The salinity of the water contained in brackish-water sediments compared with the content of diatoms and other organisms in the same sediments

by

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Abstract

By comparing the salinity of water contained in sediments with the content of organisms in the same sediments it is shown that the salinity of the interstitial water does not correspond to that of the water in which the sediments were laid down; hence, the hypothesis advanced by B. KULLENBERG in 1952 cannot be tenable. The reason for this missing correlation must be the high coefficient of diffusion found by KULLENBERG for chlorine in the interstitial water but disregarded by him because of some of his results.

Introduction.

The paper of B. KULLENBERG (1952) promised an easy and exact method for determination of the salinity in prehistoric seas. The results given in his paper seemed to indicate that the water contained in marine sediments (the interstitial water) maintained the same salinity as that of the bottom water of the sea in which the sediments were laid down, at least for very long periods (several thousand years). This was in direct disagreement with the coefficient of diffusion of chlorine in sediments found by KULLENBERG in his laboratory experiments where the coefficient of diffusion in the sediments was found to be about 20 per cent of that in water. If the rate of diffusion in the sediments was as high as that, the differences in salinity ought to have levelled off during the time which has passed since the sediments were laid down. As KULLENBERG found variations in the salinity whicht seemed to be real and not levelled off, he thought that the reason why the coefficient of diffusion determined in the laboratory was much higher than the coefficient in the sediments *in situ*, was that the sediments had been disturbed during the sampling.

In an earlier paper, (MIKKELSEN, 1949) I discussed the variations in salinity in the Baltic Sea since the beginning of the Litorina period (5500BC). The changes in salinity found in an inlet of the Baltic (Præstø Fjord) were based mainly on an examination of the content of diatoms, but the content of molluscs and higher plants was also taken into consideration. These investigations showed the relative changes in salinity, but the real values could not be given because of incomplete knowledge of the salt ecology of the different diatoms.

When I read KULLENBERG's paper I became very interested in applying his method to my material from Præstø Fjord, partly in order to determine absolute values for the salinity of the Baltic in the different periods and partly in order to compare the results found by KULLENBERG's method with the results of the earlier investigations of diatoms, molluscs and other organisms in the sediments.

In early 1953 I visited "OCEANOGRAFISKA INSTITUTET" in Gothenburg, Sweden. Dr. KULLENBERG very kindly explained his methods to me and I wish to express my sincere thanks to him for the magnificent help he rendered me at that time.

As the sea salt found in the sediments had to be related to the amount of water contained in the same sediments (KULLENBERG, 1952, p. 3) it was impossible to use the samples kept from my earlier investigation of Præstø Fjord. In the summer of 1953, however, a new investigation at Præstø was made possible by a grant from the CARLSBERG FOUNDATION. For this grant I tender my respectful thanks. This paper was worked out in the Botanical Department of the ROYAL DANISH SCHOOL OF PHARMACY and I wish to express my best thanks to professor E. STEEMANN NIELSEN for his ever lasting interest in my investigations during the long time I worked in his department.

Methods.

The samples were drawn with a peat drill of the Hiller type with a chamber length of 50 cm. The new profile was made about 1 m. from Bp. 21 in the section from Even, Dalinge Gaard. Bp. 21 was the best examined profile in the Præstø Fjord area with regard to analyses of pollen, diatoms and molluscs. The characteristic layers in the section made it possible to correlate the profile of 1953 to the profile published earlier (MIKKELSEN, 1949, fig. 10 and Plate VIII). The errors in that correlation are less than 10 cm.

The samples were collected in undisturbed sediments in the middle of the chamber and placed immediately in glass tubes which were closed with a rubber stopper. The empty glass tubes had been weighed in the laboratory with an accuracy of 1 mg. The stoppering of the glass tubes was absolutely effective; previous experiments had shown that water samples in such tubes did not loose weight, not even if they were exposed to direct sunshine for several hours. The glass tubes containing the fresh samples were stored in a metal box and taken to the laboratory where they were weighed, with the same accuracy as before, immediately after the stopper had been removed. Now it was possible to compute the weight of the fresh samples in each glass tube (averaging 2 grammes but ranging from 1 to 5 grammes).

