On the presence of sea water in the Baltic ice-lake

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Abstract

A discussion of the salinity of the interstitial water in five sediment cores from the Baltic containing mainly glacial deposits appears to prove that the Baltic ice-lake contained sea water during the early stage when only the South Baltic was laid free by the retreating ice.

The existing information regarding the complicated development of the Baltic since the first appearance of the Baltic ice-lake has been obtained by investigations above the present sea level, such as studies of shore lines, varves in glacial clay, and fossils. Fossils in the deposits have given information on the salinity of the water, and especially made it possible to decide during which periods the Baltic was a lake containing fresh water, or a sea with a more or less good connection with the ocean. In many cases observations above sea level necessitate an extrapolation beyond the shoreline, the results of which are inevitably doubtful. The development of the piston corer (KULLENBERG 1947) has made it possible to extend the investigations beyond the present shoreline by collecting sediment cores in the Baltic sufficiently long enough to reach down into the moraine, so the study of the cores should furnish information comprising the lateglacial and postglacial stages of the Baltic. An informal Danish-Swedish committee under the chairmanship of Dr HILMER ÖDUM, Director of the Danish Geological Survey, has therefore undertaken to study the bottom deposits in the Baltic by means of the piston corer with a view to extend the knowledge of the history of the Baltic. By the courtesy of the Swedish board of fisheries the research ship the "Skagerak" has repeatedly been put at the disposal of the committee, or the present writer, for these investigations. By the courtesy of Dr VEDEL-TÅNING the Danish research vessel the "Biologen" was put at the disposal of the committee on one occasion.

The committee has, among other things, tried to find evidences in the bottom deposits in the South Baltic that the present sea bottom has been raised above sea level during lateglacial or postglacial time, such as the occurrence of peat, stumps of trees, lacustrine sediments, or simply a very hard and dry crust. Finds of stumps of trees are reported by fishermen at about lat. N 55°15', long. E 14°00' at a depth of 40 m. So far, the present investigations have not verified the occurrence of anything indicating an up-heaval of the sea bottom south or east of Scania. In the area where the present water depth exceeds about 30 m a study of the sediment cores rather suggests that the area in question has been perpetually covered by water, because the sequence of strata is identical to the one that is met with in a depression 20 nautical miles north of the island of Bornholm where

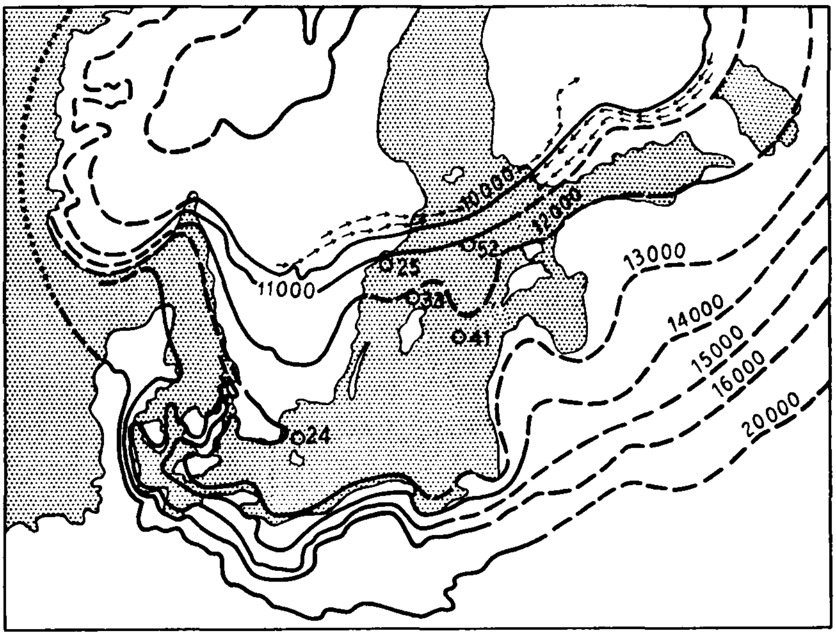

Fig. 1. Positions of coring stations. Milleniar ice-margins B.P. and influxes of salt water to the Baltic from east and west (De Geer 1954)

the depth is about 100 m. In more shallow water near the coast of Scania the bottom is covered by sand over-laying a hard moraine. The extension of the area covered by a complete sequence of varved clay and postglacial sediment strata has not yet been found out in detail. As a preliminary to a systematic examination a detailed survey with echo-sounder to a depth of 40 m was undertaken in May, 1954, using Decca for navigation.

