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 ^{14}C years B.P. Libby halftime, 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 km^3) but also the meltwater from the disintegrating Scandinavian ice sheet (>500 000 km^3) was discharged into the Skagerrak, to a large extent through the Väner basin.

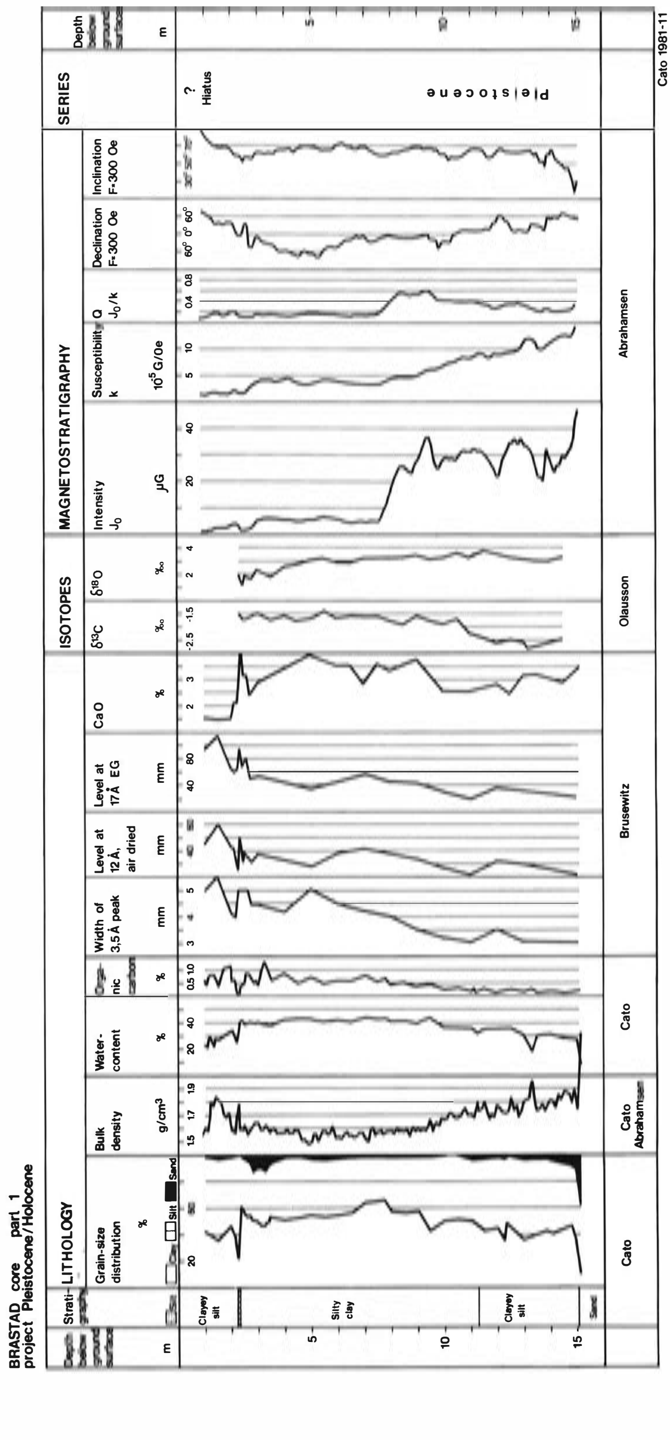

Fig. 20:1a. Part 1 of the summary diagram showing the vertical distribution of various analyses carried out on the Brastad core. Sediments from the uppermost Pleistocene and lowermost Holocene are lacking, creating a hiatus at 2.3 m depth.

