporate pollen of a Coryloid–Betuloid type (Fig. 18:2), which may be of pre-Quaternary or Quaternary origin, occurs in this zone with 5–6 %. Unidentifiable, corroded, crumpled pollen grains constitute 5–10 %.

Betula – (*Empetrum*) – Gramineae PAZ (19.5–17.9 m)

Rising values for *Betula*. Decreasing frequencies for reworked pollen and spores. Pollen of shrubs and dwarf shrubs occur with slightly higher values than in the preceding zone.

Betula – *Pinus* PAZ (17.9–6.0 m)

Tree pollen represented by *Betula* and *Pinus* increases. *Corylus* occurs with 1–3 %. Herb pollen decreases to frequencies around 10 %. There is also a marked decline in reworked pre-Quaternary pollen and spores.

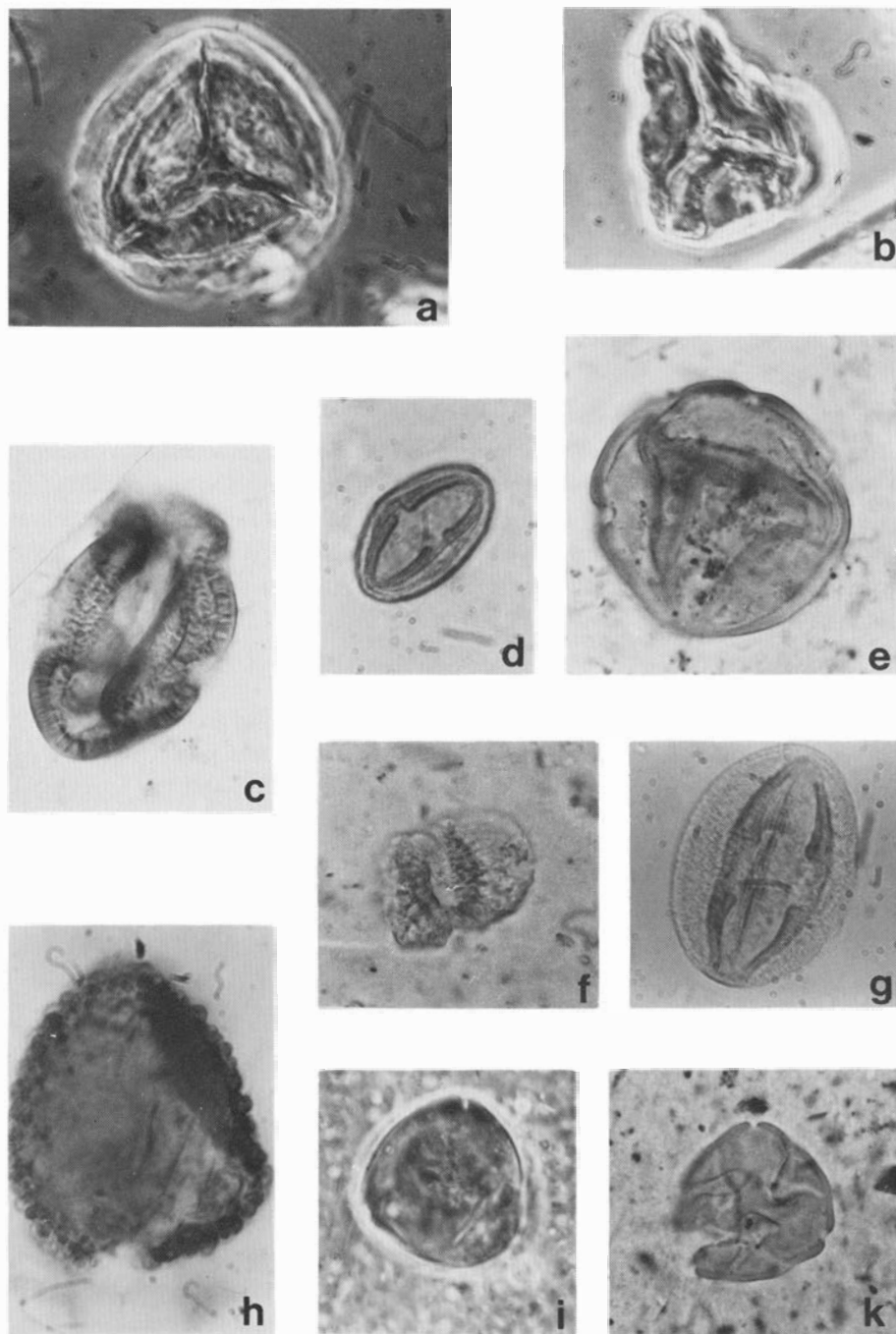


Fig. 18:2. Reworked pre-Quaternary pollen and spores from Solberga and Moltemyr. (a-b) Trilete spores, (c) *Classopollis*, (d) *Tricolporopollenites*, (e) *Carya*, (f) *Cyatonipollenites* (*Vitreisporites*), (g) *Tricolporopollenites* (cf. *Rhus*), (h) *Sciadopitys*, (i) triporate pollen of Betuloid-Coryloid type, (k) *Platycarya*. Magnification 1000x.

Pinus – Betula – Corylus PAZ (6.0–3.0 m)

This zone is characterized by tree pollen of *Pinus* and *Betula*. Increasing percentage of *Corylus*.

The zone boundary at 19.5 m, indicated by a decrease in herb pollen together with increasing frequencies of *Betula*, is presumed to correspond to the Pleistocene/Holocene boundary. The rise of the *Corylus* curve at about 5 m reflects the immigration of hazel during the early Boreal.

Vägen, 112 m above sea level

The site chosen as a terrestrial reference for Solberga is Vägen, situated about 12 km east of Solberga in the Svartedalen area. On the Geological Map sheet Göteborg NO (Fredén 1979) the Vägen site is to be found 7.5 km WSW of St. Peder's Church on the Göta River. The core was taken in an overgrown creek of Lake Stora Äggdalsjön, situated just above the local highest shoreline. The stratigraphy (Fig. 18:3) is

0–215 cm	fen peat
215–235 cm	<i>Carex</i> peat
235–260 cm	<i>Carex-Sphagnum</i> peat
260–272.5 cm	<i>Equisetum</i> peat
272.5–288 cm	gyttja
288–296 cm	clay gyttja
296–370 cm	gyttja clay
370–568 cm	clay

Diatom analysis confirms that the sediments were deposited in fresh water (see Chapter 16).

Betula – Pinus – Empetrum PAZ (360–320 cm)

In this zone the tree pollen consists of *Betula* and *Pinus* (Fig. 18:3). Pollen of *Betula nana* is frequent together with *Salix* and *Juniperus*. *Empetrum* is represented with values over 5 %. There are also high frequencies of Cyperaceae, Gramineae and *Rumex*. *Pediastrum* occurs with over 40 % in two samples. Pollen of Limnophyta occurs. This zone represents the Alleröd interstadial, during which the vegetation comprised *Betula* woods, *Empetrum* heath and open ground with Gramineae.

Artemisia – Gramineae – Cyperaceae PAZ (320–295 cm)

There is a marked increase in *Salix*, *Artemisia* and Gramineae. Chenopodiaceae, *Thalictrum*, *Dryas*, and *Rumex* were recorded among the herb pollen. Spores of Lycopodiaceae are more frequent than in the zone below. The pollen flora reflects a change in the vegetation to more open communities with *Salix* shrubs. *Artemisia* and grass dominated among the herbs.

This pollen assemblage zone corresponds to the Younger Dryas stadial.

Betula – *Empetrum* PAZ (295–287 cm)

Pronounced increase of *Betula* pollen from about 20 to 50 %. *Empetrum* pollen reaches its highest values of 9 %. There is a distinct decline in pollen of *Artemisia*, Cyperaceae, *Rumex*, and *Thalictrum*. This pollen assemblage zone represents a transition from tundra to *Empetrum* heath, shrub vegetation and *Betula* stands. Moist meadows with *Filipendula* and Gramineae also occurred.

Betula – *Juniperus* PAZ (287–275 cm)

This zone is characterized by a very marked increase of *Juniperus* pollen. *Empetrum* occurs with about 4 %. Aquatic plants are present in Lake Stora Äggsdalssjön where the gyttja was deposited. They are represented in the pollen flora by maxima for *Myriophyllum alterniflorum*, *Potamogeton* and *Nymphaea*.

Betula – *Pinus* PAZ (275–260 cm)

Pollen of *Betula* increases and reaches frequencies over 50 %. There is a decrease in pollen of *Juniperus* and *Betula nana*. *Hippophaë* occurs, which indicates that the shore is fairly near the sedimentation area.

The *Betula* – *Juniperus* and *Betula* – *Pinus* pollen assemblage zones represent the gradual change of vegetation from open heath with shrubs and stands of *Betula* to more dense birch forest. At Vägen, the Pleistocene/Holocene boundary can be placed at 295 cm. The clay gyttja above the boundary (293–289 cm) is radiocarbon dated (see Chapter 19).

VÄGEN, altitude 112 m a.s.l.
 POLLEN

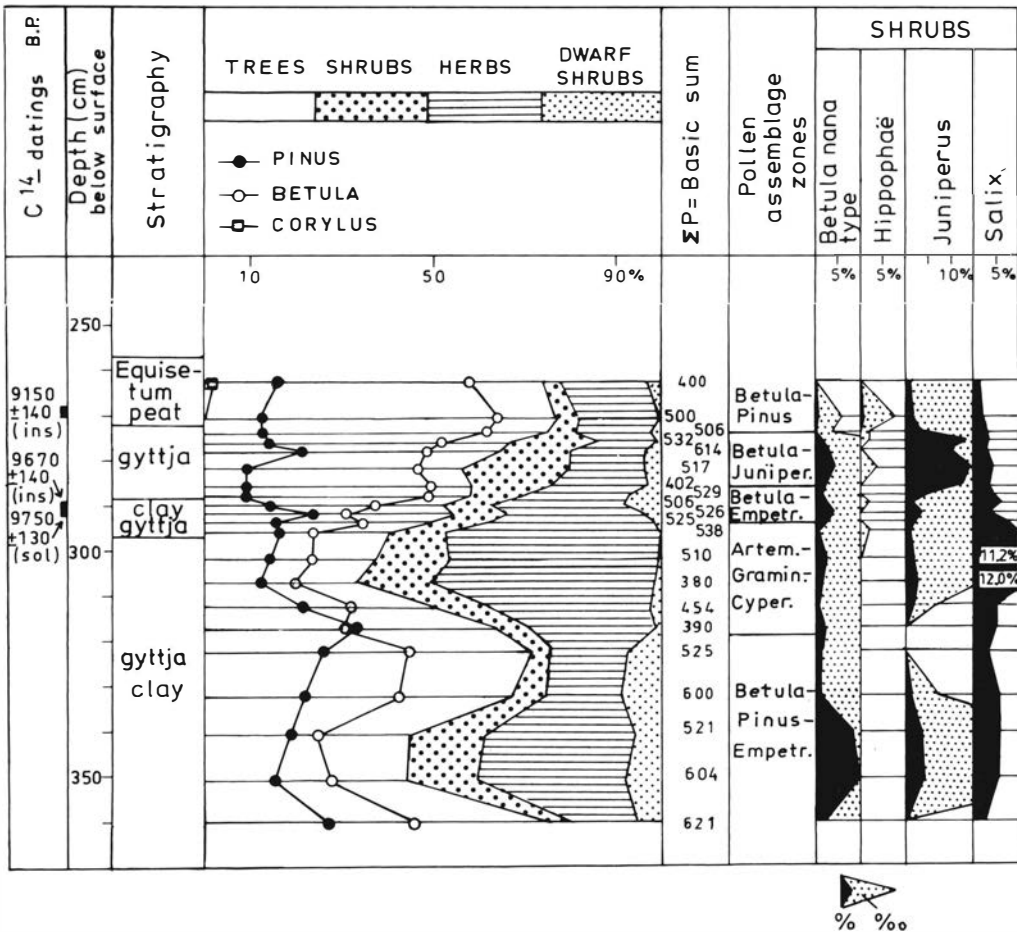
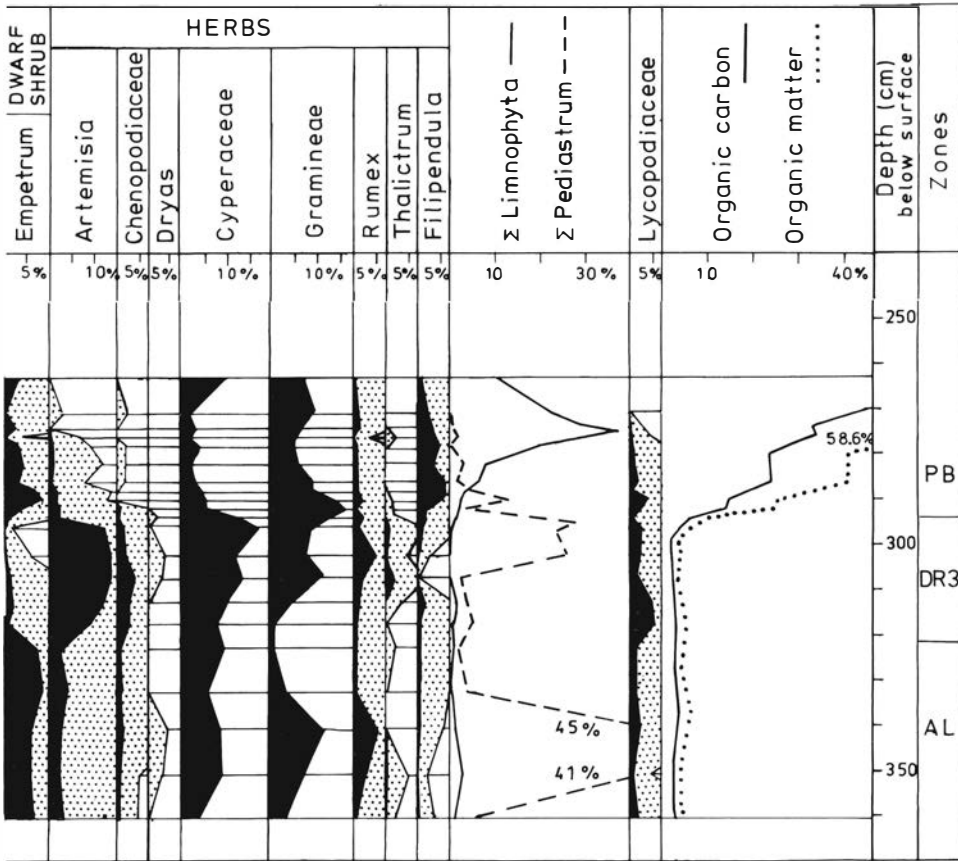


Fig. 18:3. Pollen diagram of the core from Vågen.



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Moltemyr, 55 m above sea level

Stratigraphy: See Chapters 6 and 7.

Betula – (*Pinus*) – *Artemisia* – Gramineae PAZ (620–470 cm)

High frequency of herb pollen, 30–40 %, mainly *Artemisia*, Gramineae and Cyperaceae. *Thalictrum*, Chenopodiaceae, *Helianthemum*, and Saxifragaceae too are represented with continuous curves. Pollen of shrubs occurs with frequencies over 10 %, represented by *Betula nana*, *Salix* and *Juniperus*. Redeposited pollen, pre-Quaternary and Quaternary are each represented with about 10 % (Fig. 18:4). Judging by the composition of the pollen flora, this zone may indicate sedimentation during a stadial (the Younger Dryas?).

Betula – *Juniperus* – *Empetrum* PAZ (470–400 cm)

Betula increases to values approaching 50 %. Shrub pollen from *Betula nana*, *Salix*, *Juniperus*, and *Hippophaë* are present. Pollen of *Empetrum* occurs with values exceeding 2 %. The lower boundary of this zone constitutes the transition from open *Artemisia* communities to a vegetation with more shrubs and *Betula* stands.

Betula – *Hippophaë* – *Empetrum* PAZ (400–320 cm)

Betula shows fairly constant values (around 50 %). Other tree pollen present are *Pinus* and *Populus*. *Empetrum* has a small maximum in this zone, as has *Hippophaë*, which indicates that the sedimentation area was not far from the shore.

Betula – *Juniperus* – *Salix* PAZ (320–290 cm)

Pollen of *Empetrum* decreases. *Juniperus* and *Salix* show slightly higher frequencies than in the preceding zone.