In the Great Belt a layer of peat about 75 cm thick was found in September 1953, near Nyborg at a depth of 28 m during a cruise with the Danish research vessel the "Biologen" using a 3 m piston corer adapted for the rapid collection of the uppermost sediment layers. The core is being worked up at the Danish Geological Survey, and Dr ÖDUM has kindly informed me that the deepest part of the peat layer dates from lateglacial time. Though several cores were collected in the immediate neighbourhood, only one more of them revealed traces of peat so the peat-bog is evidently quite small. This should be remembered in the search for peat-bogs inundated by the sea, and necessitates that the search be carried out with considerable thoroughness. A peat-bog is in great danger of being removed or having its size reduced by wave action in the process of inundation.

The salinity of the interstitial water of the bottom deposits in the Baltic might be a source of information regarding the salinity of the bottom during the various stages of the Baltic. According to studies in the laboratory, using a beaker as a settling tank, the salinity of the interstitial water in newly deposited sediments is identical to the salinity of the bottom water (KULLENBERG 1952). Studies of sediment samples collected in the Mediterranean and the Indian ocean don't rule out the possibility that changes occur as the sediment grows older, and especially that the salinity might be different in adjacent sediment layers with different compositions even though both layers might originally have had the same salinity. This presupposes a diffusion of some major component of the sea salt from one sediment layer to another able to bind the ions in a higher concentration. However, if such changes occur they are too small to be very important in the case of Baltic sediments, because the salinity changes in the Baltic during the last stages of the glaciation and during postglacial time should be very considerable according to the prevailing views on the history of the Baltic.

The smoothing out of vertical salinity gradients by diffusion might have an influence more prejudicial to our aim. By measurements in the laboratory I have found the coefficient of diffusion to be about $2 \cdot 10^{-6}$ cm^2/sec, but so far I have not studied the influence of the water content on the coefficient of diffusion though such an influence must certainly exist. Further, the texture of the sediment, and its degree of consolidation, should be expected to influence the coefficient of diffusion. Unfortunately, the disturbance caused to a sediment sample when it is collected and during its subsequent treatment may increase the coefficient of diffusion very much, so the value here reported is probably too large. We shall discuss the diffusion in connection with some of the cores collected in the Baltic.

Nearly hundred long cores have been collected in the Baltic and we shall here discuss the ones given in Table 1. The positions of the coring stations together with milleniar ice-margins B.P. (before present) and influxes of salt water to the Baltic from east and west according to De Geer (1954) are indicated in Fig. 1.

Table 1

Station	Latitude	Longitude	Depth	Length of the core
24	N 55°31′	E 15°08′	86 m	15.2 m
25	58 26	17 39	72	8.5
33	58 04	18 57	117	15.0
41	57 28	20 07	183	10.0
52	59 07	20 31	118	9.0

Station 24. The station is situated 20 nautical miles north of the island of Bornholm. At the lower end of the core there is a 3 m thick layer of a moraine consisting of sand, silt, and lumps of clay. Between a sediment depth of 1,240 and 1,020 cm there is a grey glacial clay with rather distinct varves, succeeded by a fine red glacial clay with indistinct varves extending to a depth of 125 cm. Between 125 and 100 cm there is a clayey

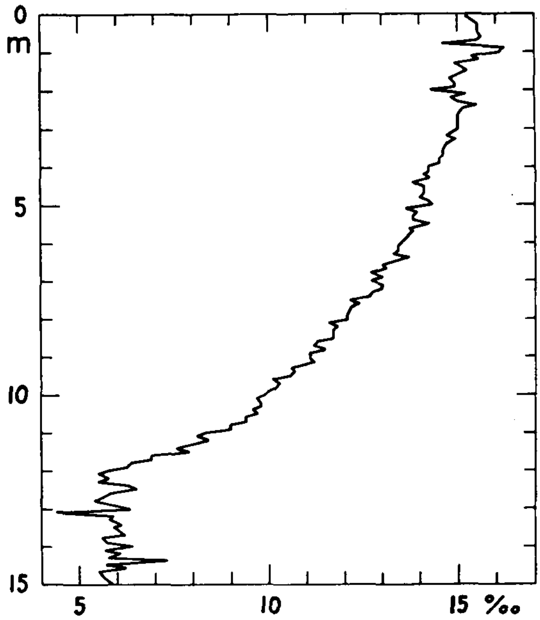

Fig. 2. The salinity of the interstitial water at station 24.

mud, light bluish grey, which is separated from the adjacent layers by very sharp boundaries. The top of the core down to 100 cm consists of a dark greenish mud with a high content of organic matter.

