# The Late Weichselian - Early Holocene Lindhov clay sequence in the Varberg area, southwestern Sweden

FREDRIK KLINGBERG

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A clay sequence with specific depositional characteristics has been found, both on land and in the sea, in the area surrounding the town of Varberg and extending north along the coast. The clay sequence, here provisionally referred to as the 'Lindhov clay', has been identified and investigated by reflection seismics and sub-bottom profiling at sea and by mapping on land. On land, the Lindhov clay is found at altitudes below 10 m above the present sea level, and in the sea in a c. 10 km wide zone outside the present coastline. The Lindhov clay is lithostratigraphically situated in the transition zone between glacial and postglacial deposits. Foraminiferal analyses of the clay sequence show that the deposition occurred in low-salinity waters during arctic - boreal to boreal conditions. The 5-20 m thick clay sequence may have been formed by redeposition during the regression when large land areas were exposed and subjected to erosion. The subsequent redeposition of the material resulted in the formation of the clay.

*Fredrik Klingberg, Geological Survey of Sweden, Division of Marine Geology, Box 670, S - 751 28 Uppsala, Sweden.*

## Introduction

The Quaternary deposits in the Swedish part of the Kattegat have recently been investigated by the Geological Survey of Sweden (SGU) as a part of a regular long-term survey of the Swedish continental shelf area. The results of this survey are presented as a map series: The marine Geological Map, SGU Serie Am, in the scale 1:100,000 (SGU, 1989, 1994, in prep). The marine survey was carried out from the vessels R/V Carolina (1985-1988) and from S/V Ocean Surveyor (1989-1992). During this work a characteristic clay sequence, here provisionally referred to as the 'Lindhov clay', was first observed in the sea northwest of the town of Varberg (SGU 1994) (Fig. 1). Stratigraphically, the Lindhov clay sequence is embedded between glacial and postglacial deposits. In this paper, the genesis and age of the clay sequence will be discussed.

The geological setting of the Kattegat region has been treated by many authors. A review of important investigations documenting the distribution and stratigraphy of both pre-Quaternary and Quaternary sediments has been made by Lykke-Andersen et al. (1993). Late Weichselian deposits have been studied by Michelsen (1967), Mörner (1969), Fält (1982), Bahnson et al. (1986), Knudsen & Nordberg (1987), Bergsten & Nordberg (1992), Seidenkrantz & Knudsen (1993) and Bergsten (1994). The stratigraphy of Holocene sediments in the southern Kattegat has been studied by Nordberg (1989) and Conradsen et al. (1994). Gyldenholm et al. (1993) suggested a division of the Quaternary sediments into four seismic units (units 0-3). Unit 3 contains deposits of supposed Late Saalian to Middle Weichselian age, unit 2 represents the Late Weichselian till, unit 1 represents the Late Weichselian waterlain deposits and is up to 100 m thick, and unit 0 represents the Holocene sediments.

The uppermost part of the clay sequence at Klosterfjorden was cored and investigated by Mörner (1969) (Fig. 1). This clay was classified by him as being postglacial and dating to the Boreal I pollen zone.

Bergsten & Nordberg (1992) studied 38 cores from the southern Kattegat and subdivided the Late Weichselian and the Holocene into four facies. The uppermost, facies I, contains faunas characterised by species typical of Holocene temperate conditions in the Kattegat and Skagerrak regions. The deposition corresponding to facies I was estimated to have occurred between 10,300 to 9,500 years B.P. Facies I was subdivided into two parts representing different water depths. The sublittoral facies Ib was characterised by foraminifer assemblages with species such as *Elphidium albiumbilicatum*, *Bulimina marginata* and *Elphidium excavatum* representing relatively shallow conditions. Facies Ia is characterised by shore/near shore foraminiferal assemblages with species such as *Elphidium williamsoni*, *Haynesina germanica*, *Elphidium guntheri* and *Ammonia beccari*. The sediment corresponding to Facies II was deposited between 10,300 and 12,700 years B.P. The fauna contain arctic, temperate, normal marine and low-salinity elements with *Elphidium albiumbilicatum*, *Elphidium excavatum*, *Cassidulina reniforme* and *Bulimina marginata*. In more shallow parts, *Elphidium albiumbilicatum* and *Elphidium excavatum* are the most abundant species (Bergsten & Nordberg 1992).