Betula – *Hippophaë* – *Salix* PAZ (290–215 cm)

There is an increase of *Betula nana* and *Hippophaë* pollen. *Salix* still appears with 3–5 %. *Corylus* is present with about 2 %. Among the herbal pollen Chenopodiaceae and *Filipendula* show slightly higher values than in the preceding zone. The upper boundary of this zone is marked by an increase in pollen of *Corylus*, which exceeds 10 % at the 210 cm level. The sediments between 222.5 and 202.5 cm are radiocarbon dated (see Chapter 19).

In the Moltemyr core the most marked change in the composition of the pollen flora occurs above 470 cm, with the increase of *Betula* and decrease of herb pollen. This transition may correspond to the Pleistocene/Holocene boundary.

Rörmyr, 115 m above sea level

The limnic locality chosen as reference to Moltemyr is situated in the Skottfjället area 4 km to the north. Rörmyr was investigated by Fries (Fries 1951, pp. 78–80).

The stratigraphy (Fig. 18:5) at the sampling point (Bp 1) about 40 m north-west of Lake Svartevatten is

500–555 cm	fen peat
555–600 cm	<i>Sphagnum</i> peat
600–625 cm	<i>Phragmites</i> peat
625–650 cm	coarse detritus gyttja
650–680 cm	fine detritus gyttja
680–690 cm	clay gyttja
690–695 cm	gyttja clay
695–720 cm	clay

Later, material was sampled for radiocarbon dating and supplementary diatom analysis. The stratigraphy at this boring point (Bp 2) is

550–565 cm	fen peat
565–630 cm	<i>Sphagnum</i> peat
630–670 cm	<i>Phragmites</i> peat
670–727.5 cm	coarse detritus gyttja
727.5–740 cm	fine detritus gyttja
740–750 cm	clay gyttja
750–762.5 cm	gyttja clay
762.5–	clay

According to diatom analysis, the sedimentary basin was isolated from the sea during the Younger Dryas. The isolation is indicated at 750 cm in Bp 2 (see Chapter 16).

MOLTEMYR, altitude 55 m a.s.l.
POLLEN

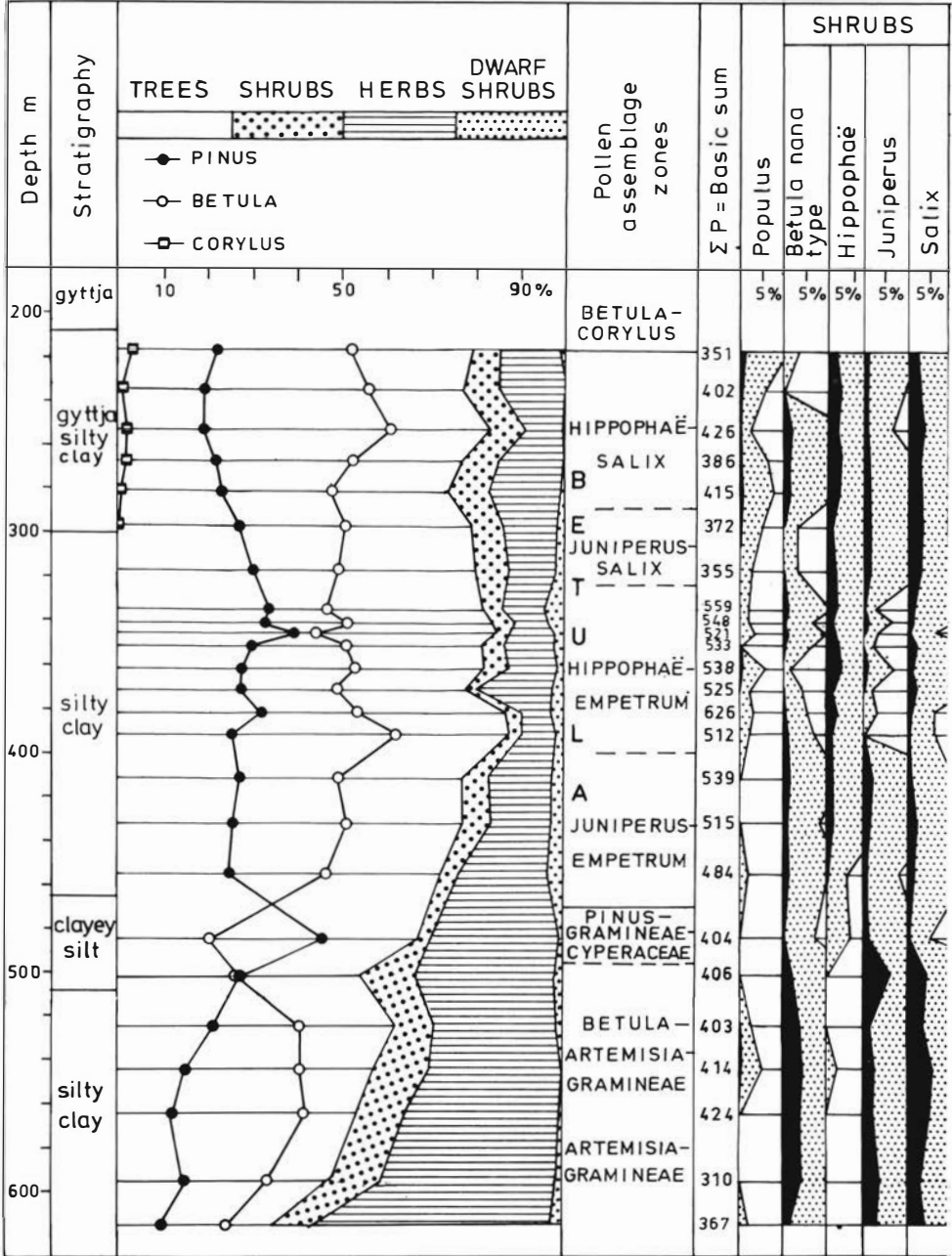
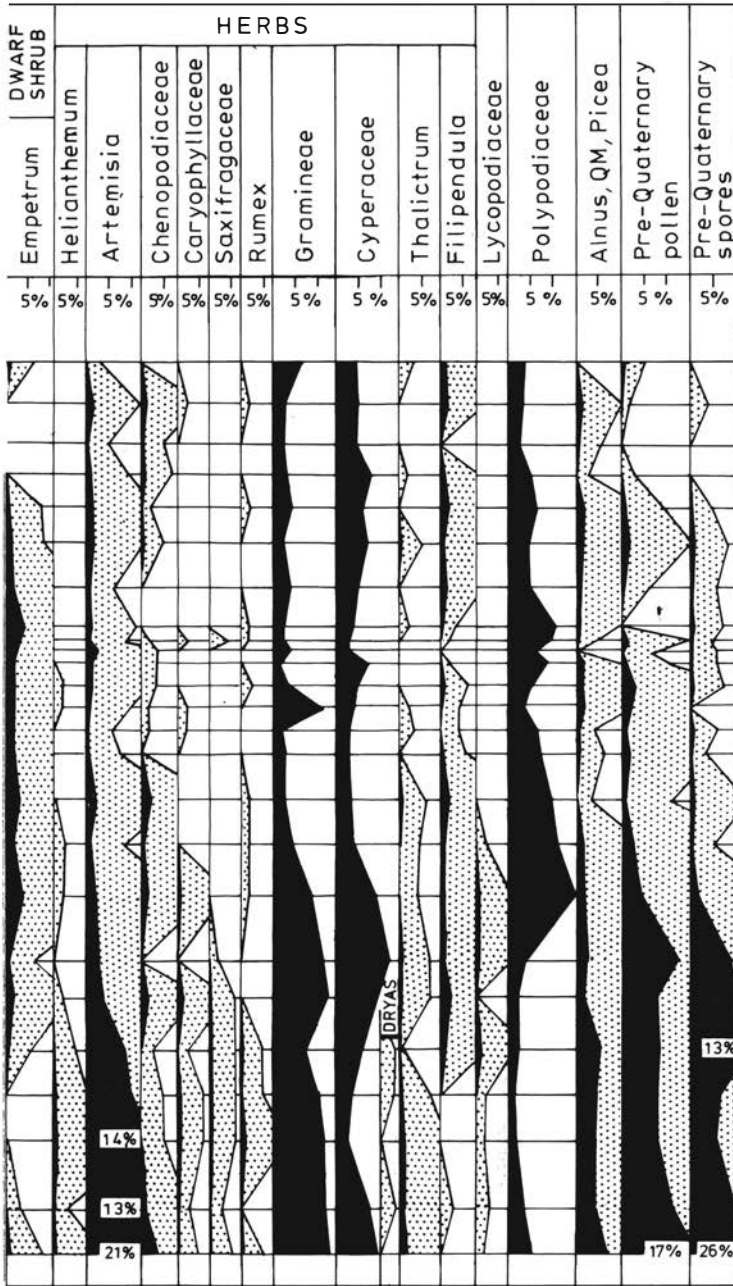


Fig. 18:4. Pollen diagram of the core from Moltemyr.





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RÖRMYR, altitude 115 m a.s.l.
POLLEN, Bp 1

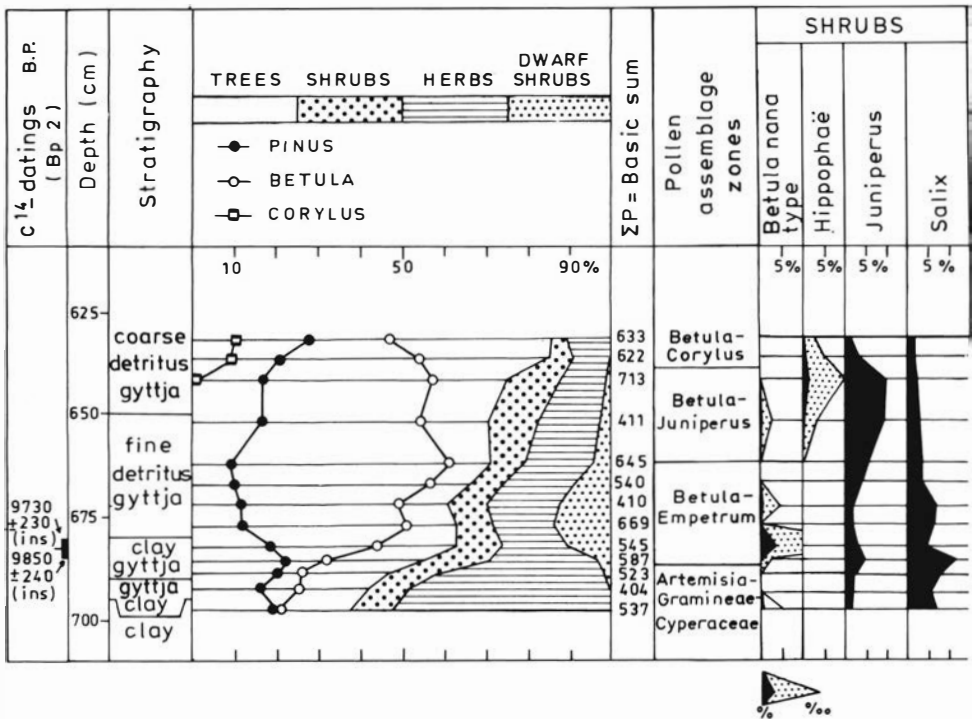


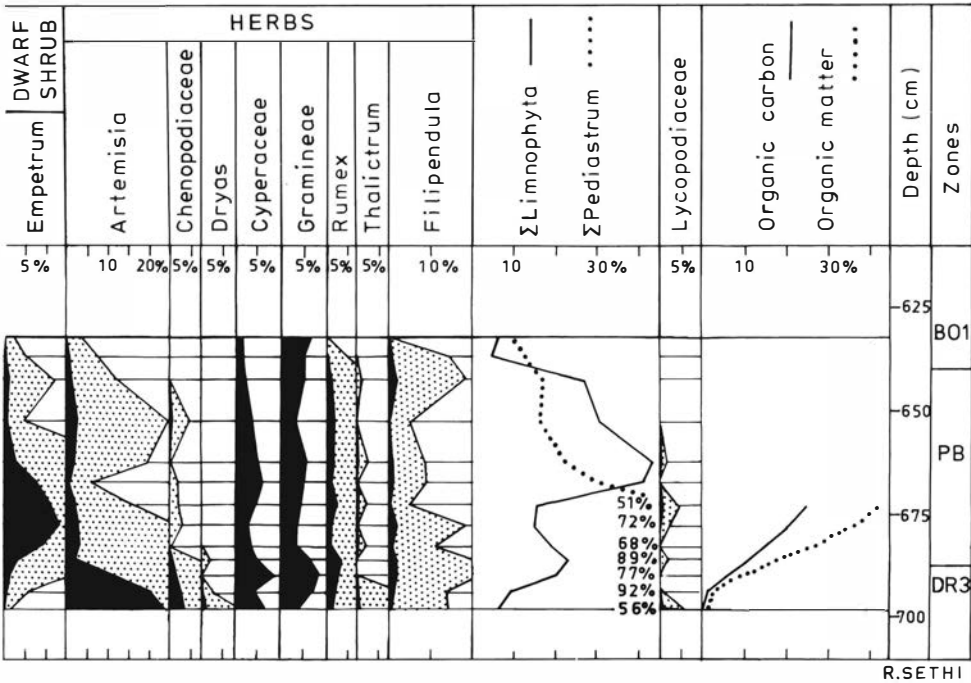
Fig. 18:5. Pollen diagram of the core from Rörmyr, Bp 1. The ¹⁴C-datings are made on material from Bp 2.

Artemisia – Gramineae – Cyperaceae PAZ (700–687.5 cm)

High frequencies of herbs and *Salix* indicate open tundra vegetation (Fig. 18:5). Apart from very high values for *Artemisia* (about 20%), pollen of *Dryas* and *Thalictrum* were observed. There is a low content of organic matter in the sediment. This pollen assemblage zone represents the Younger Dryas.

Betula – *Empetrum* PAZ (687.5–660 cm)

Pollen of *Empetrum* increases markedly together with *Betula*. *Artemisia*, Gramineae and Cyperaceae decrease. The organic content of the sediment rises from 12 to 43%. There is an increase in the frequency of aquatic plants (Limnophyta). The pollen assemblage zone reflects the transition from tundra to a vegetation dominated by *Empetrum* heaths.



Betula – Juniperus PAZ (660–640 cm)

Within this zone there is a marked decrease of *Empetrum* and rising frequencies of *Juniperus* and *Hippophaë*. The vegetation dominated by heath is replaced by shrubs of *Juniperus*. The presence of *Hippophaë* indicates areas of open vegetation and proximity to the shore.

Betula – Corylus PAZ (640 cm–)

The immigration of *Corylus* is registered at 640 cm. Pollen of shrubs and herbs decreases. The vegetation consisting of shrubs and to some extent open *Betula* forest is succeeded by dense woodland.

The Pleistocene/Holocene boundary is placed at 687.5 cm, at the distinct rise of *Empetrum* and *Betula* pollen, together with the marked decrease in *Artemisia*.

Brastad, 40–45 m above sea level

Stratigraphy: see Chapters 6 and 7.

Seven samples from between 2 and 3 m were analysed after treatment with hydrofluoric acid and acetolysis. The pollen frequencies were extremely low in five of the samples (about 10 pollen grains/slide). After preparation by the sedimentation-separation method (Påsse 1976), the analysis were repeated. The pollen content was still very low in samples from above 2.31 m. At 2.31–2.35 m and 2.50–2.55 m, herb pollen (Gramineae, Cyperaceae and *Artemisia*) constitutes about 30 % of the total pollen flora. Pre-Quaternary pollen and spores were frequent, each group represented by 10 % at both levels. The composition of the pollen flora below 2.31 m indicates that the clayey silt is of Younger Dryas age or older.

SUMMARY

A correlation was established between the limnic localities Vågen and Rörmyr and the marine sequences of Solberga and Moltemyr (Fig. 18)6). The Pleistocene/Holocene boundary has been defined by pollen analysis of the limnic sediments from Vågen and Rörmyr. Vegetational changes on nearby terrestrial areas caused by climatic improvement are reflected by distinct changes in the composition of the pollen flora in the sediments. There was a gradual transition from open herb communities to heath and shrub vegetation together with sparse birch wood. During the Preboreal denser woodland dominated by birch replaced the open vegetation.

Evaluation of pollen assemblages in marine sequences is more complicated. The pollen flora may be affected by redeposition of older pollen, corrosion and irregular transportation of pollen grains, and over-representation of some species.

However, in the Solberga core there is a marked change in the composition of the pollen flora around 19.5 m, which is presumed to correspond to the Pleistocene/Holocene boundary.