The salinity of the interstitial water as determined at intervals of 10 cm is represented in Fig. 2.

Regarding the postglacial deposits at the top of the core we shall call attention to the fact that there is no outstanding salinity minimum such as the *Ancylus* stage would have left behind itself, as the Baltic is generally considered to have been a lake at that period. Neither has any major salinity minimum indicating the *Ancylus* stage been found in the other cores investigated in the Baltic, some of which have a much thicker postglacial sediment layer than the core now deliberated. It might be that diffusion has removed the salinity minimum. The duration of the *Ancylus* stage is estimated at about 1,500 years, and the sediment layer formed during this period might be quite thin, as in fact it must be at station 24, where the total thickness of the postglacial deposits accumulated during 10,000 years is no more than 125 cm. Accordingly very great salinity gradients would appear in the core if the salinity of the bottom water was coming down to zero during the *Ancylus* stage, and the diffusion would be correspondingly intensified. However, in some areas the postglacial deposits attain a thickness of 20 m, or more, and then diffusion should be less effective. So far, the salinity has not been determined in any core containing such a thick postglacial sediment layer, and a final judgment should be postponed until this has been done. Another explanation of the lack of a postglacial salinity minimum might of course be that the salinity of *the bottom water* was not reduced appreciably during the *Ancylus* stage.

In the glacial clay between 125 and 1,240 cm the salinity of the interstitial water decreases with the sediment depth from 15 ‰ to 6 ‰. In the moraine found between 1,240 and 1,520 cm the salinity is constant except for irregular variations. Here the water content is as small as 14 per cent by weight, so the salinity cannot be determined very accurately.

It is remarkable that the salinity gradient in the clay increases with the sediment depth. This evidence appears to prove definitely that the salinity of the interstitial water in the varved clay was originally high, i.e. 10—15 ‰ even in the lower portion of the layer consisting of varved clay. In fact, a horizontal lamella of clay will lose more salt downwards per unit time than it will receive from above, because the salinity gradient is smaller at the top of the lamella than at the bottom. It is true that the coefficient of diffusion might change with the sediment depth, and if the coefficient of diffusion were reciprocally proportional to the salinity gradient each horizontal lamella of clay would lose equally as much salt downwards per unit time as it receives from above. However, as the clay is getting slightly more coarse with increasing sediment depth the coefficient of diffusion should be expected to *increase* with the depth, if it changes at all. Then a horizontal lamella of clay will certainly lose salt continually in the portion of the core between 200 and 1,200 cm. Accordingly the salinity of the interstitial water in this portion of the core will continually be reduced. The rapidity of this process is dependent on the value of the coefficient of diffusion *in situ*, which is not known but is probably less than $2 \cdot 10^{-6}$ cm^2/sec.

The diffusion of the salt is governed by the equation

$$w \frac{\partial S}{\partial t} = k \frac{\partial^2 S}{\partial t^2} \qquad (1)$$

S denoting the salinity of the interstitial water, w the water content in g/cm^3 (i.e. practically in fraction of the volume), k the coefficient of diffusion, z the sediment depth, and t the time. We will put $k/w = m$ and, by way of simplification, we will assume m to be a constant. This does not mean that we assume k/w to be generally independent of the character of the sediment (it is certainly not); we just assume this ratio to be a constant in the varved clay here in question, the general properties of which do not change appreciably though the water content does change.