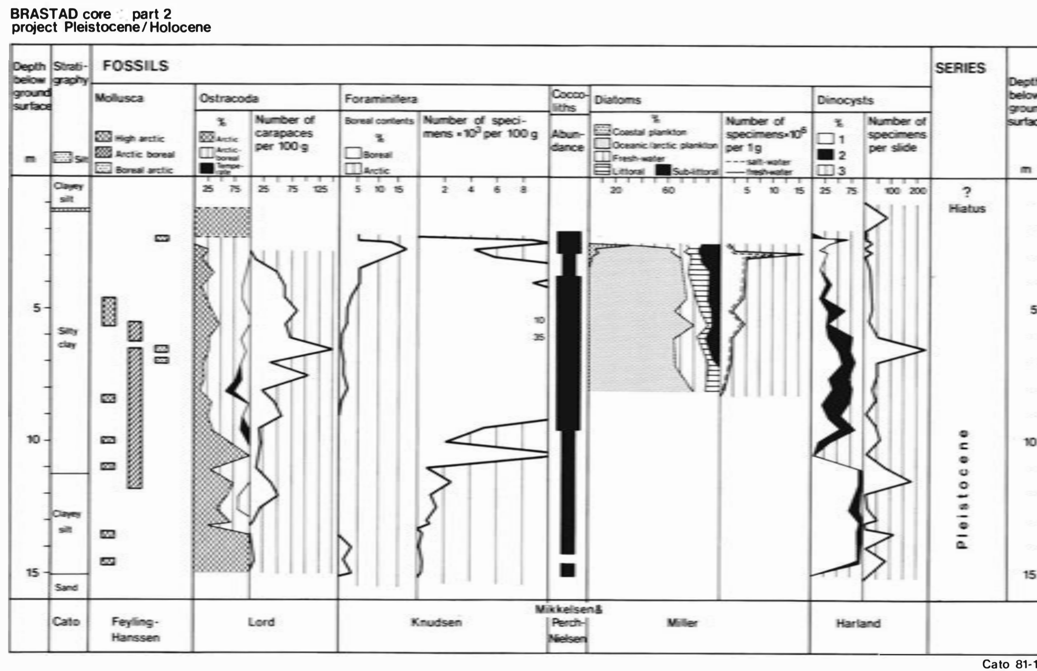

Fig. 20:1b. Part 2 of the summary diagram showing the vertical distribution of various analyses carried out on the Brastad core. Sediments from the uppermost Pleistocene and lowermost Holocene are lacking, creating a hiatus at 2.3 m depth. Legend for major dinoflagellate cyst species and/or groups:
1: *Operculodinium centrocarpum*
2: *Bitectatodinium tepikiense* and *Spiniferites* spp.
3: *Protoperidinium* spp.
Legend for ostracods. Blank = indeterminate as miscellaneous juveniles.

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 $\delta^{18}O$ 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 ± 300 and 10 220 $\pm^{560}_{500}$ ^{14}C years B.P. (uncorrected for reservoir age) respectively. The shells dated between 3.10 and 2.65 m are clearly redeposited.