At Moltemyr the transition from a more or less treeless vegetation of herbs and shrubs to a landscape with *Betula* woods seems to occur about 4.7 m.

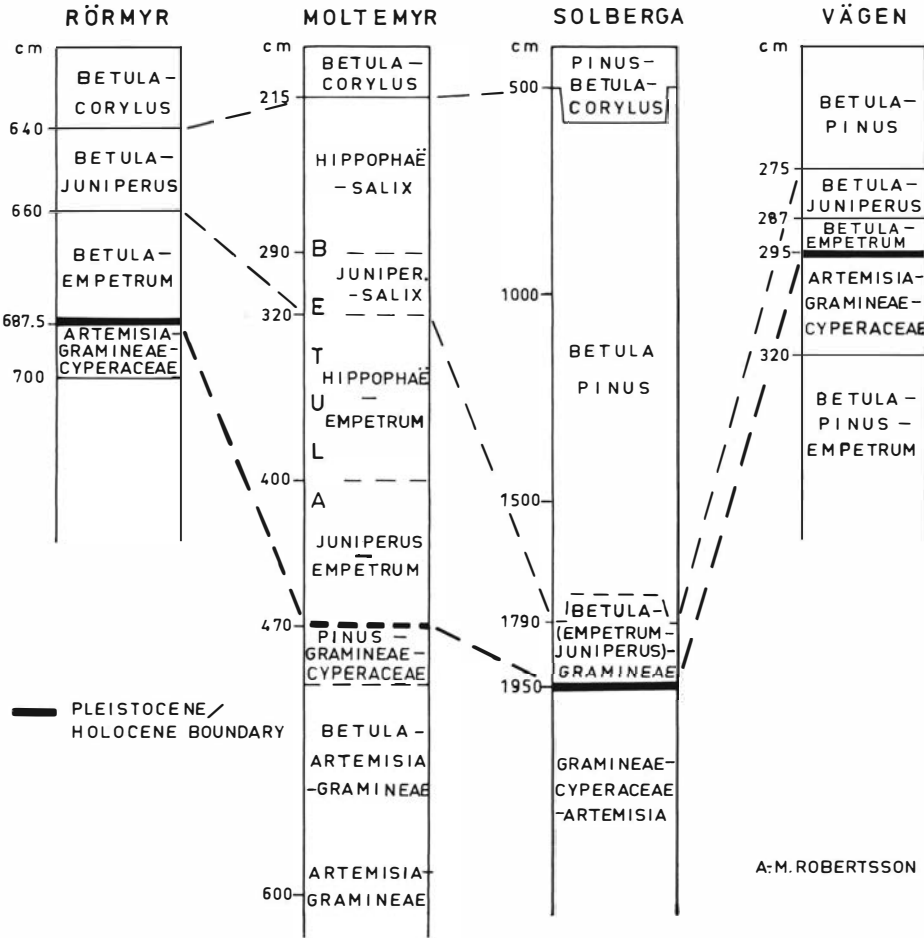


Fig. 18:6. Correlation of the pollen assemblage zones of Rörmyr, Moltemyr, Solberga, and Vågen.

ACKNOWLEDGEMENT

I wish to express my gratitude to Professor Magnus Fries, who critically read the manuscript.

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19. RADIOCARBON DATING

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INTRODUCTION

Radiocarbon dating of marine deposits, irrespective of whether they consist of shells or gyttja, is always hazardous because of contamination by older allochthonous material (Olsson 1982). Peat deposits mainly consist of autochthonous material although intrusive elements such as roots may cause the ages to appear too late (Olsson and Florin 1980). Autochthonous marine shells and gyttja will always appear too old because of the reservoir age, although a fair estimate of this can be made. It is here estimated as 330 ± 20 years (Olsson 1980). Similarly, lakes usually have a reservoir age but unfortunately this varies from lake to lake (Olsson 1982) and often with time (Geyh *et al.* 1970). The reservoir age of the lake may derive from dissolved old carbonate (Deevey *et al.* 1954), but may also be observed in soft-water lakes, being there due to supply of aged water. Although the conditions vary from one lake to another the general rule is that the risk of errors, causing the ages to appear too old, increases as the amount of carbon decreases. Some old carbonaceous material can easily be deposited together with the minerogenic material (Hörnsten and Olsson 1964, Olsson 1972, 1973, 1978, 1979). Thus every result must be evaluated, taking the origin of the sample into consideration in order to avoid mistaken association with the boundary or any other level. Apparently the fraction soluble in NaOH is more reliable than the insoluble fraction (Olsson 1973, 1979). A re-evaluation of many ^{14}C dates from Finland was made by Donner and Jungner (1973, 1974).

Earlier Mörner (1976) summarized several dates for the determination of the boundary or levels below or above that boundary. The samples used are usually clay, dy or gyttja. The dates from core B 873 derive from samples pretreated with HCl. The same applies to Näckrosdammen and at least some other samples. The pretreatment method is not described by Mörner. Each of his dates should therefore be regarded as, most probably, too early for the respective level partly because of contamination *in situ*, partly because of the reservoir effect.

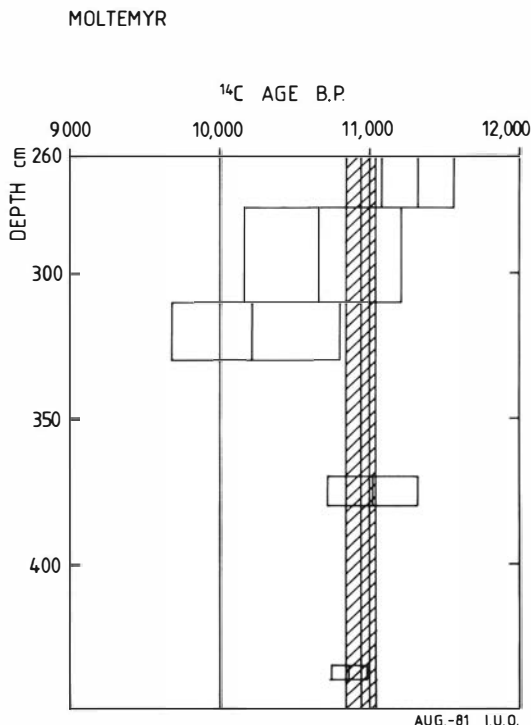


Fig. 19:1. The radiocarbon ages of shell samples from Moltemyr. The values are not corrected for the reservoir age.

THE PRESENT DATINGS

General – Samples such as peat, gyttja and clay were all treated with acid and sodium hydroxide to remove carbonate and to separate each sample into two fractions – one soluble (SOL) and one insoluble (INS) – as described by Olsson (1979). The shell samples were too small to allow the normal treatment to separate them into two or more fractions by leaching with acid after removal of the outer parts.

The radiocarbon ages are calculated using the half-life 5 570 years and given B.P. (before AD 1950). All calculations include a normalization of the sample activities to $\delta^{13}\text{C} = -25$ o/oo in the PDB scale. The international standard is used, *i.e.* 95% of the activity of the NBS oxalic acid in 1950 when this has a $\delta^{13}\text{C}$ value of -19 o/oo in the PDB scale. The uncertainties given are $\pm 1\sigma$. All estimated uncertainties connected with the activity measurements are included insofar as is possible (Olsson 1966).

Several samples were too small to allow measurements without dilution

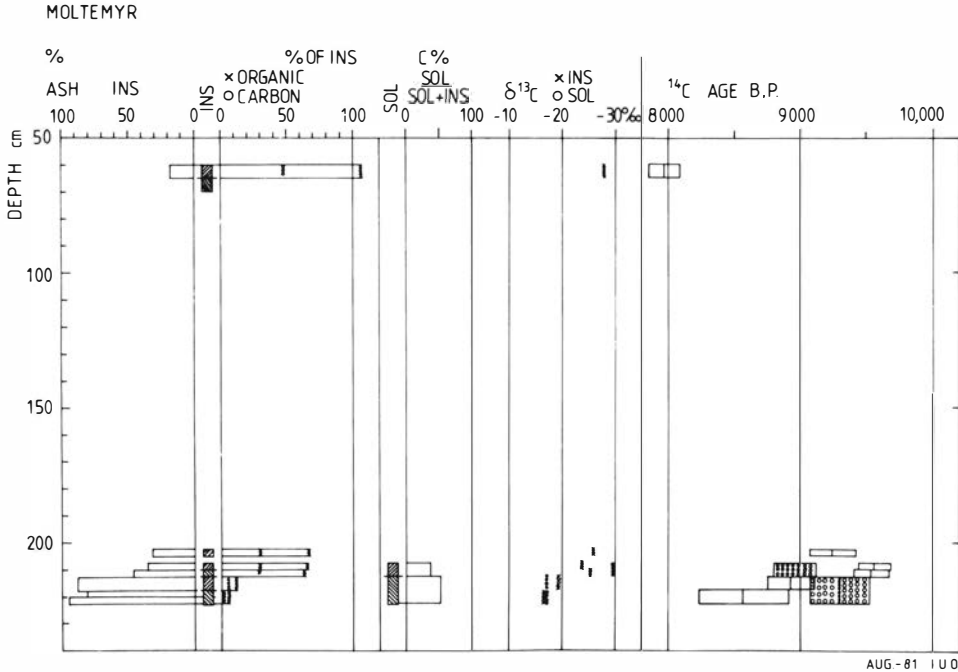


Fig. 19:2. The radiocarbon ages, $\delta^{13}\text{C}$ values, carbon content and ash of the INS-fraction, relation between the SOL- and INS-fractions, and measured organic samples from Moltemyr, not corrected for the reservoir age.

with inactive carbon. Many of these samples were measured repeatedly during a total time exceeding the normal period to reduce the statistical uncertainty. Two very small shell samples were sent as carbon dioxide to the Trondheim laboratory, measured there by Gulliksen and later returned to Uppsala where they were diluted or further diluted, respectively, before remeasurement.

In the diagrams both the ash after combustion and the content of carbon, estimated from the yield at the combustions, are given. The organic content is then estimated from the carbon content. The figures for these three components are to be regarded as estimates to guide the evaluation of the accuracy of the dates.

Samples are still submitted in close collaboration with others in the team. This paper is thus a working report giving the results as complete on Aug. 10th 1981.

Some shell samples are stored in sealed evacuated glass ampoules for later ^{14}C dating using the accelerator technique for the ^{14}C determination.

TABLE 19:1. Radiocarbon ages of the samples dated for the Pleistocene-Holocene boundary project. (Aug. 10th, 1981).

Site	Material	Dating no.	Level	$\delta^{13}\text{C}$ o/oo	^{14}C age B.P. ($\pm 1\sigma$)
Moltemyr	Shell fragments	U-4420	440-435	-0.9	10860 \pm 120
		U-4419	380-370	-2.8	11020 \pm 300
		U-4418	330-310	-0.3 ^a	10220 \pm ⁵⁸⁰ ₅₄₀
		U-4417	310-277.5	-0.3	10660 \pm ⁵⁶⁰ ₅₀₀
		U-4416	277.5-265	-0.2	11320 \pm 240
	Mean	—	—	—	10940 \pm 100
	Organic INS	U-4414	222.5-217.5	-16.6	8570 \pm 340
		U-4413	217.5-212.5	-19.3	8930 \pm 180
		U-4411	212.5-210	-25.5	9530 \pm 130
		U-4410	210-207.5	-23.9	9550 \pm ¹³⁰ ₁₂₀
		U-4409	205-202.5	-26.0	9240 \pm ¹⁸⁰ ₁₇₀
		U-4425	65-60	-27.7	7970 \pm 120
		Organic SOL	U-4415	222.5-212.5	-17.2
U-4412	212.5-207.5	-29.6	9020 \pm 170		
Rörmyr	Organic INS	U-4428	745-742.5	-20.1	9850 \pm 240
		U-4427	742.5-740	-19.9	9730 \pm 230
Solberga	Shell fragments	T-2982	2620+2624	-2.3	10610 \pm 300
		U-4407	2620+2624	-2.3	10800 \pm ⁶⁰⁰ ₅₄₀
		U-4350	2700-2675	-1.7	11520 \pm ⁴⁴⁰ ₃₈₀
			2665-2655	-1.7	
		U-4349	2655-2635	-2.2	11020 \pm 340
			2625-2605	-2.2	
	T-2983	1900-1800	-3.7	9170 \pm 400	
	U-4408	1900-1800	-3.7	9160 \pm ¹⁴⁶⁰ ₁₂₄₀	
Vägen	Organic INS	U-4422	293-289	-19.7	9670 \pm 140
		U-4421	270-267.5	-28.5	9150 \pm 140
		U-4424	170-160	-27.8	7410 \pm 120
	Organic SOL	U-4423	293-289	-22.9	9750 \pm 130

^a $\delta^{13}\text{C}$ assumed.

Moltemyr – Five shell samples were dated from levels between 440 and 265 cm down. Each sample derives from 20 cm or less of the core, but chosen to represent not too long a time. Consequently all but one sample had to be diluted. The samples did not show any trend in radiocarbon age as a function of depth, and there is hardly any significant difference between them (Fig. 19:1). The mean value is about 10 600 radiocarbon years after subtraction of the reservoir age (Table 19:1). In all probability the shells represent old assemblages redeposited at Moltemyr, as Fries suggested earlier (1951). If shells derive from a shell bank it must be remembered that different species may yield ages within a range of thousands of years (Eriksson and Olsson 1967). Donner and Jungner (1980) reviewed various sites and reported the risk of contamination by redeposition. The species

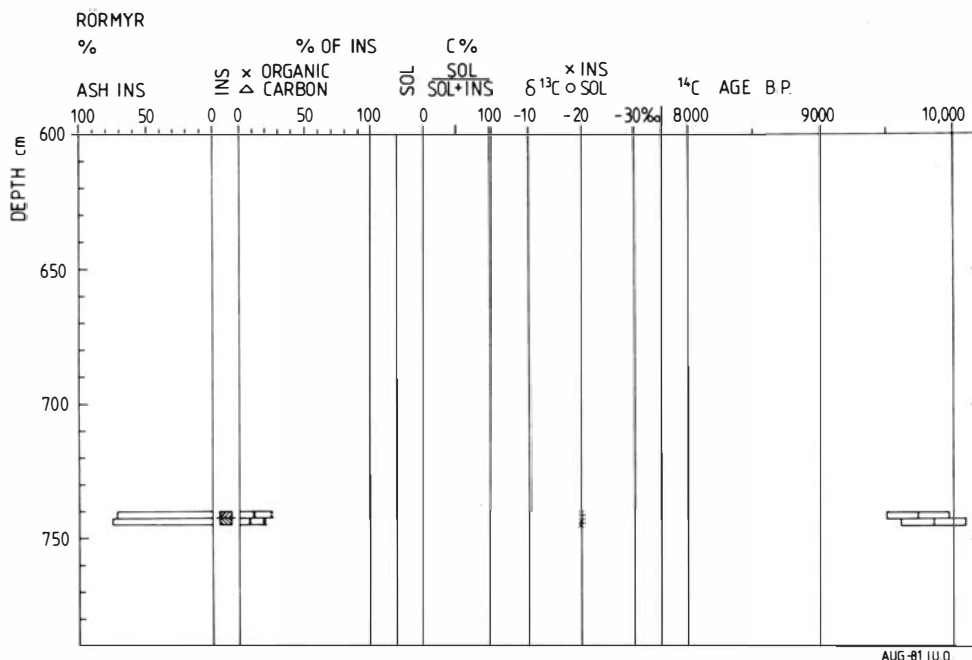


Fig. 19.3. The radiocarbon ages, $\delta^{13}\text{C}$ values, carbon content and ash of the INS-fraction, and measured samples from Rörmyr, not corrected for the reservoir age.

selected for dating may yield ages indicating when the living conditions were favourable rather than when the shells were finally deposited. Shells in the neighbourhood of Moltemyr, at Ormdal, were dated as St-5377 at $11\,090 \pm 180$ ^{14}C years B.P. (C. Fredén, pers. comm.).

The organic carbon was first dated for the levels between 222.5 and 202.5 cm down (Fig. 19:2). Five samples were dated as INS-fractions whereas two – only below 207.5 cm down – were dated as SOL-fractions. The $\delta^{13}\text{C}$ values indicate different origins below and above 212.5 cm. The two samples dated as INS-fractions below 212.5 cm appeared younger than the three samples above this level. The two SOL-fractions, being contemporary, appear to have the same age as the INS-fractions below 212.5 cm. Taken together these four dates indicate a time slightly earlier than 9 000 years B.P. With a correction for any reservoir age the result would indicate a slightly later time. The samples above 212.5 cm were apparently contaminated *in situ*.