In the depth range 500—1,200 cm the salinity is approximated quite closely by the equation

$$S = 4.5 + 0.363 \sqrt{1{,}220 - z} \qquad (2)$$

This will make

$$\frac{\partial^2 S}{\partial z^2} = -0.091 : (1{,}220 - z)^{3/2} \qquad (3)$$

Putting $m = 3 \cdot 10^{-6}$ we get

$$\frac{\partial S}{\partial t} = -2.7 \cdot 10^{-7} : (1{,}220 - z)^{3/2} \qquad (4)$$

The salinity change in 1,000 years according to eq. (4) is given in Table 2.

Table 2

Depth	$\Delta S_{1,000 \text{ years}}$
5 m	— 0.45 ‰
6	— 0.55
7	— 0.7
8	— 1.0
9	— 1.5
10	— 2.6
11	— 6.5

This imports that the salinity of the interstitial water in the varved clay is rapidly decreasing at all depths below 4 m, or that the salinity was originally greater, especially in the deeper parts of the varved clay. Supposing the selected value of the coefficient of diffusion to be approximately correct, the high rate at which the salinity is changing with time will appreciably influence the second derivative of the salinity in a much shorter time than 1,000 years. Accordingly the figures given in Table 2 are valid for the present only, especially in the deeper parts of the varved clay. Notwithstanding, the salinity will have changed at a very high rate during the past few thousand years, if the coefficient of diffusion is as high as has been assumed here. The main part of the varved clay in this core has an age of more than 12,000 years (DE GEER 1954). Even without entering into a detailed calculation it can therefore be maintained, with reference to Table 2, that the original salinity of the interstitital water in the varved clay did not fall much below 15 ‰, not even in the deepest portion of the varved clay. This conclusion would still not be greatly affected even if the coefficient of diffusion *in situ* is only one tenth of the value here adopted. If, on the other hand, there is no diffusion at all, the original salinity is given by Fig. 2.

Regarding the sand underlying the varved clay it appears probable that here the interstitial water is comparatively free to move, which would smooth the salinity gradients effectively. Unless there is a continual supply of fresh water to the sand layer able to carry away the salt brought to the sand layer by diffusion, the salinity of the interstitial water in the sand layer must be increasing and was, accordingly, originally smaller than at present. The corer did not go right through the moraine so we don't know the thickness of the sand layer. Considering the small water content of the sand layer, it has a small capacity as a recipient of salt, and it has to have a thickness of 10—20 m to be able to absorb the amount of salt carried away from the varved clay, if the original salinity of the interstitial water in the varved clay was 15 %. If the interstitial water in the sand layer contained sea salt originally, its capacity as a recipient of salt would be even smaller. It is therefore not probable that so much sea salt has flowed from the clay to the sand as would be the case if the coefficient of diffusion *in situ* were really as high as $2 \cdot 10^{-6}$ cm²/sec. In fact, at present the salinity gradient between 11 and 12 m sediment depth is 0.023 ‰ per cm. At $k = 2.10^{-6}$ cm²/sec this would make the amount of sea salt entering the sand layer by diffusion 1,450 mg/cm² in a thousand years. The water content of the sand layer being about 30 % by volume a supply of salt at this rate would raise the salinity of the interstitial water in a sand layer 80 m thick by 6 ‰ in ten thousand years. It is hardly probable that the sand layer is as thick as that.

Regarding the salinity of the bottom water in the South Baltic at the time the varved clay in the core here considered was deposited, it follows that the salinity did not fall much below the salinity found in the bottom water in the South Baltic at present, with the possible exception of the deepest part of the varved clay corresponding to a period no longer than a few hundred years. We conclude that the Baltic ice-lake contained sea water even during the early stage here in question, or at about 12,000 B.P., when only the South Baltic was laid free by the retreating ice. This does not agree with the prevailing view that the South Baltic was a fresh water lake until 10,500 B.P., when sea water began to flow into the Baltic over Finland as the ice-margin left Salpausselkä I.

The low salinity of the interstitial water in the moraine and, possibly, the deepest portion of the varved clay may be occasioned by the nearness of the ice and the ensuing masses of melt water likely to reduce the salinity, unless the cause is a horizontal leaking of fresh water through the sand layer.