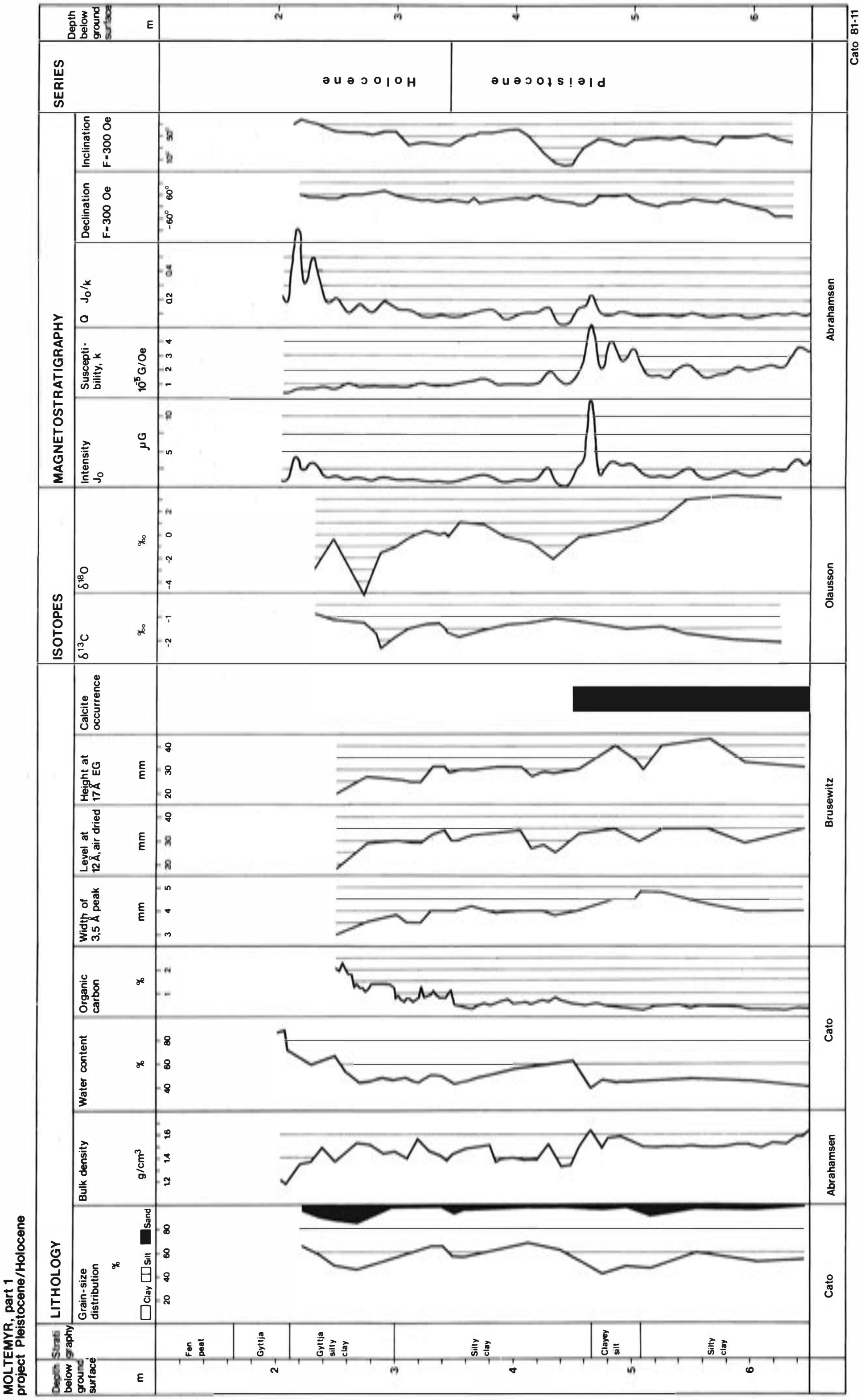

Fig. 20:2a. Part 1 of the summary diagram showing the vertical distribution of various analyses carried out on the Moltemyr core. The Pleistocene/Holocene boundary appears at 3.45 m depth.