Later on samples were chosen to date levels close to A°. The first sample, 60 to 65 cm down, was about 8 000 radiocarbon years old (Table 19:1).

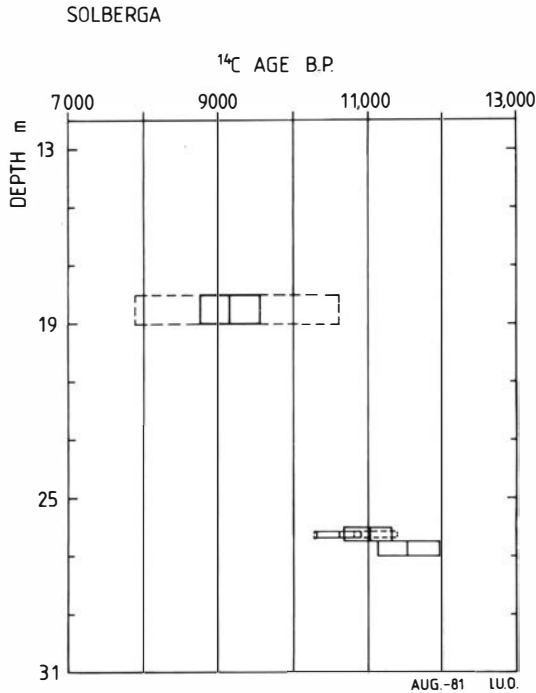


Fig. 19:4. The radiocarbon ages of shell samples from Solberga measured in Trondheim and Uppsala. The values are not corrected for the reservoir age.

Rörmyr – Two samples, clay gyttja, 740 to 745 cm down in the core, Bp 2, were dated as INS-fractions (Table 19:1). The corresponding SOL-fractions were combined in a single sample which is dated but not yet finally calculated. The INS-fractions indicate a time later than 10 000 years B.P. (Fig. 19:3).

Solberga – Shell fragments were dated from rather long sections (Fig. 19:4). The first two samples from 2700 to 2655 and 2655 to 2605 cm respectively were dated at $11\,520 \pm \frac{440}{380}$ and $11\,020 \pm 340$ ¹⁴C years B.P., before subtraction of the reservoir age. Another sample, from the two levels 2620 and 2624 cm, was dated in Trondheim and Uppsala at c. 10 600 ¹⁴C years B.P. (Table 19:1). Yet another sample was dated by both laboratories, 1900 to 1800 cm, at c. 9 200 ¹⁴C years B.P. The equipment in Trondheim allows smaller samples to be dated – with acceptable statistical uncertainty – than are feasible in Uppsala. The preparations were performed in Uppsala.

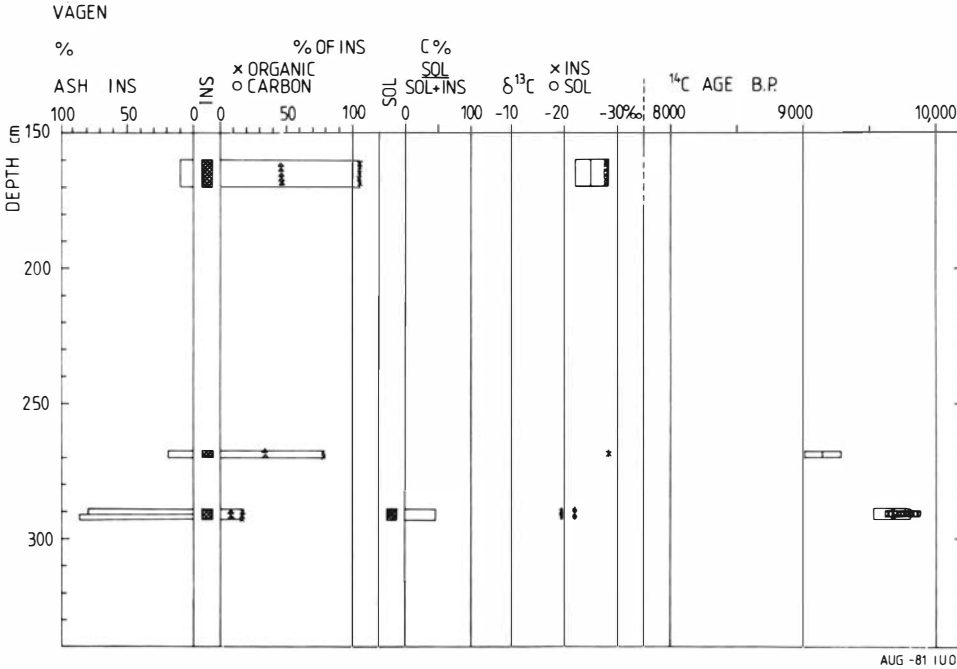


Fig. 19:5. The radiocarbon ages, $\delta^{13}\text{C}$ values, carbon content and ash of the INS-fraction, relation between the SOL- and INS-fractions, and measured samples from Vågen, not corrected for the reservoir age.

Vågen – Two samples, one consisting of clay gyttja above the assumed boundary Younger Dryas/Preboreal, and one of *Equisetum* peat at the Preboreal *Betula* maximum, were dated – the deepest as two fractions, INS and SOL, (Fig. 19:5). The $\delta^{13}\text{C}$ values confirm their different origins. The fractions of the deepest sample are c. 9 700 ^{14}C years old. The, seemingly, younger INS-fraction is not significantly younger than the SOL-fraction. The peat sample (267.5 to 270 cm down) was dated at $9\,150 \pm 140$ years. Further samples close to the assumed boundary were ^{14}C measured but the results are not yet calculated. One peat sample at a level close to A° is ready (Table 19:1).

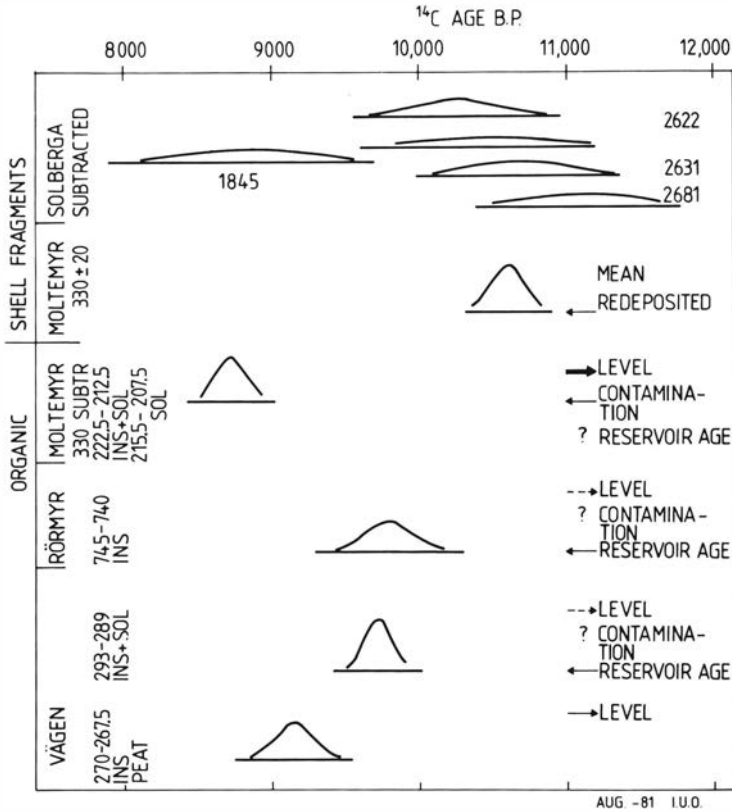


Fig. 19:6. Selected samples, which may yield upper and lower limits for the assumed boundary. A dashed arrow indicates a small possible correction, a normal arrow that a correction is needed and a heavy arrow that the correction is presumably large. A question-mark indicates that it is difficult to make predictions about the corrections or error.

DISCUSSION

Because of redeposition shells may be older than the sediment at the level at which they are found. This was obvious in the case of Moltemyr. The deepest shell layer dated is the only one which we cannot exclude *a priori*. This suggests an upper age limit for the depth 440 to 435 cm. This limit is $10\ 610 \pm 110$ ^{14}C years B.P. after subtraction of the reservoir age (Fig. 19:6). The deepest Solberga samples, too, should give an upper limit or correct results for the depth 27 to 26 m ($\sim 11\ 000$ ^{14}C years B.P. uncorrected for the reservoir age). The date for the highest Solberga shells (19 to 18 m) of $9\ 170 \pm 400$ ^{14}C years B.P. uncorrected for reservoir age may be correct or too early.

The least squares method yields an age of $9\,260 \pm 370$ ^{14}C years B.P., uncorrected for reservoir age, for the level 19.0 m at Solberga. Thus the upper limit to be used for the 19.3 m level is $9\,000 \pm 300$ ^{14}C years B.P., *assuming* a constant accumulation rate. Such an assumption is not justified from the geological evidence. The uncertainty must be increased. The level 26.22 m, dated at about $10\,300 \pm 300$ ^{14}C years B.P. (corrected for reservoir age), is, however, younger than expected from the assumption of a constant accumulation rate. The difference is insignificant. The 18.45 m level (19–18 m), dated at $8\,840 \pm 400$ ^{14}C years B.P., after correction for reservoir age, yields a low limit for the boundary zone.

The samples dated as organic fractions may yield too early results because of contamination. The reservoir age is not always subtracted since no figure for the freshwater is known. But its subtraction as regards the early Moltemyr sample is possible. The final age here may be several hundred years younger for this level above the boundary.

The Rörmyr 2 samples (745–740 cm) taken just above the tentative Pleistocene/Holocene boundary (~ 7.5 m) are probably younger than the calculated $8\,790 \pm 170$ ^{14}C years B.P., because of the reservoir age. It is too early to define the risk of contamination since the result from the SOL-fraction is not yet available.

The samples from Vågen may give some guidance. The tentative Pleistocene/Holocene boundary occurs here at 295 cm. The peat sample from 270–267.5 cm (Fig. 19:6) yields a lower limit of $9\,150 \pm 140$ ^{14}C years B.P. The gyttja sample at 293–289 cm taken just above the boundary gave $9\,710 \pm 100$ years B.P. as the mean of two fractions without correction for reservoir age and possible contamination *in situ*.

The distribution diagrams in Fig. 19:6 therefore suggest some limits for the Pleistocene/Holocene boundary, which is thus dated to a zone between 9 200 and a value probably below *c.* 9 500 ^{14}C years B.P.

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The Swedish Natural Science Research Council defrayed all the expenses of the datings performed in Uppsala by a grant to the author. I am extremely grateful to Steinar Gulliksen B. Eng. for performing two datings with extended measurement periods to achieve reasonable limits for the uncertainty. For assistance in the radiocarbon laboratory thanks are due to Tomas Kronberg and Maud Söderman and, during a shorter period, to Birgitta Hansson. I am grateful to Professor Kai Siegbahn, head of the Institute of Physics.

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20. SUMMARY OF THE INVESTIGATION

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INTRODUCTION

The working group of the Pleistocene/Holocene boundary was enjoined to find a stratotype locality which would fit the requirements laid down by the INQUA Holocene Commission in 1969. In this experiment 15 specialists studied different parameters and, independent of each other, interpreted their data from selected cores from Brastad, Moltemyr and Solberga in south-western Sweden. In some cases limnic and marine sequences from adjacent localities were also investigated. As the main task is to establish the Pleistocene/Holocene boundary the following text focuses on this level in the cores. Other and more detailed results are given in the contributions by the separate authors. However, in this context it should be mentioned that members of the group reinterpreted the Botanical Garden core B873 and found that the Pleistocene/Holocene boundary is located at a depth of 13.5 m and not 3.35 m as proposed in 1976 by N.A. Mörner.

The Pleistocene/Holocene boundary is at present defined at 10 000 ¹⁴C years B.P. Libby half-time, while waiting for an absolutely dated boundary in an approved stratotype locality. The boundary is intended to mark a more or less synchronous change in the flora and fauna, indicating the onset of the climatic improvement during the Preboreal, *i.e.* the Pleistocene/Holocene boundary should correspond to the boundary between the Younger Dryas and the Preboreal chronozones in the north-European terminology. At the beginning of the Preboreal the Scandinavian ice sheet receded from the Fennoscandian terminal moraines, and an intense deglacial period occurred. During the Preboreal not only water from the Baltic Ice Lake (~10 000 km³) but also the meltwater from the disintegrating Scandinavian ice sheet (>500 000 km³) was discharged into the Skagerrak, to a large extent through the Vänern basin.

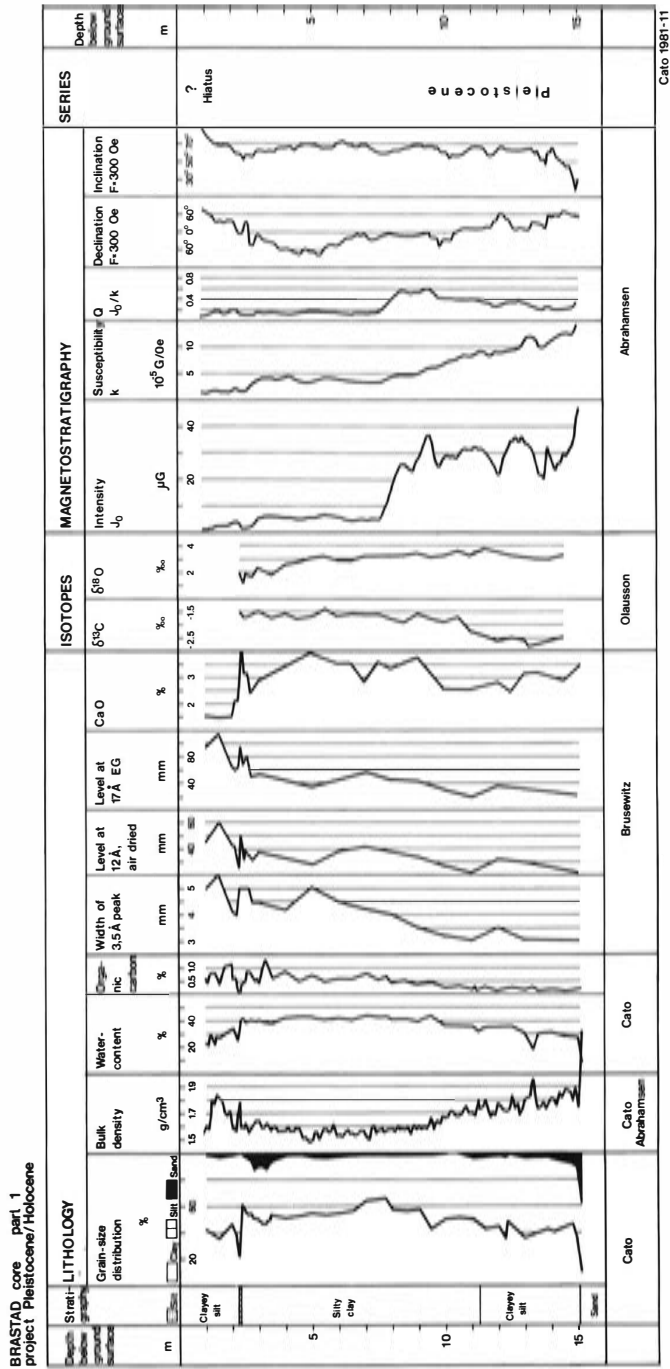


Fig. 20:1a. Part 1 of the summary diagram showing the vertical distribution of various analyses carried out on the Bråstad core. Sediments from the uppermost Pleistocene and lowermost Holocene are lacking, creating a hiatus at 2.3 m depth.

Two of the investigated sites, Brastad and Moltemyr, are located in northern Bohuslän at about 45 and 60 m above sea level respectively, while the third one, Solberga, is situated in southern Bohuslän at about 2 m above sea level. Various analyses indicated a hiatus in the Brastad core around the boundary. Thus, this core is here not further discussed. The analyses of the Brastad core are summarized in Figs. 20:1a and b. At Moltemyr and Solberga the investigations clearly showed a distinct Pleistocene/Holocene boundary. These results are illustrated in Figs. 20:2a–b and 20:3a–b, respectively.