Station 25. The station is situated 20 nautical miles east of the Swedish coast, northwest of Gotland. The corer hit a big boulder or solid rock which was covered by 8.5 m sediment. The nose of the corer was smashed by the rock. Immediately above the rock there was about 50 cm of clay and silt with pebbles. Then followed a 265 cm thick layer containing 219 rather distinct varves covered by a 32 cm thick layer containing less distinct and very thin varves. The varves are grey, and the summer sediment consists of silt. Between 490 and 70 cm there is a grey clay which did not display any varves until it had dried and even then the varves were quite indistinct. The top of the core down to 70 cm consists of a bluish grey clay containing a few lumps coloured black by iron sulphide.

The salinity of the interstitial water is represented in Fig. 3. The interface at about 5 m between the deeper part of the core containing well-developed varves, and the upper part containing indistinct varves, is displayed by a sudden decrease of the water content from 55 % by weight to (in the mean) 44 %. Large irregular variations of the water

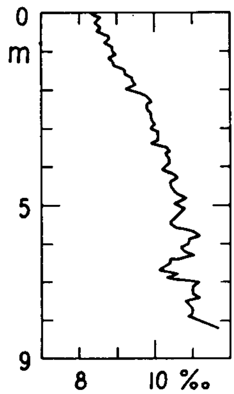

Fig. 3. The salinity of the interstitial water at station 25.

content in the deeper part of the core is due to the fact that the water content of the winter sediment is considerably higher than that of the summer sediment.

The salinity of the interstitial water increases with sediment depth from 8.4 ‰ at the top of the core to 11.7 ‰ at 820 cm, which is about 25 cm above the rock. This appears to prove that the salinity of the bottom water at this station was higher at the time the varved clay was deposited than it is now. The salinity gradient decreases with the sediment depth, and diffusion will therefore diminish the salinity throughout the core, except for the top. This imports that the salinity of the interstitial water in the varved clay was even higher originally than it is now, provided diffusion takes place.

According to Fig. 1 the deeper portion of this core was deposited a little earlier than 11,000 B.P., whereas the inflow of salt water over Finland commenced at about 10,500 B.P. Considering that the ice-margins in the Baltic are estimated on the basis of observations ashore, this discrepancy does not appear serious. On the other hand it is quite possible that the inflow of salt water in the east has nothing to do with the high salinity found in this core. In fact, cores collected nearer the entrance of the Gulf of Finland do not display a similar increase of the salinity with the sediment depth, whereas they should have done so even to a higher degree if the influx of salt water over Finland were the cause of the phenomenon. This core appears therefore to strengthen the evidence supplied by core 24, that the Baltic ice-lake contained sea water at an early stage.

Station 33. The station is situated a few nautical miles to the north of Gotland. The deepest 240 cm of the core consists of silt and sand with occasional pebbles; the colour is light reddish. Above 1,260 cm there is a varved clay containing red summer sediment and grey winter sediment; the thickness of the varves decreases from 5—8 cm at 12.5 m to 6—8 mm at 9 m. Above 915 cm the varves are not distinct, and above 880 cm no varves can be perceived in the homogeneous light reddish clay present up to 645 cm. Between 645 and 510 cm there is a grey clay with occasional thin sand layers and traces of indistinct varves. At 510 cm begins a bluish grey, clayey mud with numerous lumps coloured black by iron sulphide, especially at 510—465 and 375—305 cm. At about 135 cm the grey mud is succeeded by a greenish grey mud smelling of hydrogen sulphide with occasional thin brown layers consisting of plant debris.

The salinity of the interstitial water is represented in Fig. 4. Apart from minor irregular variations the salinity is constant in the top layer 0—135 cm consisting of green mud. It is on the whole increasing slowly with the sediment depth in the postglacial deposits 135—510 cm, from 10.2 to 11.4 ‰. In the layer consisting of homogeneous clay the salinity is again decreasing from 11.4 ‰ to about 10.6 ‰ at the top of the varved clay, and remains then constant to the undermost metre of the sand layer at the bottom of the core where the salinity decreases by about 1 ‰.

The retreating ice margin is supposed to have passed this station at 12,100 B.P., or 1,600 years before the invasion of sea water by Salpausselkä I. The number of varves present below 900 cm is less than 300 so it appears probable that most of the clay between 900 and 510 cm was deposited before Salpausselkä I. It is possible that the clay was deposited in fresh water and the salt was brought into it by diffusion after Salpausselkä I, but this does not appear likely if we consider St 24 and 25, where diffusion has not been able to smooth out the salinity gradients. It is therefore highly probable that the clay at St 33 was deposited in sea water with a salinity slightly higher than the one found there at present. The salinity in the varved clay is slightly lower than in the varved clay at the bottom of core 25 which was deposited about 400 years later according to the ice-margins laid down by De Geer, and in more shallow water.