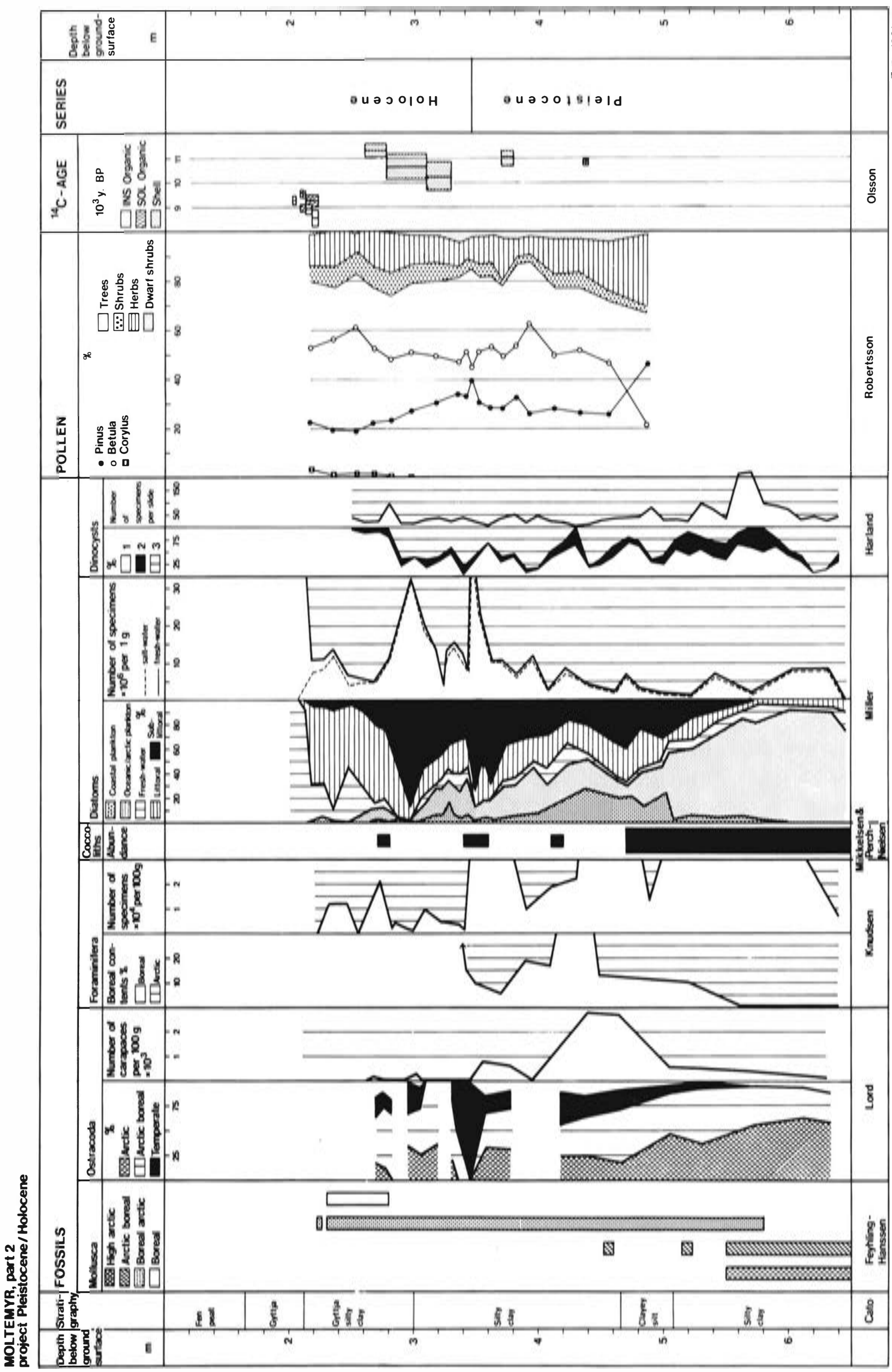

Fig. 20:2b. Part 2 of the summary diagram showing the vertical distribution of various analyses carried out on the Moltemyr core. The Pleistocene/Holocene boundary occurs at 3.45 m depth. Legend for dinoflagellate cyst and ostracod species and/or groups, see Fig. 20:1b.

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 $\delta\,^{18}O$ 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±400 ^{14}C years B.P. (uncorrected for reservoir age).