INDICATIONS OF A PLEISTOCENE/HOLOCENE BOUNDARY

MOLTEMYR

The Moltemyr site is located in a hilly landscape of bedrock outcrops close to areas above the highest shore line. At the Pleistocene/Holocene transition the relative relief between the sea bottom and the surrounding bedrock hills was 35 to 75 m. The basin, being fairly small, is assumed to reflect short term variations in the deglaciation pattern up to the beginning of the Preboreal, when the northward valleys were closed by deposits of the Fennoscandian terminal moraines. The sediments deposited during the Preboreal times are thought to reflect hydrographical changes in neighbouring coastal shallows (<30 m).

Several of the parameters studied indicate, directly or indirectly, a climatological change from colder to warmer conditions in the Moltemyr core at 3.45 m depth (Figs. 20:2a and b).

Grain-size distribution – a 10 per cent increase of the clay content at 3.3 m.

Clay minerals and chemistry – the mineralogical composition is very consistent all through the core. However, a slight change can be observed in the content of kaolinite and smectites between 3.4 and 3.3 m. The calcite content vanishes at 4.5 m, and may reflect the disappearance of calcitic organisms.

Organic carbon – a relatively strong increase at 3.45 m.

Oxygen isotopic ratio – a distinct (6 per mil) decrease in the $\delta^{18}\text{O}$ from 3.45 to 2.7 m – here referred to the meltwater spike.

Magnetostratigraphy – no changes around 3.5 m. A slight increase of the Q ratio upward in the core from 3.2 m.

Molluscs – the high-Arctic species *Portlandia arctica* is not found above 5.5 m. A change in the megafossil assemblage occurs at 3.5 m, and a Holocene fauna is present above 2.3 m.

Ostracods – a disappearance of Arctic and cold water species and a decrease in population at 3.5 m. From 4.7 m upwards there is a gradual increase of temperate specimens (e.g. *Hirschmannia* and *Leptocythere* species) simultaneously with a gradual decrease of Arctic species.

Foraminifers – a change in the foraminiferal fauna at 3.45 m where the Arctic fauna (e.g. *Cassidulina reniforme* and *Elphidium excavatum* forma *clavata*) is replaced by a Boreal one (e.g. *Elphidium magellanicum* and *Elphidium excavatum* forma *seleyensis*).

Coccoliths – only reworked coccoliths of Tertiary and Cretaceous age occur. The frequency decreases gradually upwards from 4.7 m. The Tertiary coccoliths disappear somewhere between 3.5 and 2.7 m.

Diatoms – a distinct decrease of Arctic plankton, e.g. *Thalassiosira* spp. at 5–4.8 m, followed upwards by increase of coastal plankton and littoral flora. At 3.45 m there is a marked frequency peak of marine littoral diatoms and no influx of freshwater plankton. Upwards a change in the composition of the diatom flora is registered by a decrease of littoral flora, followed by an increase of both coastal and reworked plankton.

Dinoflagellate cysts – no clear succession of climatic development is mirrored by the cysts. Poor recovery.

Pollen – no distinct climatic change in the pollen flora occurs around 3.5 m. There is either a continuous decrease in the supply of redeposited pollen from the bottom of the core up to 4.6 m, as indicated by e.g. the frequency of pre-Quaternary pollen and spores, or a gradual change of the source areas of the sediment particles. Between 4.6 and 2.9 m the supply of redeposited pollen and spores may have been fairly constant and comparatively large compared with the local production of pollen and spores.

Radiocarbon dating – the shell samples just below (3.8–3.7 m) and just above (3.3–3.1 m) the boundary were dated to $11\,020 \pm 300$ and $10\,220 \pm \frac{560}{500}$ ^{14}C years B.P. (uncorrected for reservoir age) respectively. The shells dated between 3.10 and 2.65 m are clearly redeposited.

MOLTEMYR, part 1
project Pleistocene/Holocene

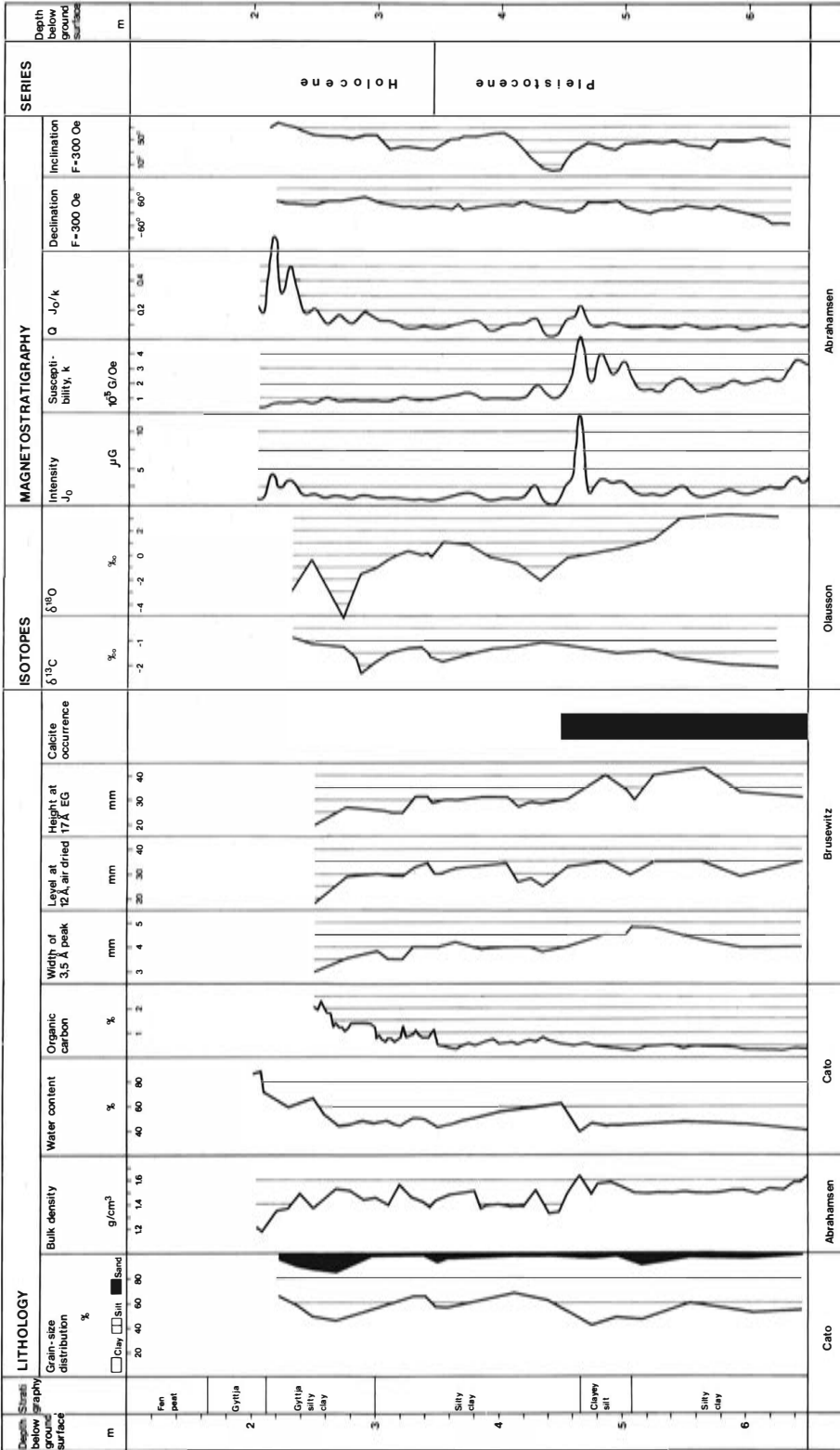


Fig. 20:2a. Part 1 of the summary diagram showing the vertical distribution of various analyses carried out on the Moltemyr core. The Pleistocene/Holocene boundary appears at 3.45 m depth.

MOLTEMYR, part 2
project Pleistocene/Holocene

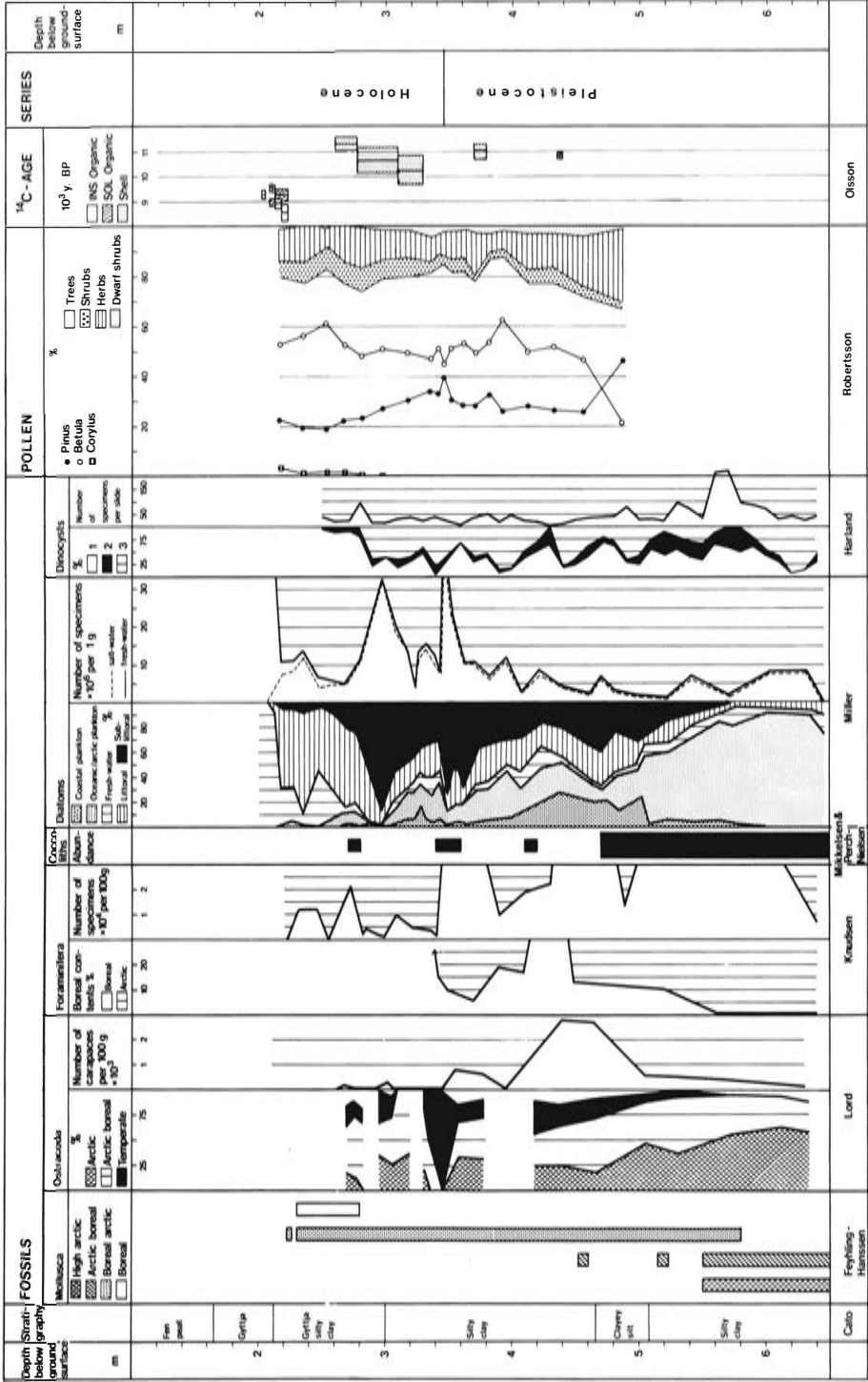


Fig. 20.2b. Part 2 of the summary diagram showing the vertical distribution of various analyses carried out on the Moltemyr core. The Pleistocene/Holocene boundary occurs at 3.45 m depth. Legend for dinoflagellate cyst and ostracod species and/or groups, see Fig. 20.1b.

SOLBERGA

The Solberga site is located in a very wide basin with a low relief. At the onset of the Holocene the relative relief between the sea bottom and the surrounding bedrock hills was about 50 m. Due to the faster rate of accumulation the Solberga area gives higher resolution of the early Holocene events than does the Moltemyr. A distinct transition zone from colder to warmer conditions occurs between 19.7 and 18.4 m (Figs. 20:3a and b).

Grain-size distribution – a distinct change in the grain-size composition between 18.4 and 17.7 m, resulting in a very homogeneous clay (80 % <2 μm) sequence extending up to about 5 m. The sequence is laminated with about 400 bands (“varves”).

Clay minerals and chemistry – a gradual but perceptible decrease in the content of kaolinite, interstratified minerals (mainly weathered materials), smectite, calcite, and sulphur between 18.5 to 17.5 m. The lower values proceed up the core to about 5 m.

Oxygen isotopic ratio – a drop by 0.5 per mil in the $\delta^{18}\text{O}$ from 19.45 to 19.3 m and a similar fall between 18.75 and 18.55 m (= the meltwater spike).

Magnetostratigraphy – a significant drop in the natural remanent magnetization (NRM) intensity and the Q-ratio between 19.3 and 18.9 m followed upwards to about 11 m by a more gentle decline simultaneously with a decrease in susceptibility. A directionally very scattered interval, due rather to postdepositional disturbances than changes in the geomagnetic field, occurs between 17 and 12 m.

Molluscs – a marked change in the molluscan assemblage at 19.3 m, where an Arctic to Arctic-Boreal fauna is replaced by Boreal and Lusitanian species as *Nuculana minuta* and *Abra longicallis*. Practically no molluscs are found between 17.2 and 4.8 m.

Ostracods – a marked change in the ostracod assemblage at 18.0–17.5 m, where high Arctic species, e.g. *Cluthia cluthae* is replaced by a modern temperate fauna characterized by *Leptocythera tenera* and *Hirschmannia tamarindus*. Almost no ostracods are found between 17 and 10 m.

Foraminifers – a sudden change in the foraminiferal fauna between 19.0 and 18.8 m, where marine and high Arctic species such as *Nonion labradoricum* and *Cassidulina reniforme* decrease and Boreal species (e.g. *Elphidium magellanicum*) increase. At about 16 m the Arctic *Elphidium excavatum*, forma *clavata* is replaced by the Boreal forma *seleyensis*. Only a few specimens occur between 18.4 and 4.7 m.

Coccoliths – a gradual reduction in the content of coccoliths from 19.5 to 17.2 m. Only a few per cent of the species are of Quaternary age. Between 17.2 and 3.6 m reworked coccoliths of Tertiary and Cretaceous age occur sporadically. Moderately preserved coccoliths assemblages with reworked as well as Quaternary species occur in the interval between 3.6 and 2.5 m.

Diatoms – a distinct decrease of Arctic plankton and increase of coastal plankton at 21.5 m, followed upwards by an increase of littoral flora. At 19.2 m, there is a marked frequency peak of marine diatoms and almost no influx of freshwater plankton. At 18 m a marked change in the composition of the diatom spectra is caused by the predominant influx of freshwater plankton, e.g. *Melosira islandica*. Between 17.5 and 5 m the diatom frequency is very low, but the freshwater species still dominate.

Dinoflagellate cysts – no clear succession of climatic development is mirrored by the cysts. Poor recovery.

Pollen – a distinct change in the pollen flora at about 19.5 m, with a marked increase of *Betula* and decrease of herbs and reworked pre-Quaternary pollen and spores. However, the changes in the composition of the pollen flora throughout the core may be related either to changes of the source area of the sediment particles or of the sedimentary conditions, cf. the herbal pollen and the pre-Quaternary pollen and spores which vary inversely with the clay content. – The immigration of *Corylus* is mirrored above 5 m.

Radiocarbon dating – the shell samples (19–18 m) were dated to $9\ 170 \pm 400$ ^{14}C years B.P. (uncorrected for reservoir age).