Station 41. The station is situated between Gotland and Latvia. Only a 10 m corer was used which was not sufficient to reach down into the moraine. The core consists of varved clay from the lower end at 1,000 cm to about 290 cm where it is succeeded by a homogeneous brown-grey clay. This is covered by a bluish-grey clayey mud found between about 170 and 6 cm containing a few layers which are coloured black by iron sulphide. At the top of the core there is a thin layer of green mud. A longer core reaching down to the moraine will be collected at this station.

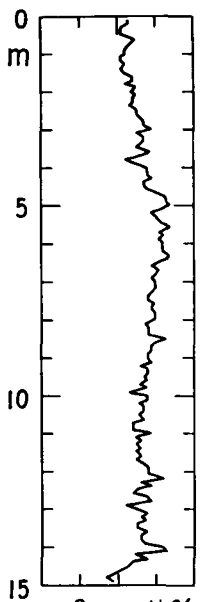

Fig. 4. The salinity of the interstitial water at station 33.

The salinity of the interstitial water is represented in Fig. 5. The salinity is decreasing with the sediment depth throughout the core, from 12,1 ‰ at the top to 9.4 ‰ at the lower end and the salinity gradient tends to increase with the depth in a similar way as at St 24. According to the ice-margins in Fig. 1 the varved clay should be contemporary with the one deposited at St 33. However, in the deeper portion of core 41 the salinity of the interstitial water is lower than in core 33, though the opposite would be the case if the deposits were really contemporary, as the water depth is greater at St 41 than at St 33. The positions of the ice-margins should be verified by varve measurements in cores collected in the Baltic. We shall postpone the discussion until this has been done and a set of cores reaching down into the moraine have been collected in this area.

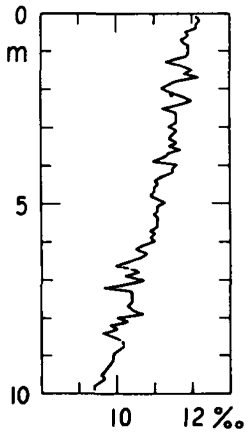

Fig. 5. The salinity of the interstitial water at station 41.

Station 52. This station is situated in the middle of the Baltic, between the island of Dagö and the Swedish coast. In the Baltic the echo-sounder commonly indicates a stratified bottom with six or more interfaces able to give rise to an echo. One of them divides the glacial clay from the clayey mud usually overlying it. In the area now in question the echo-sounder reveals that one interface giving a powerful echo rises to the surface very often, forming intervening depressions which are filled with comparatively soft deposits with a higher water content than found below the interface in question, as shown by cores collected in such depressions. At St 52 the interface in question has risen to the surface.

But for an 11 cm thick surface layer consisting of a homogeneous grey mud with a high content of organic matter, the core contains nothing but varved clay with a grey colour. The varves have a thickness of 1—2 cm near the top of the core, i.e. the distal glacial sediment is missing that should be expected on the top of the distinct varves. It would appear that erosion has removed the distal sediment. The varves are quite distinct and can be measured throughout the core. However, the varve sequence will not be discussed until longer cores have been obtained reaching down into the moraine.

The water content decreases with the sediment depth from 55 % by weight at the top of the core to 25 % at 900 cm. The salinity of the interstitial water keeps constant at about 10 ‰ throughout the core. The ice-margin is supposed to have passed this station at the same time as it passed St 25. It is noteworthy that the salinity of the interstitial water is smaller than in the deeper parts of core 25 in spite of the fact that the water depth is more than 40 m greater. As the core does not reach down to the moraine, no definite comparison with St 25 can be made, however, as it is quite possible that a longer core at St 52 would reveal an increase of the salinity with the sediment depth below 900 cm. Notwithstanding, the constancy of the salinity at St 52, as compared with the steady increase of the salinity at St 25 from the very top of the core, appears to contradict the possibility that the sea water apparently present in the Baltic at the time the varves found in the two cores were deposited, entered the Baltic from the east.

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