## Geology and palaeoceanography

The deglaciation of the eastern Kattegat started at about 14,000 years B.P. (Lagerlund & Houmark-Nielsen 1993) and the Varberg area was deglaciated at about 13,400-13,500 years B.P. (Påsse 1990). During the deglaciation the sea entered the Kattegat basin. This early Kattegat

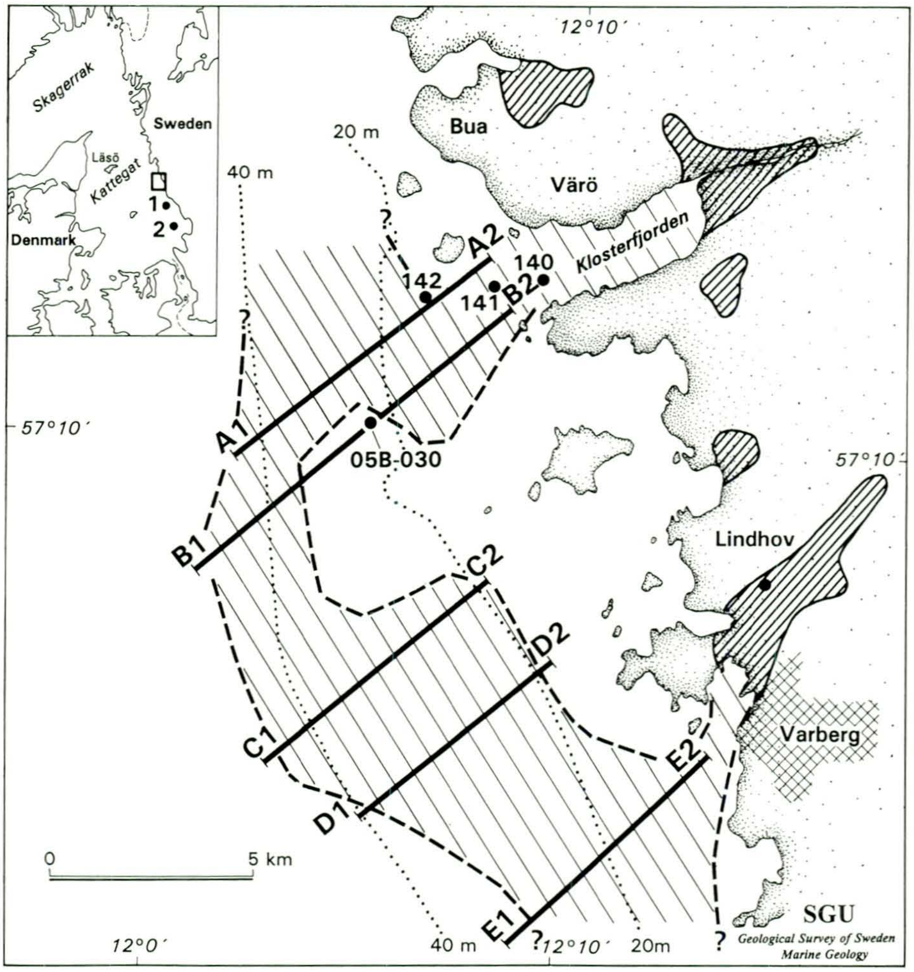


Fig. 1. Location map of southwestern Scandinavia showing the investigated area and the cores mentioned in the text. The seismic sections A1-A2, B1-B2, C1-C2, D1-D2 and E1-E2 are placed at their correct positions. The broken lines indicate present bathymetry. Point 1 is core 8502 and point 2 is core 8523 by Bergsten & Nordberg (1992). 140, 141 and 142 refer to cores by Mörner (1969). Extension of the Lindhov clay sequence according to the geological sections at sea (wide hatched) and from the survey on land (close hatched).

had a bay-like setting with the opening to the north and with contact with Atlantic water through the Skagerrak and the North Sea. In the south the Baltic Ice Lake was drained into the Kattegat through the Öresund strait between 12,700 to 10,300 years B.P. (Bergsten & Nordberg 1992). The influx of highly saline water below the meltwater in the early Kattegat created estuarine conditions with a stratified water column. During this phase, the Varberg area was still depressed below the sea level (Påsse 1990). Meltwater carrying large amounts of suspended matter