SOLBERGA core part 2
 project Pleistocene/Holocene

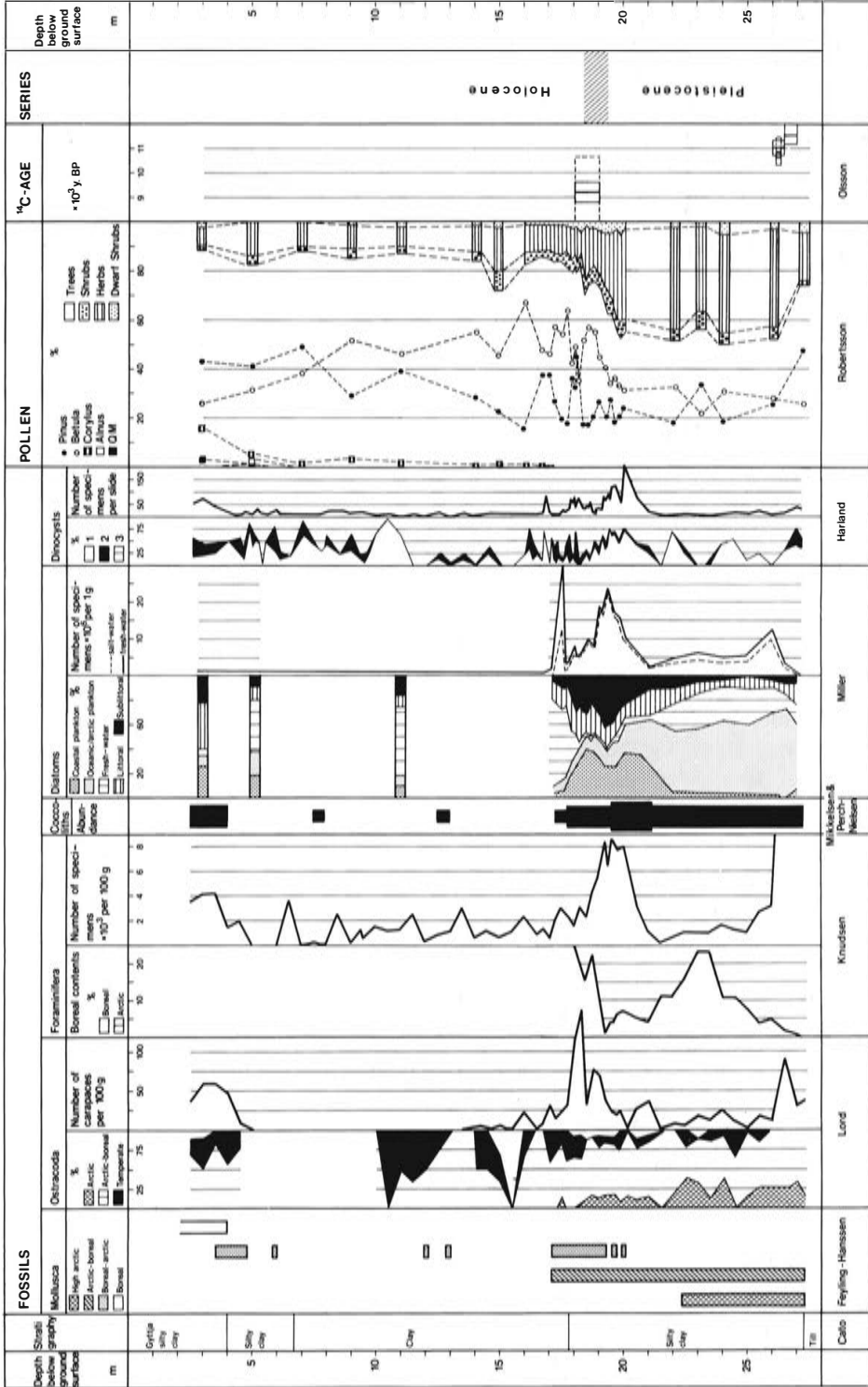


Fig. 20:3b. Part 2 of the summary diagram showing the vertical distribution of various analyses carried out on the Solberga core. The Pleistocene/Holocene boundary occurs as a transition zone between 19.3 and 18.4 m depth. Legend for dinoflagellate cyst and ostracod species and/or groups, see Fig. 20:1b.

CONCLUSION

In the attempt to define the Pleistocene/Holocene boundary in the cores investigated, all the parameters studied were considered and critically weighed together.

The response period to a climatic change differs considerably from one taxon to another. In general, the immigration and extinction of species are slow processes compared to changes in the isotope composition of organisms. The isotope composition of organisms immediately change, when the temperature and the isotope composition of the ambient sea water change, e.g. as a consequence of meltwater discharge from a disintegrating ice sheet during a climatic improvement.

Redeposition is a difficult problem to recognize and evaluate. It seems probable that in many cases changes in the frequencies of fossils such as pollen, spores, coccoliths *etc.* depict variations in the source area of the sediment rather than in the productivity of the biota in the surrounding water and land. Megafossils are complicated since their occurrence in a single core could be random.

The magnetostratigraphical results create another problem, since the knowledge of excursions of the geomagnetic field and of short-term secular variations in late Weichselian time is limited. It is worth mentioning that the geomagnetic "Gothenburg excursion," defined and dated by Mörner at about 12 350 ¹⁴C years B.P., is not recognized in the analysed cores. The Brastad and Moltemyr cores record sedimentation from well before this time.

The results from the Moltemyr core show continuous sedimentation conditions around the time of the boundary while the Solberga core reveals a distinct change in the source area and deposition rate above the boundary, mirrored clearly in the diagrams (Figs. 20:2 and 3).

It seems that $\delta^{18}\text{O}$ values and Foraminifera are the key parameters and that particularly diatoms but also other parameters give valuable information as well. There is a close relationship between the $\delta^{18}\text{O}$ and the frequency of the Boreal Foraminifera in the cores (see Fig. 20:4). The close connection between $\delta^{18}\text{O}$ and salinity suggests that the increase of Boreal Foraminifera during the Preboreal could also be a function of the decline of salinity.

As was shown above the climatic improvement started a chain reaction, which is reflected as a sharp boundary in the Moltemyr core and as a transition zone in the Solberga core, probably due to the faster sedimentation rate at this site.

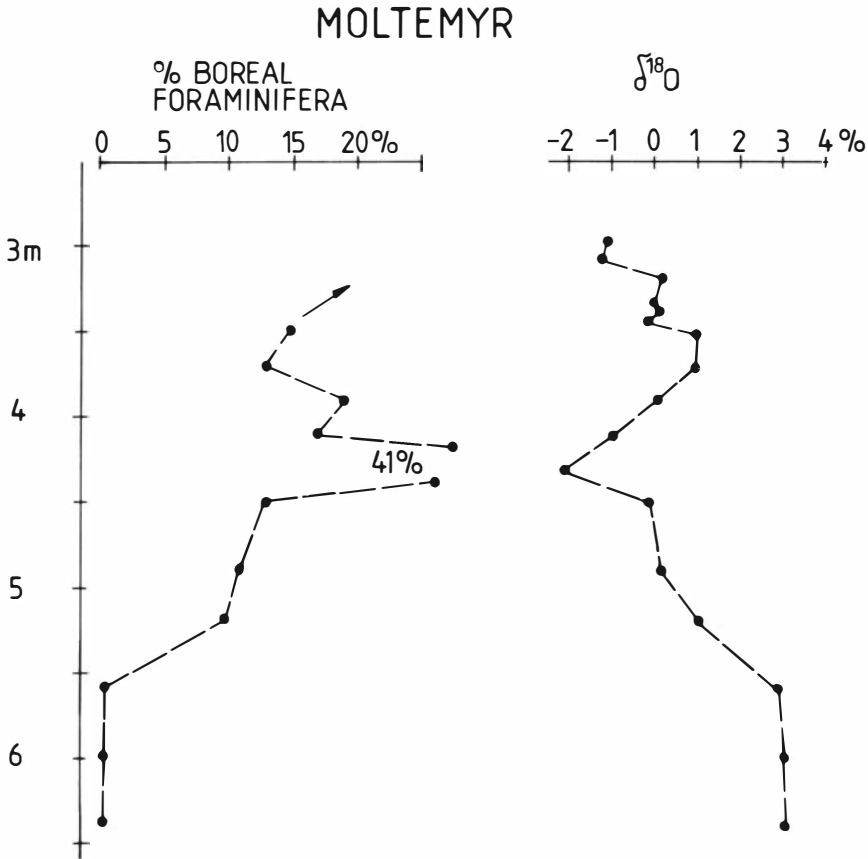


Fig. 20:4. The relationship between the $\delta^{18}\text{O}$ and the frequency of Boreal benthonic Foraminifera. Both curves mirror changes in the salinity of the bottom water.

The first real response to the climatic change at the Pleistocene/Holocene boundary is the increase of the meltwater discharge:

a $\delta^{18}\text{O}$ decline at 19.3 m in the Solberga core and at 3.45 m in the Moltemyr core. The isotopic decrease in the latter core is twice as large as the decrease at Solberga.

The climatic change is also recorded in the biota, in the section 19.3–18.9 m in the Solberga, and at 3.45 m in the Moltemyr core:

Foraminifers: transition from the Arctic *Elphidium excavatum*, forma *clavata* – *Cassidulina reniforme* fauna to faunas without *C. reniforme* and with an increasing number of Boreal species is characteristic for the whole area.

Diatoms: Arctic-oceanic plankton decrease and coastal plankton flora with *Melosira sulcata* and *Thalassionema nitzschioides* increase.

Molluscs: Boreal species increase and Arctic-Boreal ones decrease in frequency.

The lithologies of the two cores also exhibit changes at and above the boundary but in different ways. The dissimilarities make it necessary to deal with each area separately:

I. In several cores from the Göteborg area the sediment distinctly turns upward into an extremely fine-grained and often banded sequence. These strata are characterized by a very high clay content ($<2\mu\text{m}$), a clay mineralogy poor in weathered products and similar to that found in Quaternary clays in central Sweden (northern Vänern basin–Stockholm area), and a high incidence of planktonic freshwater diatoms (*Melosira islandica*) but with a low frequency of other fossils and pollen grains. This sediment layer was formed during the Preboreal times, when huge quantities of meltwater flooded the area as a consequence of the climatic amelioration and the rapid retreat of the land ice. If the banding is annual this clay sequence was formed during a little more than 400 years, *i.e.* about the time it took for the deglaciation of the northern Vänern basin.

II. Central-Bohuslän is represented by the Moltemyr core. The core from Brastad exhibits an hiatus at the boundary, probably due to erosion. In shielded areas, such as Moltemyr, sedimentation occurred continuously throughout the Preboreal. There is a slight increase in the clay content above the boundary. The improved organic productivity is clearly recognized in the Moltemyr core by the increase in the contents of organic matter and diatoms. Due to extensive sedimentation and dilution by clay particles these variations are less clear in the Solberga core. Within about 400 years after the Pleistocene/Holocene boundary the maximum in the meltwater supply was reached in the Moltemyr area followed by an increase in the $\delta^{18}\text{O}$ values. This slight Preboreal isotopic maximum is much less pronounced, or absent in the Solberga core.

In conclusion the Pleistocene/Holocene boundary occurs at Solberga as a zone between 19.5 and 18.4 m, and at Moltemyr as a sharp boundary at about 3.45 m. According to the key parameters the Solberga zone can be limited to the 19.3–18.9 m interval.

The Younger Dryas/Preboreal boundary, here taken as the Pleistocene/Holocene boundary as well, is believed to correspond to the retreat of the ice front from the Fennoscandian terminal moraine zone. This event, which is fairly well documented from several investigations besides this project,

TABLE 20:1. Summary of the dating attempts.

	Moltemyr	Rörmyr 2	Solberga	Vägen	Dates generally used; years B.P.
Pleistocene/Holocene boundary; m. below top	3.45	7.5	19.3–18.9	2.95	~10 200–10 300
Rational <i>Corylus</i> limit, C°; m below top	2.15	7	5 (-6)	2.2	~9 500–9 700
¹⁴ C age, molluscs; m below top (no reservoir corr.)					
Solberga 19–18			9 170±400		
Moltemyr 3.8–3.7	11 020±300				
Moltemyr 3.3–3.1	10 220± ⁵⁸⁰ ₅₄₀				
¹⁴ C age, gyttja; m below top (no reservoir corr.)					
Moltemyr (INS) 2.17–2.07	~9 300				
Moltemyr (INS) 2.12–2.07	~9 540				
Moltemyr (SOL) 2.22–2.12	~9 440				
Rörmyr (INS) 7.45–7.42		9 850±240			
Rörmyr (INS) 7.42–7.40		9.730±230			
Vägen (INS) 2.93–2.89				9 670±140	
Vägen (SOL) 2.93–2.89				9 750±130	
Vägen (INS) 2.7–2.67				9 150±140	
Number of varves			>400between 18.1–5.9 m		

has been regarded to be 10 200–10 300 ¹⁴C years B.P. according to numerous radiocarbon dates in the literature. These dates should indeed be scrutinized concerning the validity taken into consideration: the composition of the sample, the fraction used, if ¹³C normalization was applied *etc.* The subsequent >400 years of intense meltwater discharge are well recorded in both the Solberga and the Moltemyr cores. The end of this meltwater period coincides with the increase of the *Corylus* curve in the pollen diagrams.

A summary of our dating attempts is given in Table 20:1. The absolute date of the boundary must still be regarded as not solved. We have not been able to overcome the problems with uncertain factors such as contamination, reservoir age of ancient lakes, *etc.* However, two important events in the late Quaternary evolution of Scandinavia are closely related to the establishment of the boundary. The retreat of the land ice from the Fennoscandian terminal moraines and the somewhat later lowering of the Baltic Ice Lake surface may be directly or indirectly dated by the Swedish varve chronology, which is at the moment under revision.

FULLFILLMENT OF THE REQUIREMENTS SET UP BY THE HOLOCENE COMMISSION

- a. The cores from the Moltemyr and Solberga, south-western Sweden, are collected from areas of fair tectonic stability; the present isostatic uplift amounts to 2–3 mm per year.
- b. The cores exhibit a continuous sedimentation across the boundary in question.
- c. The interpretation of the present radiocarbon age determinations is problematical due to contamination, reservoir age *etc.*, but in future the accelerator dating technique may improve the age determination of the boundary and/or it may be possible to correlate and verify the dating of the boundary by the Swedish varve chronology, which is at present under revision.
No geomagnetic excursion is recognized in the investigated cores.
- d. Both the Solberga and Moltemyr sites are available for studies in the future.

21. PROPOSAL BY THE WORKING-GROUP¹

In accordance with the requirements set up by the Holocene Commissions in 1973, the Pleistocene/Holocene boundary is recognized and defined at two localities in Bohuslän, south-western Sweden.

At Moltemyr, situated about 55 m above sea level in a hilly region, the boundary is recognized at a depth of 3.45 m below surface. The marine sequence extends from 2.15 m down to about 26 m. The basin turned into a lake during the Boreal subage.

At Solberga, situated just above the present sea level in a wide valley with a low relief, the boundary is defined in a zone between 19.3 and 18.9 m depth in an entirely marine clay sequence. The drawn-out boundary is due to a high accumulation rate in the beginning of the Holocene.

There have not been any prerequisites for a precise radiocarbon determination of the boundary in the investigated clay sequences. However, in the near future it will be possible to date foraminiferal tests from the boundary by the aid of the accelerator dating technique. According to the known chronology of the Fennoscandian terminal moraines and to related radiocarbon determinations the amelioration, which constitutes the Pleistocene/Holocene boundary, occurred about 10 200–10 300 years B.P.

The Pleistocene/Holocene change in climate involved not only ameliorated conditions for the fauna and flora, but, due to the rapid ice retreat, also caused a strong and sudden meltwater injection, which gave rise to a distinct lowering of the oxygen isotope ratio in the foraminiferal tests. This isotopic change can also be recognized in contemporary layers in deep-sea sediments, which speaks in favour of the use of the *meltwater spike*, as the most useful signal of the Pleistocene/Holocene boundary. On a regional base the changes in the flora and fauna can be used as well. Since the successions of fossils are more detailed in the Solberga core and the $\delta^{18}\text{O}$ change is more distinct in the Moltemyr one, these localities complement each other. We therefore suggest that one of these sites is chosen as a boundary stratotype section and the other as a hypostratotype section.

¹ The members of the working-group are given in Chapter 1.

22. ON THE DEFINITION OF THE PLEISTOCENE/ HOLOCENE BOUNDARY IN DEEP-SEA SEDIMENTS

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INTRODUCTION

The terms *Holocene*, *Postglacial*, and *Recent* are commonly used interchangeably in the geologic literature, with an understanding that what is meant is the time span which had a climate more or less like today's. The term *Holocene* also has a formal meaning, that is, it stands for *the last 10 000 years*. This definition was adopted by the Holocene Commission of the INQUA in Paris in 1969. The Holocene Commission is now about to recommend a stratotype section. In the following I shall summarize how the Pleistocene/Holocene boundary has been defined and identified in deep-sea sediments, to provide some background for this contemplated action.

I should emphasize at the outset that little thought has been given to a logical definition of such a boundary. Instead, the boundary concept developed operationally from the observation that certain sediment properties show a rapid change at about the right depth (20 cm to 30 cm downcore in most cases) to qualify for an assumed correlation with a presumed flip-over from glacial to postglacial conditions. In some instances radiocarbon dating backed the assumption.