The samples were then airdried for somewhat more than a month and afterwards dried for 24 hours at 105° C, and finally the samples were placed in a dessicator and weighed.

Now it was possible first to compute the amount of water contained in each fresh sample and the dry weight of the same, and afterwards the percentage of water in each sample (based on the fresh weight). The content of water was usually very high, ranging from 78 to 94 per cent.

Each of the dry samples was then suspended in about 25 ml. distilled water and titrated with a N/20 solution of silver nitrate. The absolute strength of this solution was computed after titration of weighed volumes of normal seawater (19.379 $^0/_{00}$ Cl), diluted with distilled water to about 25 ml. 3 drops of potassium chromate were used for each titration. The titration of the water containing the suspended sample was stopped just before the absolute change in colour, the content of the cup was transferred to a glass tube for sedimentation. Afterwards, the clear solution was transferred to the cup and the titration was completed. In most cases it was necessary to repeat the last process in order to get the whole amount of salt out in the water. The amount of sea salt (based on chlorine) was determined with an accuracy of 0.1 mg.

The determinations of the interstitial water and the sea salt in the same sediments were rather exact, but because of errors caused by the sampling and the incompleteness of the drying of the samples the resulting salinity determinations were less exact than was to be expected. Thus it cannot be justifiable to record the salinity at an accuracy of more than 0.1 per mille, and the results (cfr. fig. 1) seems to indicate that only the whole per milles are correct. For two out of about 100 samples analysed the errors exceeded 1 per mille, viz. the samples taken at −495 cm and −645 cm.

Variation of the content of water and of the salinity in the samples from Præstø Fjord (Lake Even).

a. *Stratigraphy.* A more detailed description of the stratigraphy of the profile investigated will be found in MIKKELSEN, 1949, pp. 53–58. In this paper I shall only give a short summary of the description of the stratigraphy. The letters (a–g) used to identify the layers in the description and in fig. 1 are not the same as in the earlier paper.

	+20 cm.	to	−25 cm.:	Water.
a.	−25 cm.	to	−250 cm.:	Olive-grey-green slightly clayey *Ruppia*-gyttja.
b.	−250 cm.	to	−785 cm.:	Olive-grey-green *Cardium* clay-gyttja.
c.	−785 cm.	to	−809 cm.:	Dark olive-grey-green gyttja with *Najas* and *Ruppia*.
d.	−809 cm.	to	−811 cm.:	Dark olive-grey-brown gyttja with shells of *Valvata piscinalis*, *V. cristata* and *Limnaea ovata*.
e.	−811 cm.	to	−930 cm.:	Brown to dark reddish brown peat with many fruits and rhisomes of *Cladium mariscus*.
f.	−930 cm.	to	−1167 cm.:	Chalk gyttja with shells of *Bythinia tentaculata*, *Planorbis vortex* and other freshwater molluscs.
g.	−1167 cm.	to	:	Blue-grey clay (Late glacial).

b. *Water content.* The curve to the right in fig. 1 depicts the variation of the content of water (weight per cent) in the different layers. In the