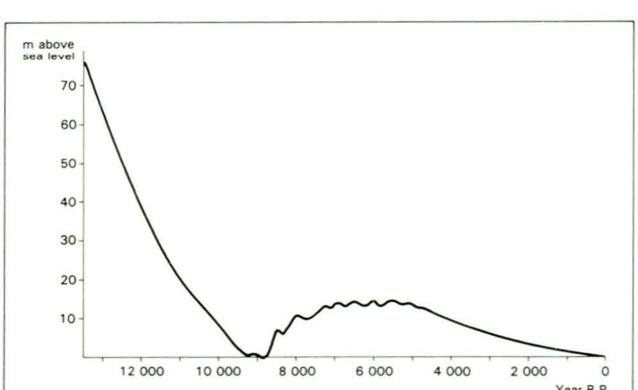


Fig. 2. Shore level displacement in the Varberg area. From Påsse (1990).

submerged the area and sediments, mainly clay, were deposited during these glaciomarine conditions. Close to the highest coastline, at about 75 m above sea level, glacifluvial coarse sediments were deposited. The shore level displacement was an important factor influencing the development of different sediment types. After deglaciation, relatively fast regression took place in the area (Påsse 1990) (Fig. 2). During the regression, redeposition of both coarse and fine glacial sediments occurred.

In the investigated area, moraine ridges run parallel to the ice margin. These ridges were originally interpreted to be end-moraines (De Geer 1893), but have been reinterpreted to be glaciotectonic ridges (Fernlund 1988,1993) formed during an ice advance called the 'Halland advance' (Fernlund 1993). Parts of the ridges were thrust over the earlier deposited glaciomarine clays. Shells from the clay have been $^{14}$C-dated to c. 12,400 years B.P. which implies that the Halland advance postdates the deposition of this clay (Fernlund 1993).