The success of this approach owes much to the low resolution of the deep-sea record ($\pm 2\ 000$ years) and also to low sampling densities (usually $> 3\ 000$ years). In cores with high sedimentation rates, and from areas where climatic fluctuations during the Glacial-Postglacial transition were amplified, difficulties can arise. A strong initial warming may then be seen to precede a substantial cooling, which in turn is followed by another warming (for example, see Caralp 1970, Leclaire and Vergnaud-Grazzini 1972).

Another type of difficulty arises when two or more climate-related signals show marked differences in the position of maximum change. Core V28-14 from the Irminger Sea (south-east of Greenland), for example, shows a rapid change from low to high carbonate values centered near 90 cm downcore. This level was identified as "Termination I" by Kellogg (1975). (The

term "Termination I" was introduced by Broecker and van Donk, 1970, to emphasize the perceived suddenness of change at the Pleistocene/Holocene boundary.) Later it was found, however, that the maximum change in oxygen isotope composition of the planktonic foraminifer "*Globigerina*" *pachyderma* occurs near 140 cm. The proposed boundary then was moved to this deeper level (Kellogg *et al.* 1978). The difference in age is about 4 000 years.

The reason for the adjustment is that, by convention, the change seen in the oxygen isotope ratios of planktonic foraminifers is the master-signal to which other sediment properties are referred. The underlying presumption is that the signal closely reflects sea level change, and that it is synchronous world-wide (Shackleton and Opdyke 1973, Emiliani and Shackleton 1974). Within the limits of resolution of deep sea cores this hypothesis is indeed useful in most cases.

DEFINITION BY FAUNAL CHANGE

Historically, the first definition of the Pleistocene/Holocene boundary in deep-sea sediments was from faunal change. Schott (1935) discovered that the planktonic foraminifer *Globorotalia cultrata* (= *G. menardii*) was intermittently extinct in the Atlantic, based on a study of gravity cores taken during the METEOR Expedition (1925–1927). He found that *G. cultrata* last reappeared at a level some 20 cm down in his cores, and that it has been present since. He proposed that this appearance of *G. cultrata* marks the beginning of postglacial time. This level has been variously used to denote the Pleistocene/Holocene boundary. It is in fact diachronous. By comparing the *G. cultrata* appearance with oxygen isotope data one can show that this foraminifer shows up earlier in equatorial sediments than in the Gulf of Mexico or off north-western Africa. The difference is on the order of several thousand years (see Emiliani *et al.* 1975 and Thiede 1977). Also, since the *G. cultrata* disappearances and reappearances are restricted to the Atlantic, Schott's method does not work anywhere else. It should be pointed out, however, that Schott's discovery yielded the first set of reasonable deep-sea sedimentation rates at the time.

G. cultrata is an extreme example of a more general phenomenon. In most regions of the world ocean the transition from glacial to postglacial conditions is accompanied by marked changes in the composition of the fossil assemblage of planktonic foraminifers. In equatorial regions the trend is from species associated with equatorial upwelling toward species more typical of low fertility regions. In the subtropics cool-water forms recede, and in middle and high latitudes "*Globigerina*" *pachyderma* and

Globigerina bulloides tend to become less abundant in the Postglacial sediments. In places, the faunal change is quite dramatic (Phleger *et al.* 1953, Parker 1958). Other marker signals which have been applied to define the boundary are changes in coiling ratio of certain foraminifers (Ericson 1959, Bandy 1960) and other morphological variations. Radiolarian faunas also have been used to define the boundary (Frerichs 1968, Duncan *et al.* 1970, Bjørklund *et al.* 1979).

The changes in faunal composition are not synchronous over the North Atlantic (Ruddiman and McIntyre 1973). Elsewhere, on the whole, the question of synchronicity has not been adequately addressed. Where checked, some differences in the timing of faunal change and of oxygen isotope change are usually evident (Imbrie *et al.* 1973). Such differences may or may not be real in a palaeoclimatic sense, as benthic mixing can produce spurious phase shifts between transitional signals (Hutson 1980).

DEFINITION BY OXYGEN ISOTOPES

Emiliani (1955) showed that the oxygen isotope composition of foraminifers from surface waters traces the warm-cold cycles of the ice ages. Two main effects are present: an ice-effect due to the locking up of ^{16}O -rich water in polar ice caps (and corresponding enrichment of sea water with ^{18}O) and a temperature effect (growth in cold water leads to ^{18}O enrichment). The two effects, while additive, are not exactly synchronous: while the ice effect spreads rapidly throughout the ocean, the temperature effect depends on time-transgressive shifts in climatic zone boundaries. Fortunately, in most cases, the ice effect dominates, so that there is a strong presumption in favor of synchronicity, with regard to oxygen isotope signals.

During deglaciation freshwater was introduced at a high rate on the top of the ocean. It is likely that this water, which floats on sea water, retarded the mixing processes of the ocean, so that salinity stratification developed (Worthington 1968, Olausson 1969, Berger *et al.* 1977). If so, the oxygen isotope signals of planktonic and benthic foraminifers cannot be synchronous (Olausson 1965, Pastouret *et al.* 1978).

At first glance it would seem an easy task to establish the case for or against synchronicity of planktonic and benthic species for the various ocean basins. This is not the case because of the afore-mentioned disturbance by benthic mixing. Oxygen isotope curves of different species have to be "unmixed" to be comparable with the same core. Even the simplest equation available to do this contains terms for the relative abundance of the carrier species (Berger *et al.* 1977). In virtually all published data, the

abundance information is not available. In cases where it is, the abundances commonly refer to a size class different from that on which the oxygen isotopes were determined, and generally abundances do not refer to total sediment (as required) but to a portion of the sand fraction.

In summary, although better than other signals, oxygen isotope transitions are somewhat diachronous. The error is on the order of several centimeters, that is, one to two thousand years. This essentially represents current limits of the resolution of the deep-sea record.

DEFINITION BY CARBONATE CONTENT AND PRESERVATION OF CALCAREOUS FOSSILS

In the Pacific the postglacial record is generally marked by a lower carbonate content than the underlying late glacial portion (Arrhenius 1952, Broecker and Broecker 1974). In the Atlantic, one observes the inverse relationship (Olausson 1960). The reason for the change in carbonate content near the Pleistocene/Holocene boundary, in the Pacific as well as in the Indian Ocean, is that carbonate dissolution greatly increased in the early Holocene (Olausson 1967, Berger 1970). This increase closely followed a marked preservational peak during deglaciation (Berger and Killingley 1977). In the Atlantic, the carbonate stratigraphy of the transition largely reflects a change in dilution from terrigenous matter (Broecker *et al.* 1958, Volat *et al.* 1980). Changes in dissolution also may play a role (Olausson 1969, Berger 1973, Gardner 1975), and a preservational peak is evident in cores from off north-western Africa, centered on the boundary (Berger 1977, Thiede 1977).

Dilution depends on the proximity of sediment sources and the efficiency of transport agents. The dilution effects are probably not synchronous across latitudinal belts and between major sedimentary basins. As far as the carbonate saturation of the deep-sea, which produces the dissolution cycles, changes are probably synchronous within the deep Pacific and within the limits set by deep-ocean mixing rates.

AGE OF BOUNDARY

The first radiocarbon dates which allowed an assessment of the Pleistocene/Holocene boundary in deep-sea cores were made by Rubin and Suess (1955, 1956). They appear together with oxygen isotope stratigraphies in Emiliani (1955). By the conventional method of setting the boundary at the midpoint

TABLE 22:1. Radiocarbon ages (by interpolation) of Glacial-Postglacial mid-transition in box cores from the western equatorial Pacific. Ages (based on bulk carbonate) are listed in Berger and Killingley (1982). Oxygen isotope data (*Pulleniatina*) and levels of maximum preservation are given in Berger *et al.* (1977). Cores are listed in order of depth of water. All depths are shallower than 3 400 m.

Core ERDC (no.)	Oxygen isotope transition (cm)	Radiocarbon age (ka)	Maximum preservation (cm)	Radiocarbon age (ka)
92	23.5	12.7	26.5	14.0
88	20.0	14.7	21.5	15.8
112	25.0	10.7	23.5	10.2
120	27.5	12.2	26.0	11.6
83	24.5	9.6	23.5	9.3
79	22.5	11.2	19.5	8.1
123	22.0	10.5, 9.4	26.5	12.2, 11.1
125	23.5	10.3	21.5	9.3
Mean	23.6 ± 2.2	11.3 ± 1.7	23.6 ± 2.6	11.3 ± 2.4
Without Core 88		10.8 ± 1.2		10.8 ± 1.9
Median		10.7		11.1

of the transition between full Glacial and full Postglacial conditions, the dates on three Atlantic cores can be read as follows: Core A 179-4, 10.0 ka; Core A 172-6, 12.5 ka; Core A 180-73, 11.0 ka. The average age of this level, then, is near 11 000 ^{14}C years B.P. This age agrees with subsequent determinations by Ericson *et al.* (1956) and Broecker *et al.* (1958). The paper most commonly cited for the 11 000 years age is the one by Broecker *et al.* (1960), in which a number of radiocarbon ages from various environments and from several laboratories are summarized. Based on the deep-sea cores considered, these authors propose “that a large portion of the Atlantic Ocean underwent a temperature increase of 6° to 10° during a period of less than 2 000 years and that the midpoint of this change was within 300 years of 11 000 years ago” (*ibid.*, p. 435). The presumed temperature increase refers to the oxygen isotope data of Emiliani (1955).

Dating of the transition in the Pacific and Indian Ocean yielded ages ranging from 7 000 years (Blackman and Somayajulu 1966) to 13 000 years B.P. (Shackleton and Opdyke 1973), with most estimates falling between 9 000 and 12 500 years B.P. (Bandy 1960, Conolly 1967, Frerichs 1968, Duncan *et al.* 1970, Bé and Duplessy 1976, Vincent 1976, Shackleton and Vincent 1978).

The best available data on the age of the Glacial-Postglacial transition in the Pacific Ocean are those on box cores from the western equatorial Pacific. There are eight good cores above the lysocline. Oxygen isotope data are given in Berger *et al.* (1977) and radiocarbon determinations are listed in Berger and Killingley (1982). The ages for the midpoints of maximum

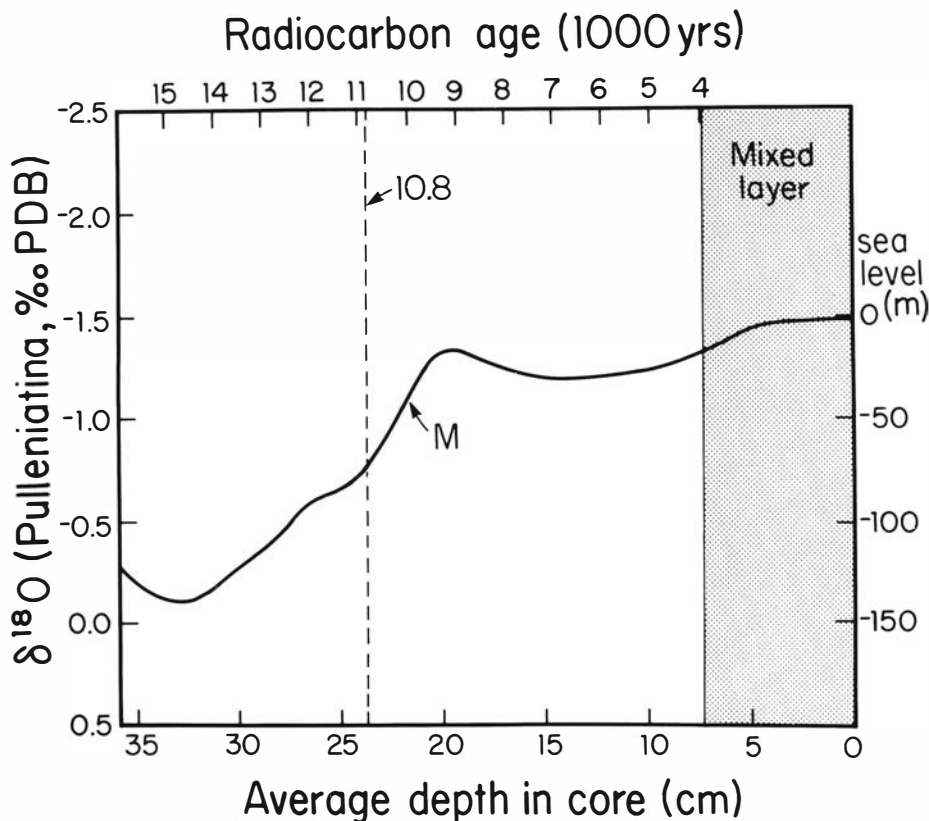


Fig. 22:1. Composite oxygen isotope signal of the Glacial-Postglacial transition as given by Berger *et al.* (1977). The curve is based on data from 8 box cores taken in the western equatorial Pacific, above the lysocline. Oxygen isotopes are those of *Pulleniatina obliquiloculata*, a planktonic foraminifer which lives in subsurface waters. More than 80 determinations are contained within the curve. The radiocarbon scale is based on about 25 analyses of bulk carbonate (listed in Berger and Killingley 1982). The broken line labelled "10.8" represents my best estimate of the position of the transition midpoint. If one assumes (albeit incorrectly) that the plotted curve represents the output, after mixing, of a step function, then the broken line marks the position of the step. M marks the spot where deconvolution of the curve produces maximum overshoot ("meltwater-spike" of Berger *et al.* 1977). The recording of palaeoceanographical information starts near 5 cm, within the lowermost part of the mixed layer. The sea-level scale is based on the convention that 0.1 ‰ in the $\delta^{18}\text{O}$ signal corresponds to about 10 m of sea-level change (Shackleton and Opdyke 1973).

change of oxygen isotopes are shown in Table 22:1, as are the ages for levels of maximum preservation. The overall average age is 11 300 ^{14}C years B.P., both for the oxygen isotope mid-transition, and for the preservation maximum. Allowing for the fact that Core ERDC 88 has an unusually low sedimentation rate within this set of cores and seems winnowed and otherwise somewhat disturbed (Berger and Killingley 1982), the average

age may be recalculated without the values from this core. The result is an average age of 10 800 ^{14}C years B.P. for both the age of the oxygen isotope transition and the age of the preservation spike (see Fig. 22:1).

This age, obviously, is not significantly different from that of Broecker *et al.* (1960). All these age determinations must be viewed with caution because of mixing processes on the sea-floor. There are at least three effects, all tending to increase the ^{14}C -age of events recorded in deep-sea sediments. Firstly, the true age of deglaciation is probably younger than recorded in the sediment. A change in concentration of a tracer such as radiocarbon is first felt at the bottom of the mixed layer, within sediment that is already several thousand years old. Hence a correction toward a younger age may be in order (Peng *et al.* 1977, Berger and Johnson 1978, Johnson 1980). Secondly, the bulk sediment age can differ substantially from the coarse fraction age (Suess 1956, Olsson and Eriksson 1965). Commonly, the fine sediment is older, due to redeposition processes (see, however, Ruddiman *et al.* 1980a). The third effect is due to the ^{14}C age of the water within which plankton shells are formed, which adds several hundred years to the apparent age of newly formed sediment (Erlenkeuser 1979). The ^{14}C age of 10 800 years B.P. here proposed is therefore, a maximum age. The real ^{14}C age of the transition very likely lies between 9 000 and 10 000 years B.P.

To find a reliable age for the oxygen isotope transition, short of taking recourse to more or less arbitrary corrections, one might consider using cores from near-continent regions, with high sedimentation rates. Unfortunately, in such areas downslope redeposition is common, and special precautions have to be taken. A high rate core from the Gulf of Mexico analyzed by Emiliani *et al.* (1975) shows the maximum change in oxygen isotope values near 140 cm, for which level the ^{14}C age is 13 000 years B.P., based on "bulk core material". Another high-rate core, taken off the Niger delta, and analyzed by Pastouret *et al.* (1978) shows the maximum change in the oxygen isotopes of *Globigerinoides ruber* between 11 200 and 11 500 ^{14}C years B.P. A core off north-western Africa (Lutze *et al.* 1979) shows the oxygen isotope transition near 10 500 years B.P. Apparently, cores with high sedimentation rates do not necessarily yield ages significantly different from those of deep-sea cores.