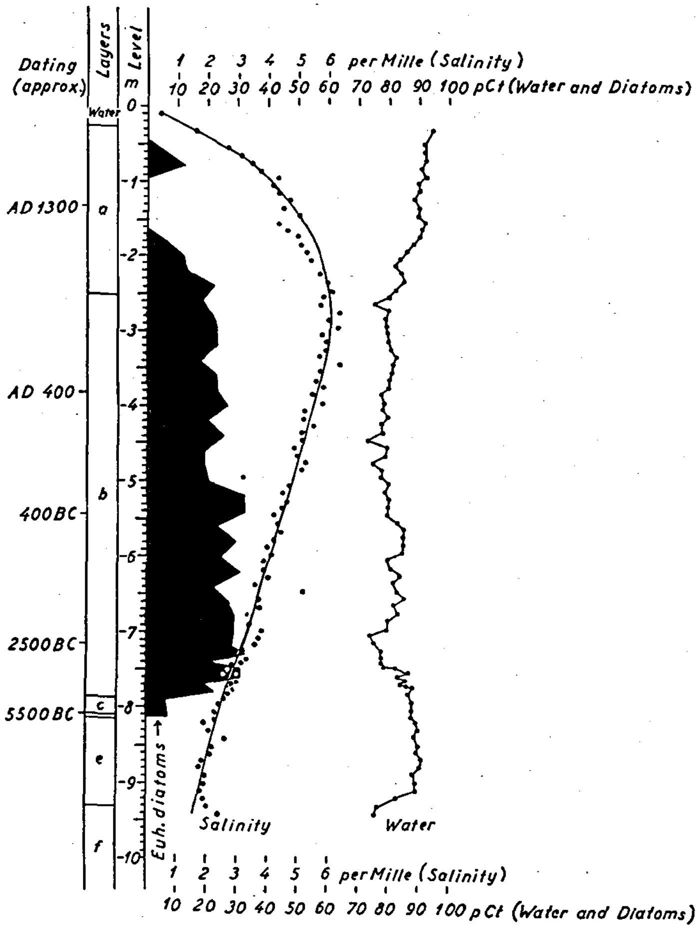

Fig. 1. From left to right: (1) black silhouette showing the percentage of euhalobious diatom species in the sediments (from MIKKELSEN, 1949, fig. 10); (2) the values of the salinity of the interstitial water at different depths (curve and big dots); (3) the percentage of water (by weight) in the sediments (curve with small dots).

upper *Ruppia*-gyttja (−25 cm to −250 cm) the water content is about 90 per cent. In the *Cardium* gyttja (−250 cm to −785 cm) there is less water (about 80 per cent), but in the gyttja between −785 and −809 the content of water increases to almost 90 per cent, and the peat (−811 cm to −930 cm) contains about 90 per cent water. In the upper part of the chalk gyttja the percentage of water again decreases to about 75 per cent in the lowermost sample.

c. *Salinity of the interstitial water.* The curve in the middle in fig. 1 shows the salinity of the interstitial water in the different layers. The values found differ only slightly from a smooth curve, and I have preferred to give the smooth curve instead of connecting the different points indicating the values of the salinity determined by the investigation.

The salinity of the water in Lake Even at Bp 21 was determined at 0.4 per mille. The interstitial water in the gyttja from −35 cm had a salinity of 1.6 per mille. From this depth the salinity increases until the gyttja between −240 cm and −350 cm, where there is a maximum of salinity of 6.0 per mille. From −350 cm downwards through the gyttja, peat, and chalk gyttja the salinity decreases to somewhat less than 2 per mille in the lowest sample investigated (at −940 cm).

As both the peat and the chalk gyttja were laid down in fresh water, no sea salt in the interstitial water could be expected according to the hypothesis of KULLENBERG; therefore I did not take samples from the lower part of the chalk gyttja. Hence it is impossible to tell to what depth the sea salt has penetrated, but the form of the curve seems to indicate that somewhere about − 1100 cm the value of the salinity will not be much above 0.

Discussion.

The changes of the salinity based on examinations of the content of molluscs and diatoms in Lake Even are discussed in MIKKELSEN, 1949, pp. 65–69 and pp. 139–147. The results may be summarized as follows:

The chalk-gyttja and the peat below −811 cm must have been formed in a fresh-water lake. Today, at least, such deposits will only be formed in fresh water, and the molluscs found in the chalk-gyttja (cfr. MIKKELSEN, 1949, Table IV, p. 65) live in fresh-water lakes today.

In view of the content of diatoms, in addition to *Ruppia* and *Najas*, the gyttja between −811 cm and −785 cm must have been deposited in a brackish-water inlet of the Baltic Sea with a salinity which was lower than that of Præstø Fjord of today (about 12 per mille) (cfr. MIKKELSEN, 1949, fig. 10 p. 68).