# Methods

*Acoustic profiling and sampling*

Acoustic profiling and sampling were carried out by the

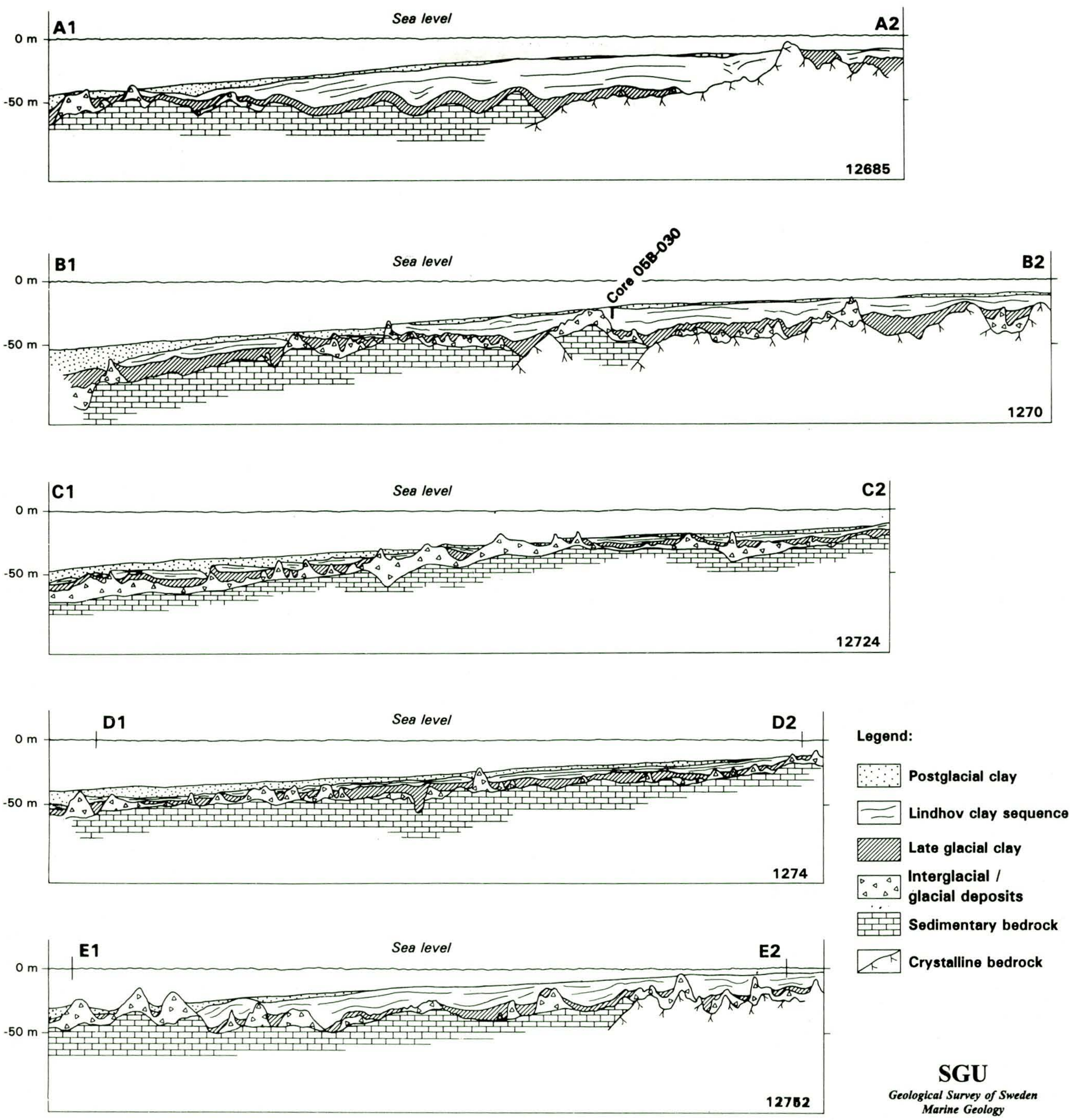


Fig. 3. Five geological cross sections interpreted from reflection shallow seismics. End-points according to Table 1 and location according to Figure 1. The position of core 05B-030 is shown.

Geological Survey of Sweden in order to establish a stratigraphy of the Quaternary sediments in the investigated area. A 3.5/7 kHz EDO Western sub-bottom profiler was used to obtain high resolution information. To acquire information on the sediments out-of-range of the sub-bottom profiler, single-channel shallow seismic reflection data were collected. The seismic sound sources used were an EG&G Sparker and an EG&G Uniboom. The received signals were filtered between 0.2 and 1 kHz.

*Sampling*

Surface samples and vibrocores were taken to verify the interpretation of the acoustic profiles. The coring was carried out with a 6 m vibrohammer core and the surface was sampled with an 'Orange Peel Bucket' grab sampler. The results from the surface samples are not presented in this paper. The grain-size distribution and biostratigraphy, especially concerning foraminifers, were analysed in subsamples of the sediments obtained. The percentage

Table 1. Length and positions of the end-points of the cross sections. The locations of the cross sections are shown in Fig. 1.

| Section name | Point | East | North | Length in m |
|---|---|---|---|---|
| 12685 | A1 | 12°02'01 | 57°09'37 | 7 831 |
| | A2 | 12°07'53 | 57°12'22 | |
| 1270 | B1 | 12°01'15 | 57°08'06 | 10 000 |
| | B2 | 12°08'24 | 57°11'50 | |
| 12724 | C1 | 12°03'06 | 57°05'39 | 6 997 |
| | C2 | 12°08'16 | 57°08'10 | |
| 1274 | D1 | 12°05'30 | 57°05'00 | 6 000 |
| | D2 | 12°09'55 | 57°07'10 | |
| 12752 | E1 | 12°09'11 | 57°03'25 | 6 710 |
| | E2 | 12°13'47 | 57°06'01 | |

Table 2. Lithology of core 05B-030.

| Depth below surface in cm | Lithostratigraphy |
|---|---|
| 0-20 | Silty fine sand. Shell-bearing. Shells from *Arctica islandica, Macoma baltica* and *Balanus sp.* A sto ne at 10-12. Olive grey, 5Y 4/2 |
| 20-565 | Fine clay, in the uppermost part gyttja clay. Scattered shell fragments. Homogeneous. 20-120 worm burrows filled with fine sand. 290-295 clayey, coarse silt with shell fragments. Sulphide spots at 500-510 and 555-565. Colour 20-350 grey 5Y 6/1,350-560, grey, 5Y 5/1. |

of sediment particles larger than 0.125 mm of the total dry weight was calculated (Figs. 4 & 5). The sediment colours were estimated according to a Munsell soil colour chart (Tables 2 & 4).

*Foraminifers*

The laboratory treatment of the foraminiferal samples was carried out according to the methods described by Meldgaard & Knudsen (1979). For quantitative analysis, when possible at least 300 specimens of foraminifers were counted from each sample. The number of specimens in each sample and the relative frequencies of selected taxa in the two profiles are illustrated in Figs. 4 and 5. When a sample contained less than 100 specimens the percentage was not calculated; instead, the occurrence of species was entered in the range chart by their actual numbers. Faunal diversity and the number of species are given in the range chart. Faunal diversity is calculated as the number of ranked species that account for 95 % of the counted fauna. LFAZ are defined as Local Foraminiferal Assemblages Zones, according to Hedberg (1976).