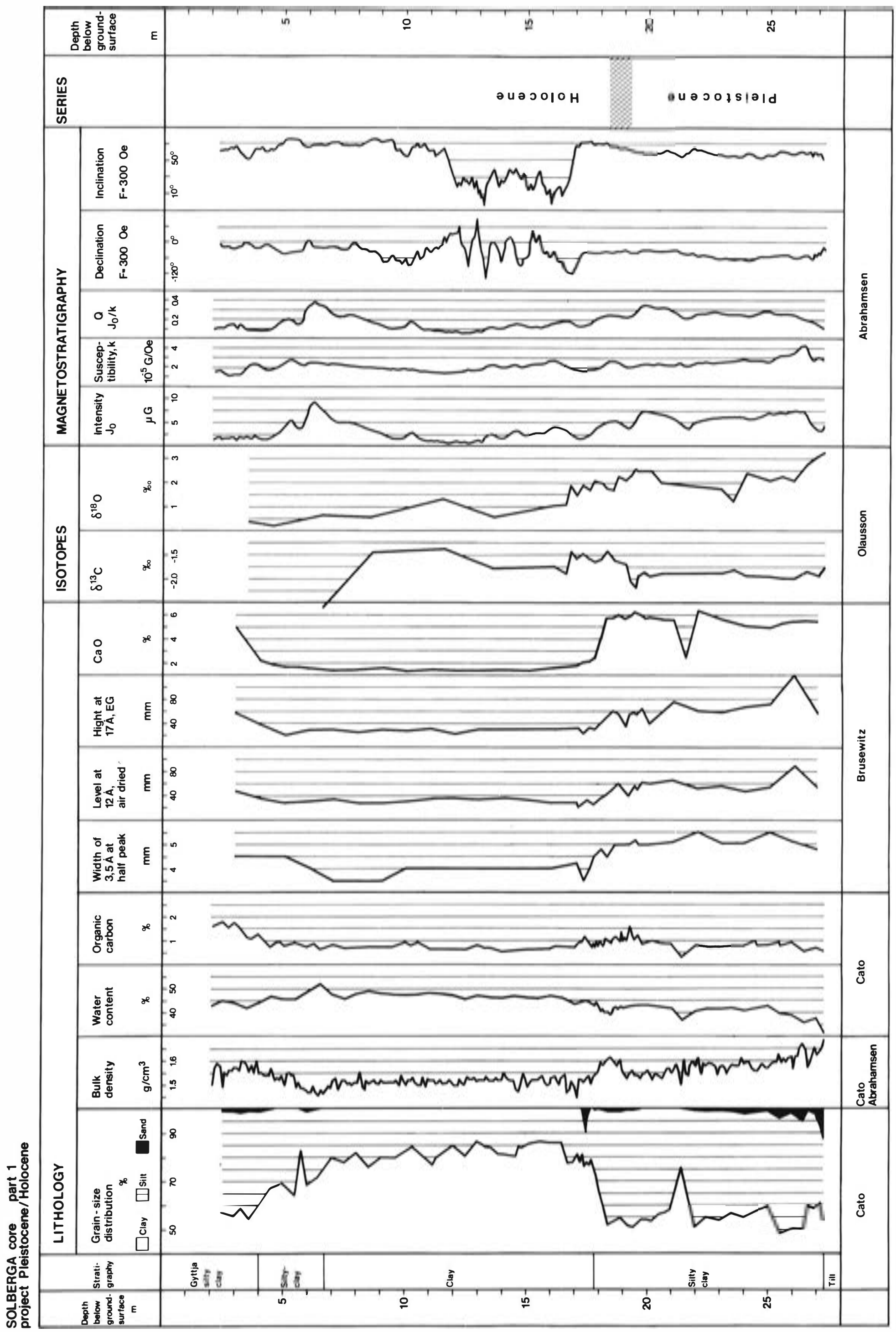

Fig. 20:3a. Part 1 of the summary diagram showing the vertical distribution of various analyses carried out on the Solberga core. The Pleistocene/Holocene boundary appears as a transition zone between 19.3 and 18.4 m depth.