The gyttja between −785 and about −500 cm contains abundant shells of *Cardium edule* and *Mytilus edulis*; about 30 per cent of the diatom species belong to the euhalobious group; today Præstø Fjord, having a salinity about 12 per mille contains only about 20 per cent euhalobious diatom species. This shows that the Even inlet of that time (5000 BC to 400 BC) must have had a higher salinity than Præstø Fjord has today. The salinity of the inlet in which the gyttja between −500 cm and −250 cm was laid down was perhaps slightly lower than the salinity of the preceding period, but even so the salinity must have been the same size as it is in Præstø Fjord today, because the percentage of the euhalobious diatom species found in the gyttja is about 20, and closed shells of *Cardium* and *Mytilus* are rather abundant in the gyttja, which show that these molluscs were still able to live in the Even inlet of that time. The gyttja above −250 cm contains very few euhalobious diatoms and abundant seeds of *Ruppia* and *Najas* and spores of *Chara*. Moreover, the content of diatoms and molluscs indicates brackish water with a salinity lower than that of Præstø Fjord of today.

The salinity of the interstitial water does not agree with the results given above. Firstly, the salt maximum of the interstitial water is found in a layer several meters above the layers which were laid down at the time when the salinity was at its maximum in the Even inlet according to the content of fossils. Secondly, the maximum value of the salinity in the interstitial water is only 6 per mille, while a salinity of about 10 per mille could have been expected in the layers where the maximum is found and of about not less than 15 per mille in the layers laid down in the period with maximum salinity (the lower part of the Cardium-gyttja). Thirdly, the salinity of the interstitial water decreases smoothly from the brackish-water sediments down through layers deposited in fresh water.

The shape of the curve depicting the salinity in the interstitial water can be explained by the fact that in the course of time the diffusion of chlorine through the sediments has levelled off the differences between the original salinity. During the 4500 years which have passed since the sediments found at −700 cm were laid down most of the sea salt then contained in the interstitial water has diffused, partly downwards to layers originally containing less (layers down to −811 cm) or no sea salt at all (layers below −811 cm) and partly upwards to layers which have lost sea salt through diffusion to the lake above the sediments.

The reason why there are still considerable amounts of sea salt in the sediments even if there is very little salt in the lake today must be that the lake is of relatively recent origin, or in other words that Even became a lake after the connection with Præstø Fjord was cut off.

These studies thus suggest that the rate of diffusion for chlorine in the different sediments must be of such a magnitude that is is impossible to determine the salinity of the water in which the sediments were laid down on the basis of the salinity of the interstitial water.

The upper part of the sediments in Lake Even consists of typical brackish-water sediments laid down, at least partly, with a considerable rate of sedimentation. As it is inconceivable that other marine or brackish-water sediments should behave differently from that of the sediments of Even, it may be said with certainty that unfortunately Kullenberg's method cannot be used to determine the salinity of prehistoric seas at least where the sediments contain gyttja.

Comments on Kullenberg's results from the Baltic Sea.

Fig. 2 (p. 12) in Kullenberg, 1952 shows the changes in salinity in the interstitial water in cores from the bottom of the Baltic Sea. The results are discussed in the same paper on p.p. 10–14. It is shown that a maximum of salinity in the interstitial water is usually found in a layer of blue clayey mud. By a pollen-analytical study of the same cores from the Baltic (not yet published), I have been able to determine the age of that layer to be contemporary with the Ancylus Lake (about 6000 BC). The maxima of salinity are not very prominent in Kullenberg's graphs, and after my investigation at Lake Even I am not quite convinced that there are any true maxima in the graphs. The variations in the curves showing the salinity may be due to unsatisfactory sampling. In any case, it would be very surprising if the Ancylus Lake contained more sea salt in the bottom water than the following Litorina Sea which, according to the fossils in its sediments, must have had a higher salinity than the present-day Baltic Sea. The rather high salinity in the interstitial water of the Ancylus Lake sediments must be due to diffusion from overlying sediments. The decrease in salinity towards the surface of the sediments in St. 15 and St. 19 may be due to a quite recent decrease in the salinity of the bottom water in the Baltic Sea. This explanation is in complete agreement with the conditions in Lake Even where there is a considerable decrease in the salinity of the interstitial water towards the surface due to the recent change in Lake Even from brackish water to fresh water. In the curve depicting the variations of the salinity in St. 10 there is a minimum between 4 and 6 metres below the surface. The sediments between these levels were laid down in the Litorina Sea; if KULLENBERG's hypothesis was correct a maximum of salinity instead of a minimum was to have been expected. The minimum in the curve, however, is not very convincing, and I do not think it is significant. The possibility cannot be disregarded that the minimum may be due to errors in determining the salinity caused by the sampling (cfr. KULLENBERG, 1952, pp. 4–5).