*Radiocarbon dating*

Two radiocarbon datings from marine molluscs were obtained by using AMS, carried out by the Tandem laboratory at Uppsala, Sweden. The radiocarbon ages were reduced by 400 years to account for the reservoir effect of sea water (Mangerud & Gulliksen 1975).

# Results

Of the five NE-SW trending cross sections presented in this paper, two (A1-A2 and D1-D2) have previously been published as part of the Marine Geological map (SGU 1994). The sections, which are between 6 and 10 km long, run parallel to the main ice movement direction (Table 1, Figs. 1 & 3). This means that the cross-sections cut through sediments deposited parallel to the ice margin, e.g. glacio-tectonised ridges.

Six different stratigraphic units (SGU 1989,1994, in prep.) were mapped during the geological interpretation of the cross sections. The lowest is the Precambrian basement which crops out by the Swedish coastline. To the west, this is overlain by sedimentary bedrock. The bedrock is covered by sediments interpreted to be interglacial/stadial/interstadial sediments deposited during the Saale, Eemian, Early and Middle Weichselian periods. These sediments were, to a certain extent, glacio-tectonised during the Late Weichselian and ridges trending NW-SE were formed. The Late Weichselian deposits, mainly tills, cover the interglacial/stadial/interstadial sediments. It is difficult to distinguish the interglacial/ stadial/ interstadial deformed sediments from the Late Weichselian sediments in the glacio-tectonised ridges. During deglaciation, glaciomarine clay was deposited conformably upon the glacial substratum.

The seismic profiles (Fig. 3) indicate that along the present coastline, a clay sequence with specific depositional characteristics, provisionally referred to as the 'Lindhov clay', was deposited above the glaciomarine clay. The base of the Lindhov clay was deposited conformably on top of the glaciomarine clay. The Lindhov clay is designated glacial clay on the marine geological maps (SGU, 1989, 1994, in prep). The top surface of the sequence is quite flat and the shift towards the Holocene clay is marked by a sharp acoustical boundary. The Lindhov clay sequences may then be cut through by Holocene sediment-filled channels. The layering of the Lindhov clay sequence dips westwards and the clay extends at most to 10 km from the coastline. The thickness is generally between 5 to 10 m and reaches a maximum of about 20 m. The Lindhov clay is silty, partly banded and has a low organic content. Above the Lindhov clay sequence there is a younger clay that has been deposited throughout the Holocene until recent time. The Holocene clay has a slightly higher organic content compared with the Lindhov clay.

# Core 05B-030

The 5.65 m long core 05B-030, positioned at N 57°10'08 E 12°05'07, was taken with the purpose of investigating the uppermost part of the Lindhov clay sequence (Fig. 1,