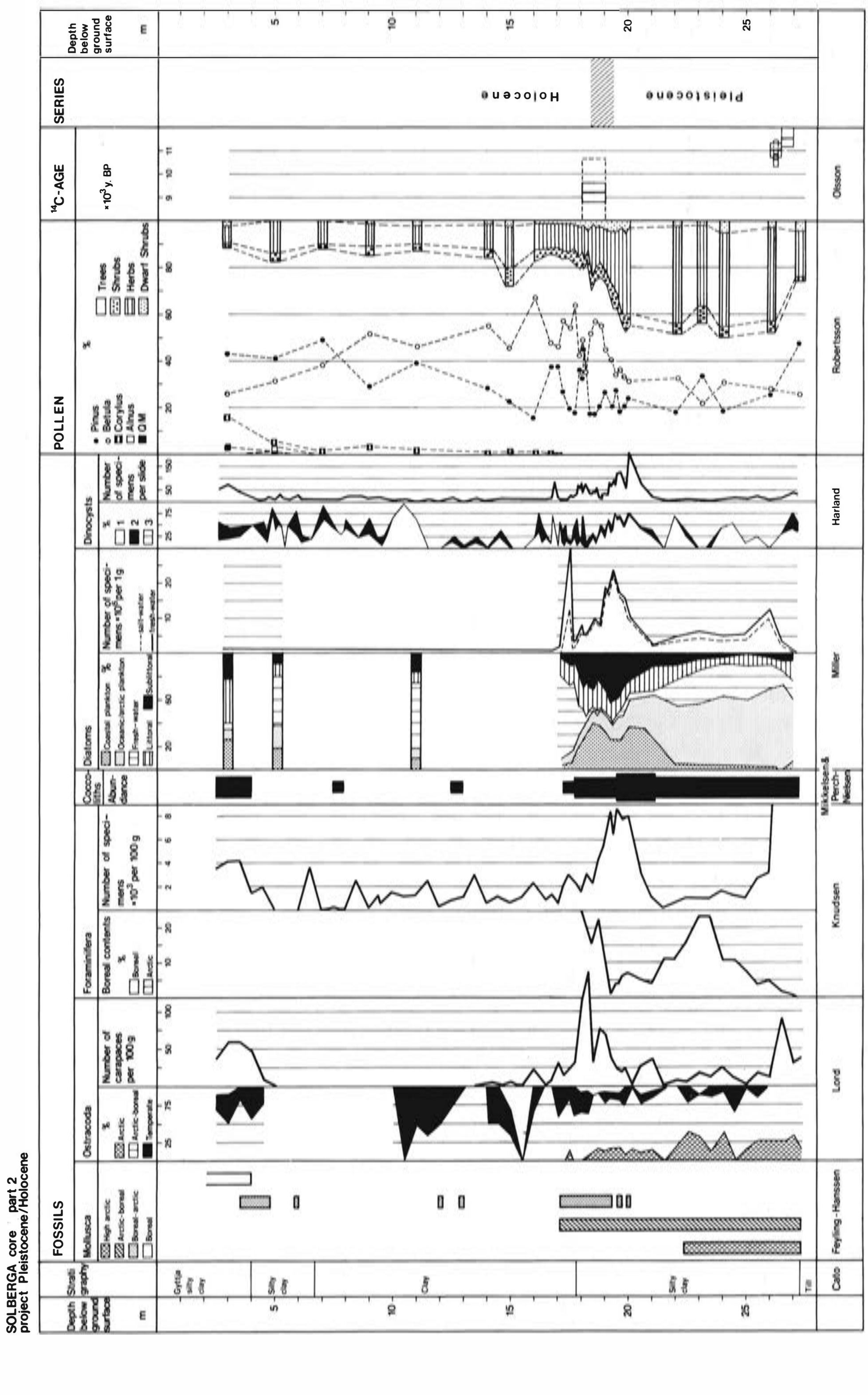

Fig. 20:3b. Part 2 of the summary diagram showing the vertical distribution of various analyses carried out on the Solberga core. The Pleistocene/Holocene boundary occurs as a transition zone between 19.3 and 18.4 m depth. Legend for dinoflagellate cyst and ostracod species and/or groups, see Fig. 20:1b.

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 disintergrating 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 ^{14}C 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 $\delta\ ^{18}O$ 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 $\delta\ ^{18}O$ and the frequency of the Boreal Foraminifera in the cores (see Fig. 20:4). The close connection between $\delta\ ^{18}O$ 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.

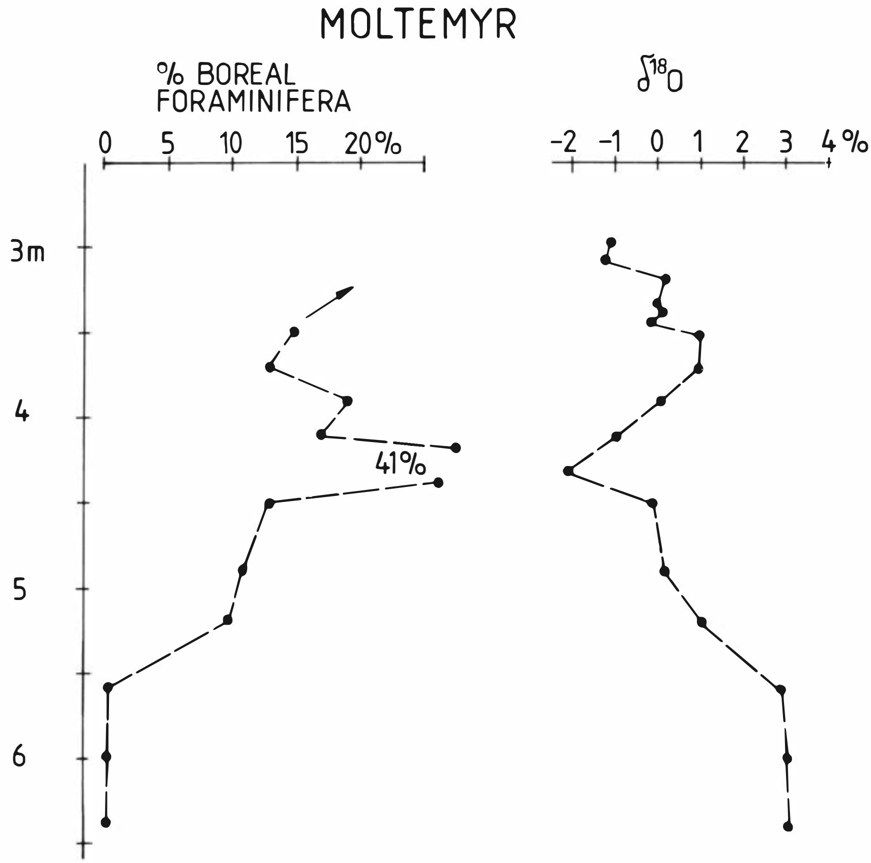

Fig. 20:4. The relationship between the δ ^{18}O and the frequency of Boreal benthonic Foraminifera. Both curves mirror changes in the salinity of the bottom water.

The first real response to the climatic change at the Pleistocene/Holocene boundary is the increase of the meltwater discharge:

a δ ^{18}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 fanuas 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 ($<2\mu m$), a clay mineralogy poor in weathered products and similar to that found in Quaternary clays in central Sweden (northernVäner 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 Väner 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 $\delta^{18}O$ 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 *Corylus* 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$\pm^{580}_{540}$				
^{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 ^{14}C 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 ^{13}C 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.