DANSK RESUMÉ

B. KULLENBERG's afhandling (1952) gav rige løfter om en nem metode til at bestemme saltindholdet i fortidens have, idet hans undersøgelser tydede på, at vandindholdet i sedimenterne i alt fald gennem årtusinder bevarede den saltholdighed, der havde været i det vand, hvori sedimentet var blevet aflejret.

I en tidligere afhandling (MIKKELSEN, 1949) havde jeg beskæftiget mig med ændringerne af saltholdigheden i Østersøen gennem tiderne, væsentlig baseret på diatome- og molluskindholdet. Det var derfor af interesse at overføre KULLENBERG's metode til mit område (Præstø-egnen) for at sammenligne resultaterne af de to metoder og, hvis KULLENBERG's metode holdt, hvad den lovede, få nøjagtigere oplysninger om ændringerne i saltholdigheden.

Figur 1 viser resultaterne af den gamle undersøgelse i Even ved Præstø fjord sammenlignet med de nye undersøgelser. Den sorte silhouet viser procenten af de mest saltkrævende diatomearter (de euhalobe) i forhold til samtlige fundne diatomearter. De store punkter viser de fundne saltholdigheder (angivet i $^0/_{00}$ havsalt) i de forskellige dybder i profilet, og den optrukne kurve svarende til dem, fordelingen af saltholdigheden gennem lagserien. Yderst til højre i figuren er givet en kurve, der viser vandprocenten (vægtprocent) i prøverne.

Fordelingen af de euhalobe diatomeer skulle give et billede af saltholdighedsændringerne i fjorden gennem tiderne, dog uden absolutte værdier. Det viser sig, at kurven over de i sedimentvandet fundne saltprocenter på ingen måde er konform med diatomekurven. Yderligere finder man ca. 2 $^0/_{00}$ salt i vandet i sedimenter aflejret i fersk vand (lagene e og f), og i den nedre del af lag b, der efter indholdet af mollusker og diatomeer må være aflejret i vand med en større saltholdighed end Præstø fjord i dag (ca. 12 $^0/_{00}$), finder man kun 4—5 $^0/_{00}$. Øverst i lag b, hvor mollusk- og diatomindholdet tyder på en saltholdighed af samme størrelse som i dag, finder man kun ca. 6 $^0/_{00}$. Lag a må være aflejret, efter at Even var spærret af fra Præstø fjord, og saltholdigheden dengang må have været væsentlig lavere end nu. I dette lag finder man i alt fald nederst saltholdigheder i sedimentvandet, der nærmer sig maksimum.

Disse forhold sammen med kurvens form tyder i høj grad på, at de saltholdigheder, man finder i de forskellige dybder i sedimentvandet, er betinget af, at de oprindelige

saltkoncentrationer er blevet stærkt udjævnet på grund af diffusionen, dels opad til den ovenliggende sø og dels nedad til ferskvandsaflejringerne. Kurven siger således intet om den oprindelige størrelse af saltkoncentrationen og heller intet om den relative størrelse af saltkoncentrationen i de forskellige dybder. Metoden er derfor ikke brugbar til det påtænkte formål. Det må bemærkes, at allerede i nævnte afhandling påpegede Kullenberg, at det næsten var utænkeligt, at diffusionen ikke havde forstyrret billedet, men nogle af hans resultater fik ham til at tro, at der i sedimenter kunne være usædvanlig lave diffusionshastigheder.

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Færdig fra trykkeriet 7. januar 1956.