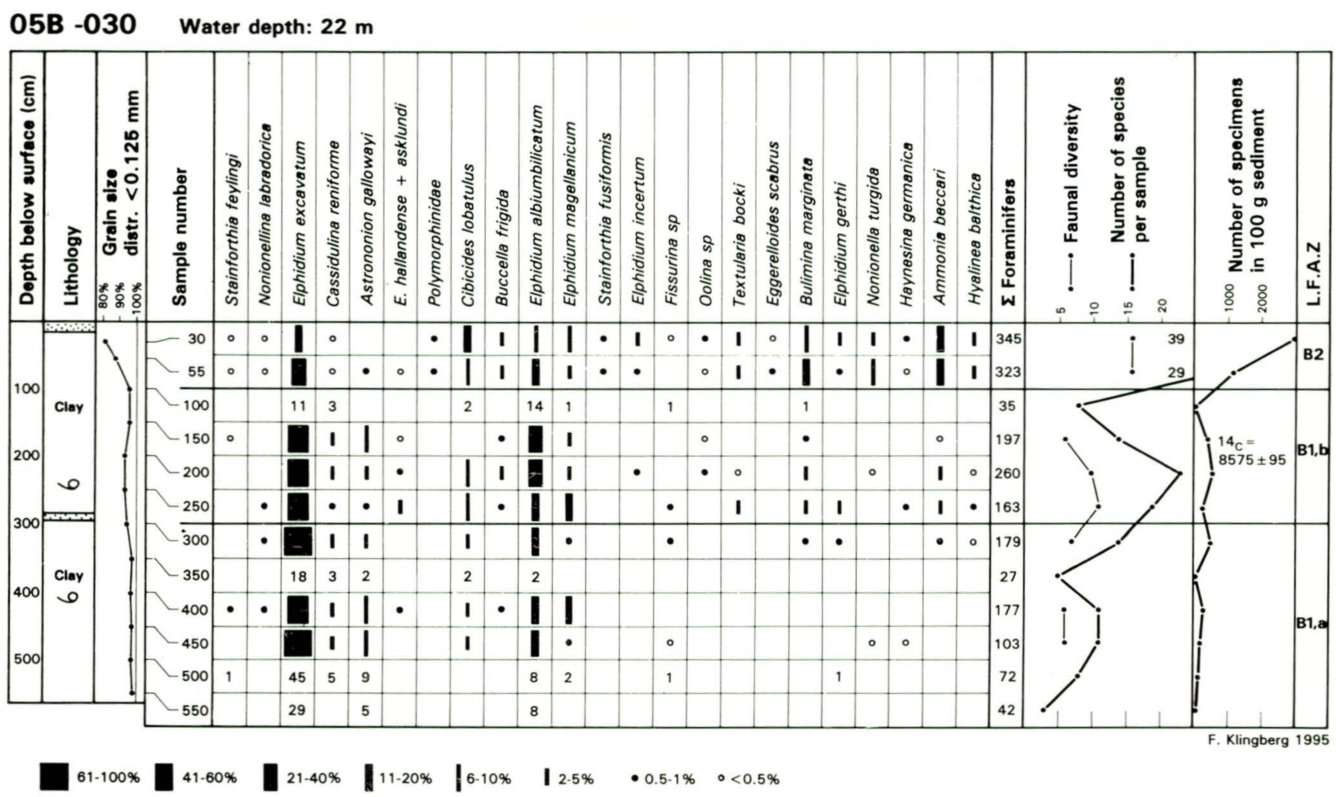


Fig. 4. Percent range chart of selected foraminiferal species from core 05B-030.