Radiocarbon ages are not true ages, because the production rate of radiocarbon from nitrogen-14 changes through time (Stuiver 1978). For the time of deglaciation the error may be considerable (Oeschger *et al.* 1980) or it may be only a few per cent (Vogel 1980). If the CO_2 -content of the atmosphere fluctuated (as suggested by CO_2 -content in ice cores; Berner *et al.* 1980, Delmas *et al.* 1980) considerable change in $^{14}\text{C}/^{12}\text{C}$ ratios probably occurred within the transition, depending on the carbon reservoirs partak-

ing in the fluctuations and their $^{14}\text{C}/^{12}\text{C}$ ratios (Siegenthaler *et al.* 1980). It appears preferable, therefore, to specify radiocarbon years whenever appropriate. The age of 13 000 years B.P. proposed by Shackleton and Opdyke (1973) for the isotopic stage boundary 1–2 is not a radiocarbon age. For this reason (and because of lack of detail) it is not comparable to the various age determinations cited.

WHERE SHOULD THE BOUNDARY BE PUT?

As I have tried to show, where geologists put the Pleistocene/Holocene boundary in deep-sea sediments, and why, is based on operational arguments rather than philosophical ones. Should this practice be changed?

It is always safe, of course, to demand that reason prevail over convenience. Yet, I do not think it makes much difference to science where one decides to put the “actual” boundary. For communication, it is preferable that researchers mean the same thing when referring to the “Holocene”, rather than various periods ranging from 9 000 years B.P. to 13 500 years B.P. In practice however, a reference to the Pleistocene/Holocene boundary has to be checked against the data available to the researcher using the term in any case. The task in studying the Pleistocene/Holocene transition in a deep-sea core is to ascertain the sequence of events within it, and to compare this sequence with similar ones elsewhere. A stratotype section might be useful in this task provided it shows a sequence of events of world-wide significance. Any of a number of such events could function as a marker for the definition of a boundary. Changes in oxygen isotopes of shallow water organisms, and faunal changes, are recommended for purposes of correlation.

My own preference is to put the beginning of the Holocene at a time when at least two thirds of the sea-level rise was completed, and when major readvances of continental ice sheets no longer occurred. Assuming that salinity stratification developed during deglaciation in the North Atlantic (Olausson 1965, Berger 1978, Ruddiman *et al.* 1980b), the Holocene, by this definition, would begin with the final dissipation of such stratification. As far as can be ascertained by the available information from deep-sea cores, this turning point is close to 10 000 ^{14}C years B.P., most likely somewhat younger.

As far as placing the boundary in deep-sea cores, my proposal would result in putting the boundary after the midpoint of the transition in the oxygen isotope signal of planktonic foraminifers, on the late portion of the transition, but where the rate of change is still strong.

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23. THE HOLOCENE BOUNDARY STRATOTYPE: LOCAL AND GLOBAL PROBLEMS

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INTRODUCTION

The late-glacial climatic warming began in the tropics around 14 000–13 500 years B.P. I attributed this (1961) to the rising solar radiation predicted by Milankovitch and also at the same time noted the inverse relationship that existed between ^{14}C flux and mean temperature (and eustatic sea level). The warm-up of the southern hemisphere, with its oceanic continuity, was extremely rapid. Not so the northern hemisphere with its high continentality and extensive ice sheets where in the ocean it was around 3 000 years later (Hays *et al.* 1977, Salinger 1981). Indeed, as one goes farther north, the Postglacial warm maximum is found to be younger and younger, until in the high Arctic it was as late as 6 000 years B.P. a classic “retardation” phenomenon (Fairbridge 1961), due largely to oceanic feed-back (Ruddiman and McIntyre 1981).

If one selects climatic proxies from different parts of the world it becomes all-too evident that one could select anything from 14 000 to 6 000 years B.P. as the most suitable time plane where a stratotype might be established (Fig. 23:1). In the early discussions, the Russian specialists tended to favour a early date, perhaps 12 000 to 12 500 years B.P. On the other hand, some of the Americans, with experience in Alaska, wanted the date closer to 6 000 years B.P.

In the deep-sea carbonate cores, the average date for the cool/warm transition (shown by foraminifers) was generally about 11 000 years B.P. (Broecker 1966). In many high-latitude terrestrial sections it was evident that 11 000 years B.P. heralded a short but sharp cooling event (the Younger Dryas pollen zone, the Loch Lomond advance of Scotland and the Valdres advance in North America). Furthermore, it is clear that an 11 000 years date in deep-sea carbonates represents an averaging, where older layers are homogenized with the younger by bioturbation. The true date must be younger.

In the middle latitudes, the critical turning point for the general warming trend, shown by innumerable pollen series, was around 10 000 years B.P.,

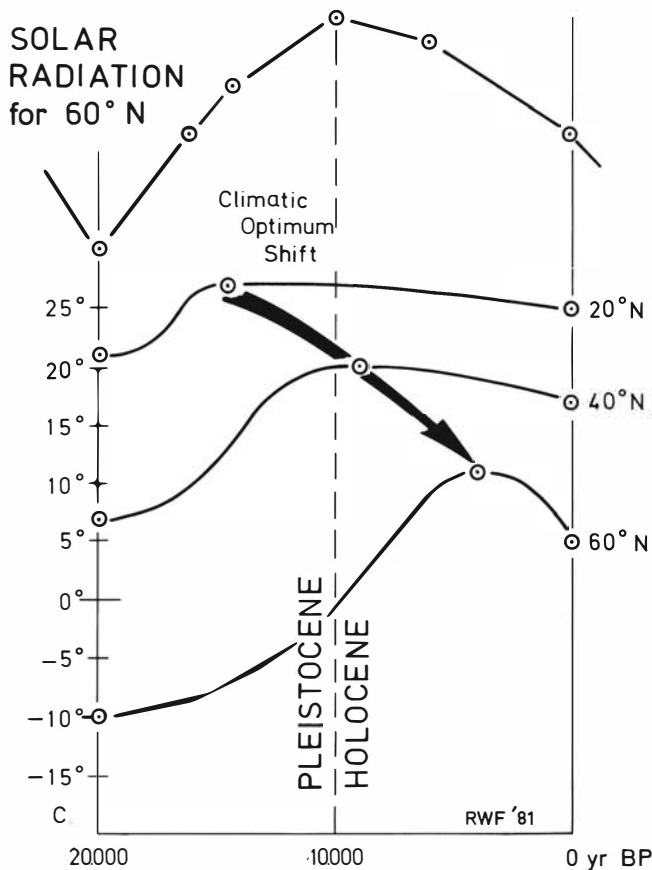


Fig. 23:1. Curves to show the diachronous nature of the late glacial and post-glacial warming in different latitudes. Estimated for the mean annual temperature at sea level on the basis of numerous climatic proxies. The first curve illustrates the early start of "post-glacial" trends at 20° (and lower) latitudes, but the low amplitude of the change. The curves for 40° and 60°N disclose progressively later warm-ups, but with increasing amplitudes (based on a figure in Fairbridge 1972, p. 297). Also indicated is the insolation curve of Milankovitch (for 65°N) which shows a peak at 10 000 years B.P., the subsequent warming being evidently reinforced by oceanic feed-back and other mechanisms.

and this seems a good average for the ocean too. Perhaps the most striking argument for the global significance of the 10 000 years B.P. turning point comes from Antarctica (Fig. 23:2). In the long ice cores this date (approximately) marks the time when the supply of world-wide dust (aerosol) fell by several orders of magnitude (Thompson and Mosley-Thompson 1981). This time marked the re-vegetation of enormous areas of Saharan desert/savannas, and of the loess-covered prairies and steppes of the higher latitudes.

Göteborg area, should receive closest attention, specifically at a level dated around $10\,000 \pm 250$ years B.P. The writer formally presented this motion at the Paris INQUA in 1969.

Through the imaginative and energetical initiative of N.A. Mörner, the first selection was core B-873 that was put down in the Göteborg Botanical Garden (Mörner 1976, Fairbridge 1976). A joint field meeting of the INQUA Commissions for Shorelines and for Holocene met in Göteborg in 1973, but a number of speakers felt that a critical part of the cool/warm transition was marred by the presence of a narrow layer of freshwater origin, and that a better section could be established. Accordingly a group led by E. Olausson, I. Cato and C. Fredén carried out numerous further borings in western Sweden, particularly in the area north of Göteborg (Olausson 1980). The undisturbed samples obtained by the Foil Piston Corer were studied by an extensive panel of experts, and the results presented at a specially convened meeting, May 5–8, 1981, at the Aspenäs-gården Conference Center, near Göteborg.

This 1981 meeting concluded that of the various cores studied in detail, the Solberga core would be the best selection, at a depth of 18–20 m, the precise details to be submitted later in the year. Most illuminating impressions at this meeting emerged from the reviews by invited experts that generated a regional palaeogeographical picture of western Sweden in late Pleistocene (Younger Dryas)/early Holocene (Preboreal) transition period. This region was then a complex archipelago of skerries (low, rocky islands) and channels receiving floods of fresh meltwater from the ice sheet margin that then lay 120 km north-east of Göteborg. These waters were probably seasonally variable in strength, spreading out over the cold water that was coming in from the west, in the manner of a gigantic estuarine salt-water wedge. The environment was evidently changing rapidly due to several other variables: the position of the ice front, the glacio-isostatic crustal uplift, and the eustatic and geoidal fluctuations.

CHRONOLOGY OF THE HOLOCENE BOUNDARY

At the 1981 meeting, the writer presented some of the evidence for constructing a new basis for a Holocene chronology that can be checked against varve chronologies, dendrochronology, isotopic time series, ice core data, geomagnetics, and other standards. It is based on astronomical periodicities, and therefore it is absolutely essential for this work for dates to be expressed in sidereal years. It greatly simplifies calculations if we

adhere to the usual geological datum year, that is AD 1950, and all ages are thus expressed as B.P. (before present) or A.P. (after present). Radiocarbon years are often distinguished as "bp" (and preferably with "¹⁴C" to make it perfectly clear). Too many articles and tables confuse the two systems of dating for want of a single word of explanation. It should also be recalled that in precise chronology, when it is required to convert B.C. to B.P. dates and *vice versa*, one should add or subtract 1949 (not 1950, because there was no zero year AD or B.C.). Warnings need to be repeated constantly against the use of precise radiocarbon dates, where a spurious accuracy is implied. First, there are variations in the isotopic flux rate that, for example, in the 7th millenium B.P. cause radiocarbon dates to be up to 1 000 years too young. Then there is the old carbon effect, which is particularly notable in shell dates near the ice margins where old water (melted ice) and old limestone (dissolved) can give dates that are 300 to 600 years too old (Mangerud and Gulliksen 1975). Shells that are too old for radiocarbon dating, such as those of 125–85K, from the last interglacial, frequently give "live dates" of 25 000–35 000 years B.P.; this is because they absorb modern CO₂ while sitting on the lab shelf waiting their turn to be dated (Olsson 1979). And not least there is charcoal, which is very reliable because it is difficult to contaminate, but the oak tree that furnished the charcoal may have been 300–400 years old (Suess 1979).

All this points up the great need for year-by-year chronologies such as provided by lake varves, tree rings and ice cores. The marine varves from the Santa Barbara basin (Psias 1978) may well lead the way towards a revolutionary new approach to climate studies, because they record surface-water temperatures (by ¹⁸O/¹⁶O studies of foraminifers) that appear to reflect pulses of the North Pacific gyre. On the Japan coast, Taira (1980) has shown that the warm pulses can be matched by high sea levels and reef-building corals. The cold interruptions are marked by volcanism, and Taira (*op.cit.*) suggests plate tectonic control. It is important to appreciate that while volcanic explosions may modify the stratospheric aerosol screen and cause a few years' cooling, the timing of the eruptions often *follows* the initiation of a cool cycle by more than 10 years (Rampino, Self and Fairbridge 1979). In other words the volcanism is not the cause of the cooling, but one of its related effects.

CONCLUSIONS

1. The purpose of stratigraphical nomenclature and stratotypes is *user-convenience*. Clarity of meaning and availability both demand and require site selection and accurate description.
2. From global studies extending over some decades, the western Swedish area was selected for the Holocene boundary stratotype, its anticipated age being $10\,000 \pm 250$ ^{14}C years B.P., this being the boundary between the (cold) Younger Dryas and the (warmer) Preboreal as indicated by terrestrial pollen on the nearby land.
3. Site selection from numerous cores in the region north of Göteborg seems to indicate that Solberga at the 18–20 m depth interval contains the most diagnostic evidence, to be reported by the separate specialists.

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24. SOME REMARKS AND RECOMMENDATIONS CONCERNING A PROPOSAL FOR A TYPE-SECTION OF THE PLEISTOCENE/HOLOCENE BOUNDARY

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According to the definition by the Holocene Commission of INQUA, the Pleistocene/Holocene boundary has an age of 10 000 years B.P. (Libby half-time of ^{14}C). Furthermore the same Commission, together with the INQUA Subcommission for North-west European shore-lines, had proposed a stratotype for this very boundary to be chosen in the Göteborg area, south-western Sweden. A working group, conducted by Eric Olausson, Göteborg, has since investigated several sites, the most appropriate being Moltemyr and Solberga, since both exhibit a long marine record, can be absolutely dated, and are easily accessible by flat borings.

The drawbacks of these sites are that

- a, they have experienced an isostatic uplift,
- b, the marine environment was replaced by freshwater later in the early Holocene,
- c, ^{14}C -datings of marine shells are prone to errors, and
- d, the former submarine topography may have exerted an unknown influence on the circulation of the ocean water. These difficulties must be taken into consideration.

In view of the handicaps a, b, and d, it must be suggested that local factors may have influenced the palaeoecological environment. Accordingly more general criteria should be chosen to accurately define the Pleistocene/Holocene boundary. With this in mind an intensive investigation of neighbouring former lakes could prove worthwhile. These may be Rörmyr and Vägen or some other site. An essential, synchronous event is the onset of long-distance transport of pollen grains of certain tree species, provided that the local vegetation was open. The pollen diagrams of Rörmyr, Vägen and Moltemyr generally exhibit the following sequence in the evolution of vegetation at about the Pleistocene/Holocene boundary and during the early Holocene: herb vegetation, dominated by *Artemisia* → *Empetrum-Salix-Betula nana* heath → juniper heath → copses of *Hippophaë* and *Betula*,

sometimes with some poplar. This sequence depicts the transition from an open, more or less treeless vegetation to sparse *Hippophaë* – *Betula* forests. It is improbable that already at the onset of this forest-formation *Corylus* could thrive in the area investigated. Thus the beginning of its pollen curve should indicate \pm synchronously the beginning of the long-distance transport. If so, this very point may be used as one reference layer, although already at the Preboreal/Boreal transition.

This horizon was preceded in Moltemyr, Rörmyr and Vägen by a phase, relatively rich in tree pollen, consisting only of birch and pine. The pollen curves of both these trees run inversely, with a very high amount of *Pinus*, when the nonarboreal pollen had predominated. This indicates long-distance transport of pine pollen, when the pollen production of the autochthonous vegetation was very low. In my view the last transition from the open, herb-dominated vegetation to the immigrating woody species, including *Betula*, should be the second synchronous reference layer, the Younger Dryas/Preboreal transition, *i.e.* the Pleistocene/Holocene boundary.

If so, this boundary is placed in the Moltemyr section at a depth of about 4.65 m and at Solberga about 18.25 m below the surface. This is in general corroborated by the mollusc fauna, although not by the diatoms, foraminifers, $\delta^{18}\text{O}$, nor the coccoliths, all of them being strongly influenced by changing depths and the chemistry of the water too.

Consequently although the Solberga section covers a longer interval, the documentation of events at the Pleistocene/Holocene boundary in the Moltemyr section seems to be better. Both these sections should be taken together as typelocalities (holo- and para-type locality) for the Pleistocene/Holocene boundary. It may be questioned whether the hitherto published ^{14}C -datings are reliable. In general they do not fit into the scheme given here, whereas palaeomagnetism (Abrahamsen) seems to corroborate the said theory.

If the suggestions made here should prove correct, the final influx of freshwater into both these basins cannot have happened synchronously, *i.e.* it cannot result from the Billingen event. This is easily understood in view of the local topography at Moltemyr. Finally I recommend the complex investigations to be continued, principally to detect general governing factors at that time, *i.e.* true climatic factors. This could be done by a continuation of the pollen-analytical work, implying a comparison of the pollen spectra of lacustrine *versus* marine environments, further by geomorphological, geological and palaeontological definitions of the Billingen event and its correlative sediments in the palaeoecology of the Göteborg area.

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