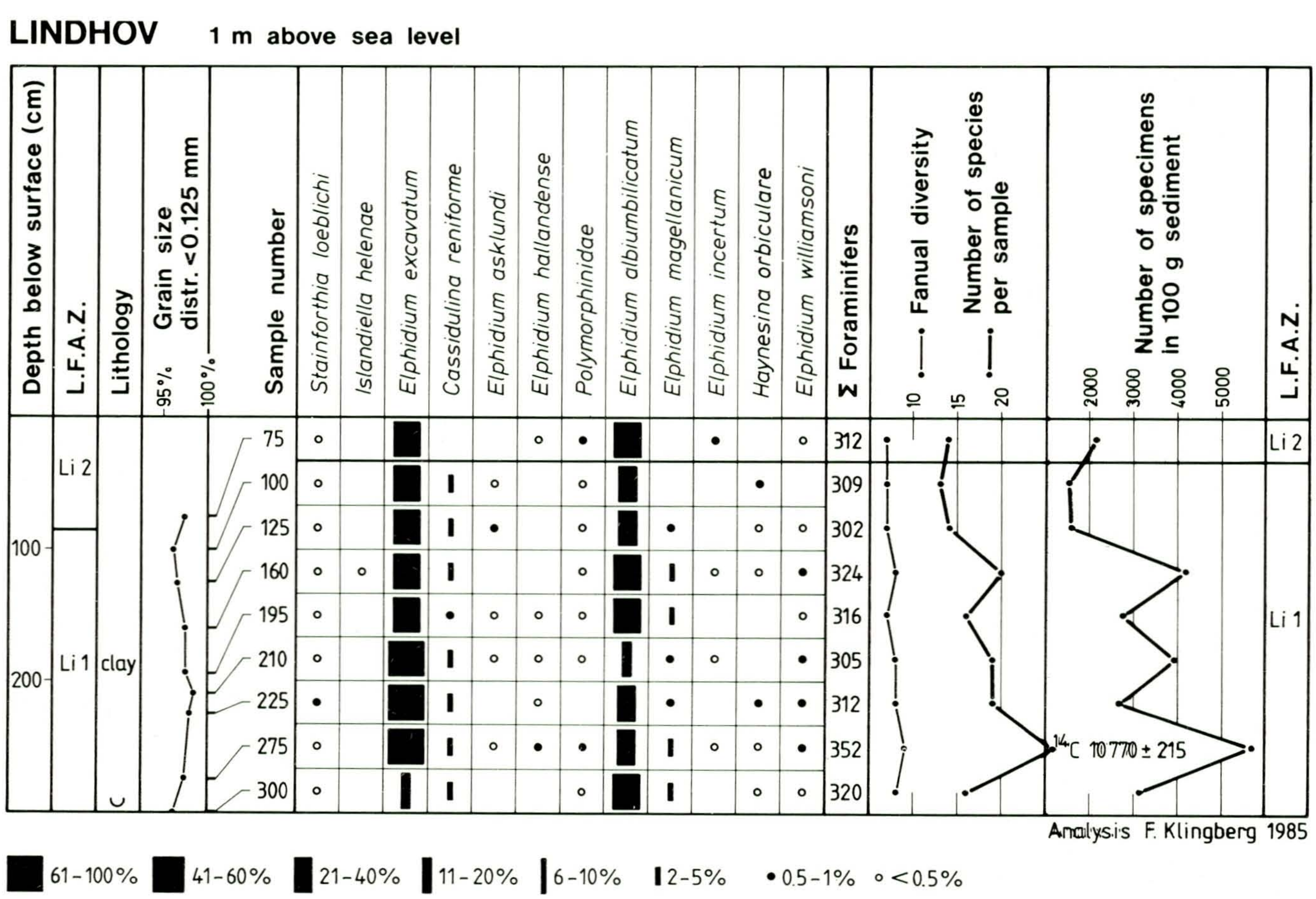


Fig. 5. Percent range chart of selected foraminiferal species from Lindhov.

*Table 3. Local foraminiferal assemblages zones (LFAZ) in 05B-030*

| *Zone* | *Depth below surface in cm* | *LFAZ* |
|---|---|---|
| *B 2* | *0-80* | *Elphidium excavatum - Elphidium albiumbilicatum - Bulimina marginata - Ammonia beccari* |
| *B 1, b* | *80-275* | *Elphidium excavatum - Elphidium albiumbilicatum - Ammonia beccari* |
| *B 1, a* | *275-565* | *Elphidium excavatum - Elphidium albiumbilicatum* |

Table 4. Lithology at the Lindhov road-cut.

| Depth below surface in cm | Stratigraphy |
|---|---|
| 0-70 | Dry crust |
| 70-270 | Fine clay, grey, 5Y 5/1 |
| 270-300 | Fine clay, grey, 5Y 5/1, fragments of shells, diffuse sulphide banded, 5Y 3/1 |

Table 2). Holocene sediment is present in the uppermost part of the core. The core was taken at a water depth of 22 m.

Radiocarbon dating at core-level 160 cm on unspecified shell fragments gave an uncorrected age of 8,975±95 years B.P. on the insoluble fraction (Ua-4801). The corrected age is 8,575±95 year B.P.

*Foraminifers*

Twelve samples were investigated for the content of foraminifers (Fig. 4). The sequence can be divided into two LFAZ, B1 and B2 (Table 3). The number of specimens per 100 g sediment in the lowermost zone B1 is relatively low and varies between 70 and 550. In the uppermost zone B2 the concentrations of specimens range between 1200 and 3000. The number of species per sample varies between 3 and 23 in LFAZ B1 and 29 and 39 in LFAZ B2. The most important species are *Elphidium excavatum* and *Elphidium albiumbilicatum*. In LFAZ B1, the arctic species *Astrononion gallowayi* and *Cassidulina reniforme* are important accessory species. *Elphidium magellanicum* and *Cibicides lobatulus* are also common. In LFAZ B2, important accessory species are the boreal species *Ammonia beccari*, *Bulimina marginata* and *Nonionella turgida*. These species usually occur in recent sediment in the Kattegat region (e. g. Conradsen et al. 1994).

*Interpretation*

The foraminifers display boreal-arctic to boreal bottom water conditions. The foraminiferal concentration in LFAZ B1 suggests a high accumulation rate, which is not seen in LFAZ B2. Both foraminifer assemblages are characterised by a fauna showing low salinity. In LFAZ B1 there are a few arctic species whereas LFAZ B2 contains mainly boreal species. The clayey, coarse silty layer at 290-295 cm probably represents a hiatus.

# Lindhov

The samples were collected in a 3 m deep cut during a road construction at Lindhov, 3 km north of Varberg at the position N57°08'18 E12°15'52 (Fig. 1, Table 4). Lindhov is situated on a very flat coastal plain only a few metres above sea level. The distribution of the sediment can be seen on the map-sheet Varberg NO (Påsse 1990). The highest coastline is about 70 m above sea level in the Varberg area (Fig. 2).

Radiocarbon dating was performed on foraminifers in sample 275 in AMS. The uncorrected age is 11,070±215 years B.P., and the corrected age 10,770±215 years B.P.

*Foraminifers*

Nine samples were investigated for their foraminiferal content (Fig. 5), and the sequence was divided into LFAZ Li1 and Li2 (Table 5). The number of specimens per 100 g sediment is between 1,000 and 5,700 and the number of species ranges between 14 and 26 per sample. The predominating species are *Elphidium excavatum* and *Elphidium albiumbilicatum* which account for > 95% of the fauna in all samples. The arctic species *Cassidulina reniforme* is the most important accessory species in LFAZ L1, but it is lacking in LFAZ L2.

*Interpretation*

The foraminifers indicate an arctic - boreal bottom water environment. The extremely low diversity reflects extreme ecological conditions, caused by a lowered salinity in the bottom water during deposition.

# Discussion

The Lindhov clay found off the coast of Varberg has also been found on land. On land, the clay sequence occurs at levels below 10 m above the present sea level in the area north of Varberg. The top surface of the clay sequence is quite flat on land, which is a usual feature in the region, and explains why this sequence was termed postglacial clay on the land maps (Påsse 1986, 1990) and probably in

Table 5. Local foraminiferal assemblages zones (LFAZ) at Lindhov.

| Zone | Depth below surface in cm | LFAZ |
|---|---|---|
| Li 2 | 90-70 | Elphidium excavatum - Elphidium albiumbilicatum |
| Li 1 | 300-90 | Elphidium excavatum - Elphidium albiumbilicatum - Cassidulina reniforme |

other areas (Fredén 1983, Påsse 1988, Adrielsson & Klingberg, 1989) as well. The sequence at Lindhov confirms the interpretation that the clay sequence on land is the same sequence that was formed off the coast. The 'Lindhov clay' is here provisionally named after the locality where the clay was first observed on the Lindhov farm, situated 3 km north of the town of Varberg. The distribution of the Lindhov clay sequence has been tentatively estimated (Fig. 1).

A core (8502) taken 40 km south of the investigated area penetrated a clay sequence which was dated to 10,000 and 10,400 years B.P. (Bergsten & Nordberg 1992) (Fig 1). These authors suggested that the clay sequence was deposited during the Younger Dryas. Comparison of the foraminiferal assemblages shows a similarity to those at Lindhov and core 05B-030. They are characterised by the same dominant species and also by the same accessory species. Therefore, it is believed that the Lindhov clay sequence found in the Varberg area is the same as that found south of the investigated area.

Core 8523 was taken about 70 km south of the investigated area (Bergsten & Nordberg 1992) (Fig 1). The foraminiferal assemblages have very high percentages of *Elphidium albiumbilicatum*, which suggests lower salinity conditions than in the investigated area. The sediment sequence in this core can also be related to the Lindhov clay sequence. The sediment in core 8523 was estimated to have been formed between 11,700 and 10,300 years B.P.

However, it is not known whether the Lindhov clay extends further to the south and to the north.

The foraminiferal analyses show that deposition of the Lindhov clay took place in boreal to arctic - boreal bottom water conditions. A strong freshwater influence can be determined from the large number of specimens which are tolerant to brackish water, mainly the species *Elphidium albiumbilicatum* and *Elphidium magellanicum*. Arctic species occur with low frequency in LFAZ Li1 and Li2. The assemblages indicate that the temperature of the bottom water had begun to increase but that it was still cold enough for these arctic species to survive in small numbers. The arctic species might, however, also have been redeposited. The sedimentation at Lindhov appears to have ended earlier than at 05B-030 and it thus relates to an earlier phase. The accumulation rate was slower at Lindhov compared to 05B-030.

The dating of the Lindhov clay sequence is uncertain. One $^{14}$C-date from Lindhov gave the age as 10,700 B.P.. The age of 8,575 B.P. at 05B-030 is more recent than the presumed hiatus and therefore represents Holocene sediment. The lowermost part of core 05B-030, which displays the Lindhov clay, is not dated.

Even if the dating of the clay sequence is unclear, it is suggested that deposition of the Lindhov clay began shortly after deglaciation of the area. During the subsequent regression of the sea, the areas around Varberg were eroded. Redeposition of this material together with suspended load from the rivers and streamrunoff, resulted in the formation of the Lindhov clay sequence. The sediments were deposited upon the late glacial clay sequences, showing a transition from conformable deposition in the lower part to typical basin fill in the uppermost part. The accumulation of the Lindhov clay may have ended at the same time as the peak of the regression at 9,300 years B.P.

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